International Association of Geodesy

TRAVAUX

Volume 42

Reports 2019 – 2021

Edited for the IAG Scientific Assembly
Beijing, China
June 28 – July 2, 2021

Editor: Markku Poutanen

IAG Office
Finnish Geospatial Research Institute
Geodeetinrinne 2
02430 Masala, FINLAND

e-mail: IAG.Office@nls.fi
web: https://www.iag-aig.org

Contents

Introduction

The International Association of Geodesy (IAG) is publishing its reports regularly since 1923 (Tome 1). They were called "*Travaux de la Section de Géodésie de l'Union Géodésique et Géophysique Internationale*" in the first years. According to the renaming of the IUGG Sections as Associations, the name was changed in 1938 to "*Travaux de l'Association de Géodésie*". They are published on occasion of the IUGG General Assemblies, which were held every three years until 1963, and since then every four years. These volumes serve as a comprehensive documentation of the work carried out during the past period of three or four years, respectively. The reports were published until 1995 (Volume 30) as printed volumes only, and since 1999 (Volume 31) in digital form as CD and/or in the Internet.

Since 2001, there are also midterm reports published on occasion of the IAG Scientific Assemblies in between the General Assemblies. Usually they are presented before the Assembly to the IAG Executive Committee (EC) and are discussed in the EC meetings in order to receive and give advices for the future work. The present Volume 42 contains the midterm reports of all IAG components for the period 2019 to 2021 and is presented at the IAG Scientific Assembly in Beijing, China, June 28 to July 2, 2021.

The editors thank all the authors for their work. A feedback of the readers is welcome. The digital versions of this volume as well as the previous ones since 1995 may be found in the IAG Office homepage (http://www.iag-aig.org).

Markku Poutanen
IAG Secretary General

Commission 1 – Reference Frames

https://com1.iag-aig.org

President: Christopher Kotsakis (Greece)
Vice President: Jean-Paul Boy (France)

Structure

Sub-Commission 1.1:	Coordination of Space Techniques
Sub-Commission 1.2:	Global Reference Frames
Sub-Commission 1.3:	Regional Reference Frames
Sub-Commission 1.3a:	Europe
Sub-Commission 1.3b:	South and Central America
Sub-Commission 1.3c:	North America
Sub-Commission 1.3d:	Africa
Sub-Commission 1.3e:	Asia-Pacific
Sub-Commission 1.3f:	Antarctica
Sub-Commission 1.4	Interaction of Celestial and Terrestrial Reference Frames
Study Group 1.2.1:	Relevance of PSInSAR analyses at ITRF co-location sites
Joint Working Group 1.1.1:	Intra- and Inter-Technique Atmospheric Ties
Joint Working Group 1.2.2:	Methodology for surveying geodetic instrument reference points
Joint Working Group 1.2.3:	Towards reconciling Geocenter Motion estimates
Joint Working Group 1.4.3:	Consistent realization of TRF, CRF and EOP
Working Group 1.2.1:	Assessing impacts of loading on Reference Frame realizations
Working Group 1.3.1:	Time-dependent transformations between reference frame in deforming regions
Working Group 1.4.1:	Improving and unification of geophysical and astronomical modelling for better consistency of reference frames
Working Group 1.4.2:	Improving VLBI-based ICRF and comparison with GAIA-CRF

Overview

Commission 1 activities have been dealing with the theoretical aspects of how best to define terrestrial and celestial reference systems, and how such reference systems can be used for practical and scientific applications in Geodesy and the Geosciences. The reader is referred to the Geodesist's Handbook 2020 for further details on the objectives of Commission 1 and the descriptions of its entities. As shown above, Commission 1 consists of 4 Sub-Commissions (SC), whereby SC 1.3 is composed of 6 regional SCs, and also several Working Groups, Joint Working Groups and Study Groups. Most of these entities have been closely interacting with other IAG components including Commissions, Services, ICCT, ICCC and GGOS, where reference system aspects are of major concern. This report presents the activities performed during the period 2019-2021 by the various entities of Commission 1, most of which were very productive and made significant progress in their stated objectives and program of activities despite the severe impacts of the Covid-19 pandemic.

Activities during the reporting period 2019-2021

In addition to the work performed by the sub-components of Commission 1, the following list summarizes major activities in 2019-2021 that were pursued on behalf of the entire Commission:

- A new web site for Commission 1 was established at *https://com1.iag-aig.org* with the cooperation of the IAG Communication and Outreach Branch (COB), and it is hosted by the Department of Geodesy and Surveying at the Budapest University of Technology and Economics.
- The terms of reference and structure of Commission 1, as well as the membership and the descriptions of its sub-components were detailed in our contribution to the Geodesist's Handbook 2020.
- A new Steering Committee was formed, which is composed of the President and Vice-President, the Chairs of the 4 Sub-Commissions, one representative from IGS (Paul Rebischung), one representative from IERS (Detlef Angermann) and one IAG member-at large (Guangli Wang, China). During the 2019-2021 period, the Commission 1 Steering Committee did not meet physically due to travel restrictions imposed by the Covid-19 pandemic. Commission-related business were mostly conducted through email discussions and electronic exchange of information. The next business meeting of the Steering Committee is planned to take place during the IAG Scientific Assembly, Beijing, China in late June 2021.
- Traditionally, Commission 1 is linked with COSPAR and its Sub-Commission B2 "International Coordination of Space Techniques for Geodesy". Under the dual role as chair of Sub-Commission B2 and IUGG representative to COSPAR, the President of Commission 1 participated in several COSPAR-related events including the two-day COSPAR Council Meeting that was held in January 2021 during the 43rd COSPAR Scientific Assembly.
- Commission 1 was represented at all IAG Executive Committee Meetings, at which brief progress reports were presented:
    1. San Francisco, USA (December 2019);
    2. Online Zoom meeting (October 2020);
    3. Online Zoom meeting (March 2021).
- Commission 1 is represented in the Steering Committees of various IAG components, including the Inter-Commission Committee on Theory (ICCT), the Inter-Commission Committee on Climate Change (ICCC), the Inter-Commission Committee on Marine Geodesy (ICCM) and the IAG Project "Novel Sensors and Quantum Technology for Geodesy". Commission 1 is also represented in the ILRS Governing Board and the GGOS Executive Committee.
- The Commission President contributed an article to the IAG's regular column in *GIM International* featuring the Commission's scope, objectives, structure and scientific liaisons. The article appeared in the September/October magazine issue that was published in 2020 (Issue 4, vol.34).
- *IAG Scientific Assembly 2021, Beijing, China*. Commission 1 was strongly involved in the preparation of the scientific program of the virtual IAG Scientific Assembly 2021. The organization of Symposium 1 "Reference Frames" was coordinated by the President and it is

divided into 6 different sessions, some of them to be held jointly with Commission 2 and ICCT, with a total number of about 80 presentations.

- *Other events.* During the reporting period 2019-2021, Commission 1 was involved in the organization of several scientific conferences and workshops, as well as thematic sessions at EGU, AGU and COSPAR meetings, which are presented in detail in the following activity reports. Naturally, however, all these activities were severely limited due to the Covid-19 situation.
- *REFAF 2022.* Commission 1 is planning its next major scientific event, namely the IAG International Symposium on "Reference Frames for Applications in Geosciences", which will take place in October 2022 at Thessaloniki, Greece. Depending on the progress of the Covid-19 pandemic, it is foreseen that this will be a normal physical meeting in continuation of the traditional series of previous REFAG conferences.
- *COSPAR 2022.* In liaison with the COSPAR Sub-Commission B2, Commission 1 is organizing a scientific event entitled "*Space geodetic reference systems and frames: current state and future challenges for geodynamical investigations*" to take place in July 2022 during the 44th COSPAR Scientific Assembly at Athens, Greece.

Activities of Working and Study groups

Four WGs (WG 1.2.1, WG 1.3.1, WG 1.4.1, WG 1.4.2) are reporting to Commission 1 via the Sub-Commissions 1.2, 1.3 and 1.4. Four JWGs in cooperation with other entities, that is JWG 1.1.1 (jointly with GGOS and Sub-Commission 4.3), JWG 1.2.2 (jointly with IERS), JWG 1.2.3 (jointly with IERS) and JWG 1.4.3 (jointly with IERS and IAU Commission A2) are also reporting to Commission 1 via the Sub-Commissions 1.1, 1.2 and 1.4. Additionally, one SG (SG 1.2.1) is reporting to Commission 1 via the Sub-Commission 1.2. The activity reports of all these groups can be found in the following chapters of this document.

Commission 1 is actively involved in 8 JSGs and 1 JWG as a partner, but none of these groups report directly to Commission 1. Their activity reports can be found under the respective sections of the leading IAG entities (ICCT, ICCC, GGOS, Commissions 2 and 3).

The following pages provide individual reports for all IAG components that are primarily affiliated with Commission 1 and its Sub-Commissions.

Sub-commission 1.1: Coordination of Space Techniques

Chair: *Urs Hugentobler (Germany)*

Overview

Sub-commission 1.1 focuses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates, troposphere parameters, clock parameters, etc. As a result of their increasing tying options, the space geodetic techniques will be more and more closely linked together. The majority of GNSS satellites are e.g. equipped with SLR retroreflectors and it is foreseeable that a new generation of products makes joint use of GNSS and SLR measurements to the satellites. ESA is studying the technical feasibility of placing VLBI transmitter on Galileo satellites which would offer additional space ties between the techniques. As a consequence the Technique Services will be more tightly linked together too. A promising example was the organization of a joint ILRS-IGS session at the IGS workshop that was planned for Boulder in 2019 (but which unfortunately had to be postponed due to the Covid-19 situation), triggered through the representation of Commission 1 in the IRLS Governing Board.

The activities of the Joint Working Group 1.1.1 (which largely continues the work that was performed in the JWG 1.3 from the previous period 2015-2019) focus on the multi-sensor fusion through atmospheric ties in addition to already established ties such as the global (Earth rotation) and local (station coordinates) ties. More details on the recent and forthcoming activities of this working group are provided in following sections of this report.

Topics related to the work of Sub-Commission 1.1 were discussed at several conferences, including the AGU 2019 and 2020 Fall meetings, the EGU 2020 and 2021 meetings, and the COSPAR 2020 Scientific Assembly, in sessions related to geodetic infrastructure, consistent geodetic products, reference frames, and precise orbit determination. Several articles published in the period 2019-2021 address the combined use of the different space geodetic techniques (see below).

Bruni S, Rebischung P, Zerbini S, Altamimi Z, Errico M, Santi E (2018) Assessment of the possible contribution of space ties on-board GNSS satellites to the terrestrial reference frame. J Geod 92, 383-399, 10.1007/s00190-017-1069-z.

Bury G, Sośnica K, Zajdel R (2019) Multi-GNSS orbit determination using satellite laser ranging. J Geodesy 93, 2447-2463. 0.1007/s00190-018-1143-1.

Bury, G., Sośnica, K., Zajdel, R. et al. Determination of precise Galileo orbits using combined GNSS and SLR observations. GPS Solut 25, 11 (2021). 10.1007/s10291-020-01045-3.

Klopotek, G., Hobiger, T., Haas, R., Otsubo, T (2020): Geodetic VLBI for precise orbit determination of Earth satellites: a simulation study. J Geod 94, 56, 10.1007/s00190-020-01381-9.

Sośnica K, Bury G, Zajdel R, Strugarek D, Drożdżewski M, Kazmierski K (2019) Estimating global geodetic parameters using SLR observations to Galileo, GLONASS, BeiDou, GPS, and QZSS. Earth Planets Space 71(1):20. 10.1186/s40623-019-1000-3.

Štěpánek, P., Duan, B., Filler, V., Hugentobler, U. Inclusion of GPS clock estimates for satellites Sentinel-3A/3B in DORIS geodetic solutions. J Geod 94 (2020), 10.1007/s00190-020-01428-x.

Working Groups of Sub-commission 1.1

JWG 1.1.1: Intra- and Inter-Technique Atmospheric Ties

Chair: *Kyriakos Balidakis (Germany)*
Vice-chair : *Daniella Thaller (Germany)*

Members

- *David Coulot (France)*
- *Mateusz Drożdżewski (Poland)*
- *Claudia Flohrer (Germany)*
- *Changyong He (France)*
- *Robert Heinkelmann (Germany)*
- *Chaiyaporn Kitpracha (Germany)*
- *Frank Lemoine (USA)*
- *Lisa Lengert (Germany)*
- *Tobias Nilsson (Sweden)*
- *Arnaud Pollet (France)*
- *Víctor Puente (Spain)*
- *Marcelo Santos (Canada)*
- *Benedikt Soja (Switzerland)*
- *Krzysztof Sośnica (Poland)*
- *Jungang Wang (Germany)*
- *Xiaoya Wang (China)*
- *Dudy Wijaya (Indonesia)*
- *Karina Wilgan (Germany)*
- *Florian Zus (Germany)*

Activities and publications during the period 2019-2021

The activities of JWG 1.1.1 (hereinafter JWG) have been inspired by IAG JWG 1.3 of the 2015-2019 term. Building on the experience garnered during the last IUGG term, and the advances in the volume of geodetic data, the quality of space geodetic data analysis, as well as numerical weather prediction, JWG ventures further with its overarching goal being the enhancement of multi-sensor fusion employing atmospheric ties in addition to already established ties such as the global (Earth rotation) and local (station coordinates) ties. Some of the main obstacles in achieving that are the fact that there are very few software packages capable of performing consistent state-of-the-art analysis of space geodetic data from VLBI, GNSS, SLR, and DORIS, and that poorly understood – hence sub-optimally handled – effects manifest into spurious signals in the parameters of interest, that is, station coordinates, polar motion, length of day, and atmospheric delay coefficients. The next paragraphs provide an outline of our recent activities towards that goal.

A website describing the activities of this working group has been set up:
https://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/iag-jwg-atmospheric-ties/
as well as an area for sharing data and meeting (two so far) minutes:
ftp://ftp.gfz-potsdam.de/pub/home/kg/kyriakos/iag_jwg_atmospheric_ties/
and a mailing list: *atmtie@gfz-potsdam.de.*

The comparison of atmospheric delay coefficients (usually zenith delays and gradient vector components) estimated from the analysis of observations collected from co-located stations employing microwave signals has a scatter of 1cm or better. This figure varies as a function of time, instrumentation, site, analysis software, and sometimes analyst. To better understand these discrepancies, two studies were undertaken. First, to assess the performance of atmospheric tie determination employing different data sources (in situ observations, high-resolution numerical weather data, empirical meteorological models) and to understand the atmospheric delay coefficients' discrepancy stemming from instrumentation, we have organized an experiment. We have set up four GNSS stations with identical receivers and antennas on the rooftop of building A20 at GFZ Potsdam, varying the absolute height and whether a radome is installed. The results prove that all schemes tested to calculate atmospheric ties have similar performance, no instrumental effects were to be found in the atmospheric delay residuals, and employing or not a radome and near-field multipath effects introduce small but significant biases to the zenith delays at gradients. These investigations have been published in Kitpracha et al. (2021a). Second, since the observation geometry in space geodetic data analysis forces the estimates for station coordinates to be highly correlated with the atmospheric delay coefficient and clock estimates, we investigated the VLBI clock estimates. We have identified that a large number of jumps in the station clock time series have little to do with the performance of the local frequency standard (active hydrogen maser) and are associated with erroneous auxiliary data, namely spurious in situ meteorological observations, measurements of cable and phase calibration, as well as poor ambiguity resolution. Mis-handling these effects often manifests into erroneous signals in the estimated atmospheric delays, what impedes the rigorous intra- and inter-system combination employing atmospheric ties. Details may be found in Balidakis et al. (2021).

We have performed an intra-technique VLBI combination at the normal equation level during the VLBI CONT17 campaign, which offers the unique opportunity of having three networks overlapping in time. Kitpracha et al. (2021b) have performed the combination employing all available local and global ties, as well as atmospheric ties derived from the sigma-pressure levels of hourly ERA5 fields for the co-location sites at Wettzell (Germany) and Kokee Park (Hawai). An improvement was identified when atmospheric ties were imposed in addition to the other inter-system constraints (local and global ties).

A breakthrough regarding atmospheric tie investigations at the GFZ came with the implementation of a VLBI and SLR module in the GFZ version of the PANDA software, as well as the implementation of the capability to perform consistent combination of GNSS, VLBI, and SLR data at the observation level (Wang, 2021). While the combination at later stages (normal equation level or parameter level) is theoretically identical provided certain conditions are met, there are some practical implications which no longer pose a problem at the observation equation level. Early results involving all VLBI CONT campaigns suggest a large improvement in station coordinates, Earth orientation parameters, and atmospheric delay coefficients following a combination employing stochastic equality constraints to tie these three groups of unknown parameters. The weighting of these constraints has been thoroughly investigated and an optimal approach has been proposed. Since the number of GNSS observations employed in a global network solution is orders of magnitude larger than the number of VLBI observations in a typical IVS-R4 or even modern CONT session, of the two VLBI benefits the most. Further details may be found in Wang et al. (2021a; 2021b).

Calibration and instrumental issues aside, atmospheric ties between co-located stations observing in the same frequency domain are mainly driven by the height difference. While a first-degree ansatz is accurate enough to predict zenith delays between stations that differ tens of metres in terms of height, they are not reliable for differences of hundreds of metres or more. To this end, we have investigated how hydrostatic and non-hydrostatic atmospheric delays decay as a function of height, and we have proposed a parsimonious approach to reproduce profiles up to 15 km (Wang et al., 2021c).

Intra-technique comparisons are crucial to achieve the goal of JWG. Within a research DFG project Advanced MUlti-GNSS Array for Monitoring Severe Weather Events (AMUSE) performed at GFZ and TUB, different tropospheric parameters, i.e. zenith total delays (ZTDs), tropospheric gradients and slant total delays (STDs) from multi-GNSS solutions were calculated and compared. Three solutions: GPS-only, GPS/GLONASS and GPS/GLONASS/Galileo based on a dense German network SAPOS and a global network (GFZ/IGS) were taken into consideration. For the ZTDs and gradients all three solutions obtained very similar level of agreement against global numerical weather models (NWM): ERA5 and ICON (forecast model provided by DWD). For STDs, the GRE and especially the Galileo-only solution had a slightly better agreement with the NWM data, probably due to the use of the post-fit residuals, which contain more tropospheric information and less noise for Galileo than for the other systems. Some information about the project can be found in Wickert et al. (2020).

Since not all co-location sites are equipped with meteorological sensors and in most cases the relative position between the meteorological sensor and the reference point of the geodetic stations is not known accurately enough, numerical weather models are an invaluable resource in the derivation of atmospheric tie vectors. Prior to adopting these constraints in the combination procedure, the relative compatibility in the high- and low-frequency domain needs to be checked. The GNSS-derived precipitable water vapour (PWV) as one of the main products of GRUAN (Global Climate Observing System Reference Upper-air Network) of the World Meteorological Organization (WMO) has been developed during the last years at GFZ, the Central GNSS Data Processing Centre for GRUAN (Dick et al., 2021). In order to provide a timely quality check of the PWV estimates a monitoring system was installed at the GFZ. As a part of this system the timeseries of GNSS and ERA5 PWV for the GRUAN stations are accessible under
`ftp://ftp.gfz-potsdam.de/pub/GNSS/products/nrttrop/MONITORING_IFS/`.
A comprehensive study of employing ERA5-derived atmospheric delay models (mapping functions, zenith delays, higher order gradient components) has been undertaken as well. Different schemes of introducing these models into the VLBI data adjustment have been examined by Nilsson and Balidakis (2021).

A service for atmospheric delay models for geodetic systems employing microwave and optical waves has been developed at the GFZ and has been made publicly available. We employ ECMWF's ERA5 data at the native spatio-temporal resolution at hybrid sigma-pressure levels. For example, gridded zenith delays and mapping function coefficients are accessible through: `ftp://ftp.gfz-potsdam.de/pub/GNSS/products/gfz-vmf1/`.

IGN-France has considered the ties of both tropospheric delays and gradients as potential constraints in the TRF computation, since the tropospheric effects of the microwave techniques (GPS, VLBI and DORIS) are frequency-independent and follow the same theory. A brief summary is given as follows.

1. Different external sources of tropospheric delay and gradients to calculate the ZTD ties are examined. These sources include the model and reanalysis data: GPT3, VMF1-grid & VMF3-grid, ERA-Interim and ERA5.

2. Tropospheric ties from GRAD data provided by TU Wien are examined. No other gradient products are accessible. But 0 of gradient ties are reasonable if collocation sites are within a specific distance.
3. Different uncertainties of tropospheric ties are investigated (std = 0 mm, ~1 mm and ~10 mm) during the CONT14 campaign.
4. The influence of delay and gradient ties on the ZTD differences (GPS-DORIS and GPS-VLBI) is investigated separately during the CONT14 campaign.
5. The influence of tropospheric ties on the estimation of station positions is evaluated during the CONT14 campaign.

Further results from IGN-France will be presented at the IAG Scientific Assembly 2021.

SHAO has focused on the following during the first term: (i) nonlinear terrestrial reference frame and EOP determination based on the Singular Spectrum Analysis Method (Zhang et al.,2019); Update software for GNSS/SLR data processing and perform an SLR and GNSS repro following the resolutions of IGS and ILRS (Xi et al,2020,2021; Shao et al.,2019,2021; Zhang et al.,2019); (iii) preparation for the future STRF2020 nonlinear TRF and EOP, which will be provide new models and longer data; and (iv) preparation for atmospheric parameter combination via atmospheric ties. In particular, this nonlinear TRF is a little different from ITRF2014. Firstly, SHAO added the unlabelled jumps detection based on the sequential t-test analysis of regime shifts (STARS) algorithm which is an effective method for detecting jumps in GPS stations time series (Rodionov, 2004; Bruni, 2014). SHAO used the STARS algorithm combined with the generalized extreme studentized deviate (GESD) algorithm (Rosner, 1983) and manual inspection to detect unlabelled jumps contained in the time series. After that SHAO introduced them into the jump information file and recalculated the TRF. SHAO found that the station discontinuities have been repaired very well. Secondly, SHAO found there are some time-varying amplitude periodic signals in the GPS coordinate residual data which caused the station coordinates and velocity determination to be estimated incorrectly. And the accuracy and stability of the TRF are adversely affected. Therefore, SHAO used the Singular Spectrum Analysis (SSA) method to model non-linear time-varying amplitude periodic signals and fit all periodic signals (including annual, semi-annual and seasonal signals) not only annual and semi-annual signals, and also not the same periods for all sites. Thirdly, based on SSA variable-amplitude periodic signals extraction including annual and semi-annual, 34 weeks, 20.8 weeks, 17.3 weeks and so on periodic signals SHAO corrected the non-linear periodic signals and reprocessed the terrestrial reference frame to obtain a nonlinear terrestrial reference frame by CERS TRF and EOP established by SHAO. The two solutions of linear-STRF and nonlinear-STRF are named SOL-A and SOL-B respectively. SHAO compared and analysed its accuracy change from the aspects of the TRF datum definition parameters, station coordinates/velocity, and EOP results. After introducing periodic information and recalculating, the stability of the translation and scale is improved, but it is not particularly obvious, especially the translation parameters. It is maybe because that the periodic signal are mainly focused on GPS, and GPS does not participate in the determination of datum definition. Therefore, after introducing and eliminating the nonlinear time-varying amplitude periodic signals of GPS, the changes of the translation and scale factor are not big. For GPS sites, 10.8% of the station coordinate accuracy is better than 1mm and 4.4% of the station velocity accuracy result is better than 0.1mm/yr. The accuracy of the non-linear STRF (SOL-B) is significantly higher than that of the linear STRF (SOL-A), i.e. more stations are distributed in the high-precision level and less stations are distributed in the lower-precision level. For GPS, 44.5% of the station coordinate accuracy is better than 3mm, and 47.5% of the station velocity accuracy is better than 0.5mm/yr. For VLBI, 3.1% the accuracy of station coordinate comparison is better than 1mm and 3.1% the accuracy of station velocity is better than 0.1mm/yr. But for the SLR and DORIS, there are currently no station with coordinates and velocities better than 1mm and 0.1mm/yr. But there are 7.2% and 3.9% of the total stations with coordinates accuracy better than 3mm respectively and 11.3% and 4.5% of the total stations with velocity accuracy better than 0.5mm/yr for non-linear STRF (SOL-B) and the linear STRF (SOL-A) respectively. In comparison, DORIS results in lower precision. SHAO can conclude that the accuracy of the nonlinear TRF has been further improved after considering the influence of the time-varying amplitude periodic signals.

Unfortunately, state-of-the-art (past the ITRF2020 repro) SLR data analysis does not involve the modelling of atmospheric delay asymmetries, an effect usually treated by setting up gradient vector components as unknowns in the VLBI and GNSS adjustments. Since consistent modelling is a prerequisite for the inter-technique combination, Drożdżewski et al. (2019a; 2019b; 2020) and Sośnica et al. (2019a; 2019b) has investigated the improvement of applying gradients in the SLR data adjustment as well as refined mapping functions. An overall improvement was achieved by reducing the low-elevation angle residuals, and reducing the bias between SLR-derived polar motion with respect to polar motion from GNSS, VLBI, and the IERS C04 product, as well as mitigating a geocenter motion bias. The models used for this work are provided under: `ftp://ftp.gfz-potsdam.de/home/kg/kyriakos/PMF/SLR/`.

An overview of the JWG's past and planned activities will be presented at the session related to "Terrestrial and space geodetic ties for multi-technique combinations" during the IAG Scientific Assembly 2021.

Plans for the period 2021-2023

The main inter-institute activity planned is a combination benchmark/exercise. Given separate SINEX from the consistent analysis of GNSS, VLBI, SLR, and DORIS observations as well as SINEX including information regarding the local and atmospheric ties for two two-week periods (CONT14 and CONT17), we will perform a multi-technique combination where the parameter space will be inhabited by station coordinates, Earth orientation parameters, and atmospheric delay coefficients. Thus far, five different institutes have agreed to provide such a solution given the SINEX pool. Past the submission of the multi-technique solutions, an evaluation will be carried out. The most important conclusions will feature in an article authored by the contributors. Upon the article release, the SINEX pool will be made publicly available under a DOI. The timing for this exercise is opportune, since all institutes that plan a contribution have turned in a multi-year solution for at least one technique in the framework of the ITRF2020 re-processing, what might bring a higher consistency, or are officially involved in the multi-technique combination for ITRF2020.

Publications

Balidakis, K., J.M. Anderson, L. McCallum, J. McCallum, J. Wang, R. Heinkelmann, H. Dobslaw, H. Schuh (2021) On the Origin of Clock Breaks Detected in Geodetic VLBI Data Analysis (in preparation)

Dick, G., J. Jones, J. Wang, K. Rannat, J. Wickert, F. Zus, K. Balidakis, and K. Wilgan (2021) GNSS-based Precipitable Water Vapor: Certification for the Global Climate Observing System. First workshop of the Inter-Commission Committee on Geodesy for Climate Research of IAG, March 30th, 2021

Drożdżewski, M., J. Boisits, F. Zus, K. Balidakis, and K. Sośnica (2020) Recent studies on troposphere delay modeling for SLR, EGU2020

Drożdżewski, M., K. Sośnica, F. Zus, and K. Balidakis (2019a) Troposphere delay modeling with horizontal gradients for satellite laser ranging, Journal of Geodesy, doi: 10.1007/s00190-019-01287-1

Drożdżewski M., K. Sośnica, F. Zus, K. Balidakis, J. Boisits, J. Böhm, G. Bury, R. Zajdel, and D. Strugarek (2019b) Troposphere delay modeling in SLR solutions, ILRS Technical Workshop, Stuttgart, Germany

Kitpracha, C., R. Heinkelmann, M. Ramatschi, K. Balidakis, B. Männel, and H. Schuh (2021a) Validation of tropospheric ties at the test setup GNSS co-location site Potsdam, Atmospheric Measurement Techniques, doi: 10.5194/amt-2021-87

Kitpracha, C., T. Nilsson, K. Balidakis, S. Modiri, R. Heinkelmann, and H. Schuh (2021b) The impact of estimating common tropospheric parameters for co-located VLBI telescopes on geodetic parameters during CONT17, Journal of Geodesy (under revision)

Nilsson, T. and K. Balidakis (2021) Calibrating the Tropospheric Delays of VLBI Observations using Numerical Weather Prediction Models, EGU2021, doi: 10.5194/egusphere-egu21-11956

Shao Fan，Wang Xiaoya，He Bing， et al., Effect Analysis of the Weighting Scheme with Modified FCM Clustering Algorithm on Precision of SLR Orbit Determination[J],Acta Geodaetica et Cartographica Sini-ca,2019,48(10):1236-1243.

Shao Fan，Wang Xiaoya, Method Research and Feature Analysis on the Geocen-ter Motion Derived from SLR,PROGRESS IN ASTRONOMY[J], 2020, Vol.38(1):106-119.(In Chinese)

Sośnica, K., M. Drożdżewski, G. Bury, F. Zus, K. Balidakis (2019a) Consequences of Neglecting Horizontal Gradients of the Troposphere Delay in SLR Solutions, 27th General Assembly of the IUGG, Montréal, Canada.

Sośnica, K., M. Drożdżewski, F. Zus, K. Balidakis, J. Boisits, J. Böhm (2019b) Proposed Model for Horizontal Tropospheric Refraction Gradients, Unified Analysis Workshop, Paris, France.

Wang, J., K. Balidakis, M. Ge, R. Heinkelmann, and H. Schuh (2021) Integrated Processing of GNSS and VLBI on the Observation Level (in preparation).

Wang, J., K. Balidakis, M. Ge, R. Heinkelmann, and H. Schuh (2021) Improving VLBI Solution by Tropospheric Ties in GNSS and VLBI Integrated Processing (in preparation).

Wang, J. K. Balidakis, F. Zus, X. Chang, M. Ge, R. Heinkelmann, and H. Schuh (2021) Improved vertical modeling of tropospheric delay for space geodetic techniques (in preparation).

Wang, J. (2021) Integrated Processing of GNSS and VLBI on the Observation Level, Technische Universität Berlin.

Wickert, J., G. Dick, T. Schmidt, M. Asgarimehr, N. Antonoglou, C. Arras, A. Brack, M. Ge, A. Kepkar, B. Männel, C. Nguyen, T.S. Oluwadare, H. Schuh, M. Semmling, T. Simeonov, S. Vey, K. Wilgan, F. Zus (2020) GNSS Remote Sensing at GFZ: Overview and Recent Results, Zeitschrift für Geodäsie, Geoinformation und Landmanagement, doi: 10.12902/zfv-0320-2020.

Xi Kewei, Wang Xiaoya,Zhang Yan et al., Updates of IGS14 terrestrial refer-ence frame and its effect on GPS precise prbit determination ［J］.Science of Surveying and Mapping, 2020,Vo1.45(8):26-32.(In Chinese)

Xi Kewei, Wang Xiaoya, Higher order ionospheric error correction in BDS precise orbit determination[J],Advances in Space Research, 67 (2021) 4054–4065.

Zhang Jing, Wang Xiaoya, Hu Xiaogong, Analysis of GPS stations'time series Based on PCA method, Journam of Geodesy and Geodynamics, 2019,39(06):613-619. (In Chinese)

Zhang Yan，Wang Xiaoya，Xi Kewei，et al. Impact Analysis of Solar Irradiance Change on Precision Orbit Determination of Navigation Satellites ［J］. Transactions of Nanjing University of Aeronautics and Astronautics, 2019, 36(6): 889-901.

Sub-commission 1.2: Global Reference Frames

Chair: *X. Collilieux (France)*

Contributors to this report:
L. Sanchez
Z. Altamimi

Overview

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). It studies fundamental questions and more practical aspects that can improve current terrestrial reference frame (TRF) determinations. The terms of reference of the sub-commission can be found in pages 94-95 of (Poutanen and Rózsa, 2020) and won't be repeated here.

Numerous activities related to this topic are realized in other IAG-related structures, namely:

- International Earth Rotation and Reference Systems Service (IERS)
- Other relevant IAG services (IGS, ILRS, IVS, IDS)
- IAG Global Geodetic Observing System (GGOS):
- GGOS Focus Area "Unified Height System"
- BNO C1: GGOS Committee on Performance Simulations and Architectural Trade-Offs (PLATO)

We therefore encourage the reader to refer to their individual reports. In addition to this report, updated information on the activity of the sub-commission 1.2 can be found on the IAG commission 1 website at *https://com1.iag-aig.org/sub-commission-12*.

Activities during the period 2019-2021

ITRF2020

A call for participation for providing ITRF2020 input data was realised by the IERS in January 2019 (IERS, 2019). The IERS technique services are expected to provide geodetic station time series with their covariance matrices (or normal equations) for their respective techniques by May 2021. Compared to ITRF2014 (Altamimi et al., 2014), six years of additional observations will become available, including new sites and new local tie vectors. At the time of the writing of this report, the input solutions provided by the international Doris Service (IDS), the international GNSS service IGS, the International Laser Ranging Service ILRS and International VLBI Service (IVS) are under analysis by the IERS combination centers, namely DGFI, IGN and JPL. Details on the combination centres and their contribution to previous ITRF2014 analysis can be found in (Altamimi Z. and Dick W. R. (eds.), 2020; Dick and Thaller (eds.), 2020).

The Session 1.1 of the IAG 2021 Scientific Assembly entitled "1.1: International Terrestrial Reference Frame: strengths, weaknesses and strategies for future improvements" will be dedicated to presentations and discussion about ITRF2020 analysis and the processing of its input data.

Global height reference frame

The GGOS Focus Area "Unified Height System" works on the implementation of the International Height Reference System (IHRS) and its realization, the International Height Reference Frame (IHRF). During the last two years, a strategy for the establishment of the IHRF was defined. This strategy comprises the appropriate handling of permanent tide effects in the determination of IHRF coordinates in the mean-tide system, the determination and evaluation of IHRF coordinates depending on the data availability (specially surface gravity data and topography models), the improvement of the input data required for the determination of IHRF coordinates, the station selection in regional and national densifications of the IHRF, and the organizational infrastructure required to ensure the usability and long-term sustainability of the IHRF (see Sánchez et al. 2021). The IHRF is based on the combination of a geometric component given by ITRF station coordinates and a physical component given by the determination of potential values at the positions defined by the ITRF coordinates. Consequently, the link between IHRF and ITRF is unavoidable. Currently, the GGOS Focus Area "Unified Height System" is focused on the determination of a first static solution for the IHRF. More details can be found in the GGOS Focus Area "Unified Height System" report.

Correspondent member of the sub-commission: L. Sanchez

Publications

Altamimi Z, P. Rebischung, L. Métivier, X. Collilieux, K. Chanard, 2021, ITRS Center Report : IERS DB72, presentation to the IERS directing board meeting 72, may

Altamimi Z. and Dick W. R. (eds.) (2020), Description and evaluation of DTRF2014, JTRF2014 and ITRF2014, (IERS Technical Note ; 40) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2020. 167 p., ISBN 978-3-86482-137-0 (print version)

Altamimi, Z., P. Rebischung, L. Metivier, and X. Collilieux (2016), ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, J. Geophys. Res. Solid Earth, 121, doi:10.1002/2016JB013098

IERS, 2019, ITRF2020 Call for participation, https://itrf.ign.fr/doc_ITRF/CFP-ITRF2020.pdf

Dick W. R. and D. Thaller (Ed.) (2020), IERS Annual Report 2018, Edited by. International Earth Rotation and Reference Systems Service, Central Bureau. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2020. 207 p., ISBN 978-3-86482-136-3 (print version)

Poutanen, M. and Rózsa, S. (2020). The Geodesist's Handbook 2020. *Journal of Geodesy*, *94*(11), 1-343.

Sánchez L., Ågren J., Huang J., Wang Y.M., Mäkinen J., Pail R., Barzaghi R., Vergos G.S., Ahlgren K., Liu Q. (2021). Strategy for the realisation of the International Height Reference System (IHRS). Journal of Geodesy, 95(3), https://doi.org/10.1007/s00190-021-01481-0

Working Groups of Sub-commission 1.2

WG 1.2.1: Assessing impacts of loading on Reference Frame realizations

Chair: *Anthony Mémin (France)*
Vice-chair : *Anna Klos (Poland)*

Members
- Jean-Paul Boy (France)
- Kristel Chanard (France)
- Benjamin Maennel (Germany)
- Anthony Mémin (France), Chair
- Laurent Métivier (France)
- Manuela Seitz (Germany)
- Giorgio Spada (Italy)
- Daniela Thaller (Germany)
- Wouter van der Wal (The Netherlands)

Activities during the period 2019-2021

Due to the global health crisis the activity of the working group has been low. However several papers have been published by the group members about topic directly related to the group activities. These papers are highlighted below.

We have also created a list of references related to loading and geodetic studies that will be available online by the end of 2021 and updated regularly.

A meeting with the group members will be organized by the end of 2021 and a workshop will be organized in 2022 (in Nice ?).

In May 2021, Anna Kloss (Poland) accepted to co-chair the working group.

Publications

Bian Y, Yue J, Li Z, Cong K, Li W, Xing Y (2020) Comparisons of GRACE and GLDAS derived hydrological loading and the impact on the GPS time series in Europe. Acta Geodyn Geomater 17(3):297–310. https:// doi. org/ 10. 13168/ AGG. 2020. 0022

Chanard K, Métois M, Rebischung P, Avouac J-P (2020) A warning against over-interpretation of seasonal signals measured by the Global Navigation Satellite System. Nat Commun 11:1375. https:// doi. org/ 10. 1038/ s41467- 020- 15100-7

Ferreira VG, Liu Z, Montecino HC, Yuan P, Kelly CI, Mohammed AS, Han LY (2020). Reciprocal comparison of geodetically sensed and modeled vertical hydrology loading products. Acta Geodaetica et Geophysica 53, 23–49. DOI:10.1007/s40328-019-00279-z.

Ferreira VG, Montecino HD, Ndehedehe CE, del Rio RA, Cuevas A, de Freitas SRC (2019). Determining seasonal displacements of Earth's crust in South America using observations from space-borne geodetic sensors and surface-loading models. Earth, Planets and Space 71, 84. DOI:10.1186/s40623-019-1062-2.

Glomsda M., Bloßfeld M., Seitz M., Seitz F. (2021), Correcting for site displacements at different levels of the Gauss-Markov model – A case study for geodetic VLBI, Advances in Space Research, https://doi.org/10.1016/j.asr.2021.04.006

Glomsda M., Bloßfeld M., Seitz M., Seitz F. (2020). Benefits of non-tidal loading applied at distinct levels in VLBI analysis, J. Geodesy, 94 (90), doi: 10.1007/s00190-020-01418-z

Klos A., Dobslaw H., Dill R., Bogusz J. (2021). Identifying the sensitivity of GPS to non-tidal loadings at various time resolutions: examining vertical displacements from continental Eurasia

Lenczuk A., Leszczuk G., Klos A., Kosek W., Bogusz A. (2020). Study on the inter-annual hydrology-induced deformations in Europe using GRACE and hydrological models, J. Appl. Geodesy, 14 (4), 393-403

Lin W., Thaller D., Susnik A., Dach R. (2021). Improving the products of global GNSS data analysis by correcting for loading displacements at the observation level, EGU General Assembly

Männel B, Dobslaw H, Dill R, Glaser S, Balidakis K, Thomas M, Schuh H (2019) Correcting surface loading at the observation level: impact on global GNSS and VLBI station networks. J Geod 93:2003–2017. https:// doi. org/ 10. 1007/ s00190- 019- 01298-y

Mémin, A., Boy J.-P., Santamaría-Gómez A.(2020). Correcting GPS measurements for non-tidal loading, GPS Solutions, 24, 45, doi: 10.1007/s10291-020-0959-3.

2019

Nicolas, J.; Verdun, J.; Boy, J.-P.; Bonhomme, L.; Asri, A.; Corbeau, A.; Berthier, A.; Durand, F.; Clarke, P. (2021) Improved Hydrological Loading Models in South America: Analysis of GPS Displacements Using M-SSA. Remote Sens., 13, 1605. https://doi.org/10.3390/rs13091605

Singh V. V., Biskupek L., Müller J., Zhang, M. (2021), Impact of non-tidal station loading in LLR, Adv. Space Res., 67, 3925-3941, doi: 10.1016/j.asr.2021.03.018

Springer A, Karegar MA, Kusche J et al (2019). Evidence of daily hydrological loading in GPS time series over Europe. Journal of Geodesy 93, 2145–2153. DOI: 10.1007/s00190-019-01295-1.

JWG 1.2.2: Methodology for surveying geodetic instrument reference points

Chair: *Ryan Hippenstiel (USA)*
Vice-chair : *Sten Bergstrand (Sweden)*

Members (Member list will be updated as WG develops and confirmation is received.)
• Zuheir Altamimi (IGN, France)
• Sten Bergstrand (BIPM, France)
• Steven Breidenbach (NOAA/NGS, USA)
• Benjamin Erickson (NOAA/NGS, USA)
• Cornelia Eschelbach (FRA UAS, Germany)
• Kendall Fancher (NOAA/NGS, USA)
• Charles Geoghegan (NOAA/NGS, USA)
• Rudiger Haas (Chalmers, Sweden)
• Ryan Hippenstiel (NOAA/NGS, USA)
• Christopher Holst (Technische Universität München, Germany)
• Kevin Jordan (NOAA/NGS, USA)
• Jack McCubbine (GA, Australia)
• Damien Pesce (IGN, France)
• Jerome Saunier (IGN, France)
• Elena Martínez Sánchez, (Observatorio de Yebes, Spain)
• Daniela Thaller, (BKG, Germany)

Correspondent Members
• Xavier Collilieux (IGN, France)
• Mike Pearlman (Harvard/GGOS, USA)
• Robert Heinkelmannm, (GFZ, Germany)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation. Our group has a new set of terms and has received confirmation of new participants in the group. We would continue to encourage participation from any agency or community that is conducting research, improving protocols, or completing field surveys of local ties as sites with various space geodesy techniques present. Our group has continued to share improved protocols, technologies, and instrumentation to provide the most accurate tie measurements possible for all sites around the world. We reminded participants to share their contributions of local tie data for inclusion into ITRF2020 and many were submitted.

Activities during the period 2019–2021

Improvements have been made to standardize report and data submissions of local tie surveys to provide consistency across all agencies. Survey data has recently been reported with new standards in place.

The group is continuing to explore methodologies to measure and quantify antenna deformation. Research and continued field tests using laser scanning and terrestrial inSAR have been discussed. Members completed and documented work researching site-dependent GNSS antenna calibrations to account for systematic errors and biases.

Measurements were collected at the Zeppelin Observatory (Svalbard, Norway) and Hartebeesthoeck has been reprocessed (Muller et al., 2020). The latter was assisted by updating of local software to allow estimating VLBI and SLR references points from raw survey data into one single processing.

The US National Geodetic Survey conducted an IERS local site survey at the National Radio Astronomy Observatory in Maui (GNSS and SLR), the Table Mountain Geophysical Observatory in Colorado (new GNSS, gravity), Midway Naval Research Laboratory's OTF in Virginia (GNSS and SLR), and the International Earth Rotation and Reference Systems Service (IERS) Mauna Kea site (VLBA). Surveys were paused in the spring of 2020 due to the COVID pandemic and have not yet resumed fully. It is hopeful that recon and survey efforts will begin again in the fall of 2021.

NGS fully implemented the use of an absolute laser tracking system (Leica AT402) into all completed tie surveys, enhancing precision of terrestrial observations. Progress was made on technical memorandum documenting current NGS procedures which will be released and reflect upon IERS TN39.

NGS has developed deflection of vertical (DoV) measurement capabilities utilizing a robotic total station and camera, and will continue testing equipment in 2021 for hopeful deployment on upcoming local tie surveys.

Publications

Eschelbach, C., Lösler, M., Haas, R., Greiwe (2020) A.: Untersuchung von Hauptreflektordeformationen an VGOS-Teleskopen mittels UAS. In: Wunderlich, T.A. (Eds.): Ingenieurvermessung 20: Beiträge zum 19. Internationalen Ingenieurvermessungskurs, Wichmann, pp. 411-424, ISBN: 978-3-87907-672-7

Eschelbach, C., Lösler, M., Haas, R., Fath, H. (2019) Extension and Optimization of the Local Geodetic Network at the Onsala Space Observatory. In: Proceedings of the 10th IVS General Meeting, Svalbard, pp. 27-31, NASA/CP-2019-219039.

Fancher, K., Hippenstiel, R. (2019) US National Geodetic Survey - Recent and Planned Local Site Survey Activites. Proceedings of the Unified Analysis Workshop 2019.

http://ggos.org/media/filer_public/ff/67/ ff679767-62ec-4065-acfc-3394ae85d573/uaw_sitesurvey_1-hippenstiel_usnationalgeodeticsurvey.pdf

Lösler M., Eschelbach C., Riepl S., Schüler T. (2019) A Modified Approach for Process-Integrated Reference Point Determination. Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, 17-19 March 2019, Las Palmas de Gran Canaria, Spain, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, :172-176 DOI: 10.7419/162.08.2019

Lösler, M., Haas, R., Eschelbach, C., Greiwe, A. (2019) Gravitational Deformation of Ring-Focus Antennas for VGOS - First Investigations at the Onsala Twin Telescopes Project. Journal of Geodesy, Vol. 93(10), pp. 2069-2087, DOI: 10.1007/s00190-019-01302-5

Mähler, S., Klügel, T., Lösler, M., Schüler, T., Plötz, C. (2019) Permanent Reference Point Monitoring of the TWIN Radio Telescopes at the Geodetic Observatory Wettzell. In: Proceedings of the 10th IVS General Meeting, Svalbard, pp. 251-255. NASA/CP-2019-219039

Pesce, D., Saunier J. (2019) IGN Recent and Planned Local Site Survey Activities & Contribution to the EURAMET GeoMetre Project. Proceedings of the Unified Analysis Workshop 2019. http://ggos.org/media/filer_public/9f/b6/9fb60a43-3d60-4218-9f48-89ac81073b79/ uaw_sitesurvey_2-saunier_ignrecentactivities.pdf

<u>Co-location survey online reports:</u>
http://itrf.ign.fr/local_surveys.php
https://www.ngs.noaa.gov/corbin/iss/

- Erickson, B., Breidenbach, S., Jordan, K. Maui co-location survey, June 2019
- Jordan, K., Hippenstiel, R., Erickson, B., Fancher, K. Stafford co-location survey, October 2019
- Jordan, K., Hippenstiel, R., Fancher, K. Table Mountain co-location survey, October 2019
- Jordan, K., Hippenstiel, R., May, J. Mauna Kea co-location survey, October 2019
- Muller J.-M., Pesce D., Collilieux X., 2014 Hartebeesthoek co-location survey reprocessing report, dec 2020

JWG 1.2.3: Toward reconciling Geocenter Motion estimates

Chair: Kristel Chanard (France)
Vice-chair : Alexandre Couhert (France)

Members

- Kristel Chanard (France), Chair
- Xavier Collilieux (France)
- Alexandre Couhert (France), Vice-Chair

• Robert Dill (Germany)
• Suzanne Glaser (Germany)
• Christopher Kotsakis (Greece)
• Flavien Mercier (France)
• Laurent Métivier (France)
• Paul Rebischung (France)
• John Ries (USA)
• Ricardo Riva (Nehterlands)
• Krystof Sosnica (Poland)
• Dariusz Strugarek (Poland)
• Xiaoping Wu (USA)
• Radoslaw Zajdel (Poland)

Overview

The objective of this working group is:

- To review all methods to estimate geocenter motion, both from geodetic data and forward geophysical modelling, and systematically compare results.
- To focus on discrepancies in geocenter motion estimates and investigate potential biases in methods and/or systematic errors in geodetic products.
- To study the relative merit of geocenter motion data types (SLR, DORIS, GNSS, GNSS+LEOs). Special emphasis should be placed in evaluating the network-effect biases.
- To evaluate consistencies in methods used to retrieve geocenter motion (translational and inverse approaches, forward modelling).
- To assess the impact of errors in geocenter motion through variability in estimates for operational and scientific users.

Activities during the period 2019-2021

Two papers, Meyssignac et al. (2019) and Blazquez (2020), relevant to this working group were recently published. Their work highlighted for the first time that the geocenter (with GIA) correction was the highest uncertainty in GRACE-based global water budgets and estimations of the Earth’s Energy Imbalance. Such results further provide strong arguments towards the need to improve our understanding and modeling of this motion, especially to assess the current status of climate change and its future evolution.

Publications

Blazquez A. (2020) “Satellite characterization of water mass exchange between ocean and continents at interannual to decadal timescales”, Phd, Université Paul Sabatier - Toulouse III

Couhert, A., Bizouard, C., Mercier, F., Chanard, K., Greff, M. and Exertier, P. (2020) Self-consistent determination of the Earth’s GM, geocenter motion and figure axis orientation. Journal of Geodesy, 94(12), pp.1-16.

Meyssignac Benoit, Tim Boyer, Zhongxiang Zhao, Maria Z. Hakuba, Felix W. Landerer, Detlef Stammer, Armin Köhl, et al. (2019) “Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance”. *Frontiers in Marine Science* 6.

Study Groups of Sub-commission 1.2

SG 1.2.1: Relevance of PSInSAR analyses at ITRF co-location sites

Chair: Xavier Collilieux (France)

Members
• Xavier Collilieux (ENSG Paris, France)
• Thomas Fuhrmann (Geoscience Australia, Australia)
• Stefan Friedländer (BKG, Germany)
• Thomas Gruber (TU Munich, Germany)
• Clément Courde (CNRS, France)
• Christoph Gisinger (DLR, Germany)
• Francesco DeZan (DLR, Germany)
• Amy Parker (Curtin University/CSIRO Australia)
• Munekane Hiroshi (GSI Japan, Japan)

Correspondent Members
• Ann Chen (UT Austin, USA)

Overview

The objective of the working group is to investigate if PSInSAR technique can be used to supplement local tie survey at ITRF multi-technique sites. The program of activities is the following:

• List strength and weakness of the PSInSAR technique for this application
• Collect all studies related to INSAR and more particularly PSInSAR at co-location sites
• If relevant, make an inventory of SAR images (for all missions) available at ITRF co-location sites
• If relevant, identify multi-technique co-location sites where PSInSAR processing should be performed and compare InSAR results from various software packages
• Compare results of free, but low-resolution, Sentinel-1 data with commercial high-resolution data (e.g. TerraSAR-X) where available; investigate whether a request for a supersite could be used to obtain additional high-resolution data (see *https://www.earthobservations.org/documents/gsnl/20120918_GSNL_CEOSSelectionProcess.pdf*)
• Investigate the relevance of installing corner reflectors or transponders at co-location sites
• Report conclusions and recommendations in IUGG2023 proceedings

Activities during the period 2019-2021

Two papers related to InSAR determination of ground motion at co-location sites are worth mentioning in this report. Poreh and Pirasteh (2020) studied ground deformation at Medicina co-location site from the end of 2009 to the end of 2011 using CosmoSkyMed X-band images. Indeed, in this site, a VLBI telescope and two GNSS stations are co-located. Unfortunately, the density of the Persistent Scatterers (PS) they obtained was not sufficient to investigate relative motion between instruments. No PS has been found on the VLBI telescope probably due to continuous VLBI telescope motions. However, Parker et al. (2019) showed than when oriented toward satellites, VLBI instruments can be efficient radar reflectors.

A web-meeting of the study group will be organized in mid-2021.

Thomas Fuhrmann (Australia) who actively contributed to the creation of the study group cannot continue his activity as vice-chair of the group.

Publications

Collilieux, X., C. Courde, B. Fruneau, M. Aimar, G. Schmidt, I. Delprat, D. Pesce and G. Wöppelmann (2021) *Radar Corner Reflector installation at the OCA geodetic Observatory (France)*, IAG 2021 general assembly, jun 2021, *submitted*

Poreh, D., Pirasteh, S. (2020). InSAR observations and analysis of the Medicina Geodetic Observatory and CosmoSkyMed images. Natural Hazards, 103(3), 3145-3161.

Parker, A. L., McCallum, L., Featherstone, W. E., McCallum, J. N., & Haas, R. (2019). The potential for unifying global-scale satellite measurements of ground displacements using radio telescopes. Geophysical Research Letters, 46(21), 11841-11849.

Sub-commission 1.3: Regional Reference Frames

Chair: Carine Bruyninx (Belgium)

Overview

Sub-commission 1.3 contains six regional Sub-commissions (SC)

- Sub-commission 1.3 a: Europe
- Sub-commission 1.3 b: South and Central America
- Sub-commission 1.3 c: North America
- Sub-commission 1.3 d: Africa
- Sub-commission 1.3 e: Asia-Pacific
- Sub-commission 1.3 f: Antarctica

and one Working Group (WG) "Time-dependent transformations between reference frames in deforming regions".

This mid-term report gathers the contributions of the above regional sub-commissions and WG for the period 2019-2021. As stated in the Terms of Reference, IAG Sub-commission SC1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organizations.

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:

- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the efforts of the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) towards a sustainable Global Geodetic Reference Frame (GGRF).

The reports of all regional sub-commissions (except Africa) are presented hereafter.

Sub-Commission 1.3a: Europe (EUREF)

Chair: Martin Lidberg (Sweden)

Introduction and Structure

The long-term objective of EUREF, as defined in its Terms of Reference is "the definition, realization and maintenance of the European Reference Systems, in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-Commission projects) as well as EuroGeographics". For more information, see *http://www.euref.eu*.

The results and recommendations issued by the EUREF sub-commission support the use of the European Reference Systems in all scientific and practical activities related to precise georeferencing and navigation, Earth sciences research and multi-disciplinary applications. EUREF applies the most accurate and reliable terrestrial and space-borne geodetic techniques available, and develops the necessary scientific principles and methodology. Its activities are focused on a continuous innovation and on evolving user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- Maintenance of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade of the respective realizations;
- Refining the EUREF Permanent Network (EPN) in close cooperation with the International GNSS Service (IGS);
- Improvement of the European Vertical Reference System (EVRS);
- Contribution to the IAG Project GGOS (Global Geodetic Observing System) using the installed infrastructures managed by the EUREF members.

These activities are reported and discussed at the meetings of the EUREF Governing Board (GB), which take place three times a year, and the annual EUREF Symposia, an event that occurs every year since 1990. The EUREF symposia have an attendance of about 100-120 participants from more than 30 European countries and other continents, representing mainly Universities, Research Centres, and NMCAs (National Mapping and Cadastre Agencies). EuroGeographics (the consortium of the European NMCAs) supports the organization of the EUREF Symposia, reflecting the importance of EUREF for practical purposes. The latest EUREF symposia took place 2018 in Amsterdam, The Netherlands and 2019 in Tallinn, Estonia. The 2020 symposium scheduled for Ljubljana, Slovenia, was cancelled. The 2021 symposium is organized as online event by the Slovenian colleagues.

Members

- *Elmar Brockmann (Switzerland)*
- *Carine Bruyninx (Belgium)*
- *Rolf Dach (Switzerland)*
- *Ambrus Kenyeres (Hungary)*
- *Karin Kollo (Estonia, EUREF secretary, ex-officio)*
- *Juliette Legrand (Belgium)*
- *Martin Lidberg (Sweden, EUREF chair, ex-officio)*
- *Tomasz Liwosz (Poland)*
- *Rosa Pacione (Italy)*
- *Martina Sacher (Germany)*
- *Wolfgang Söhne (Germany, GB chair)*
- *Christof Völksen (Germany)*

A. Araszkiewicz (Poland), *Z. Altamimi* (France), *A. Caporali* (Italy), *M. Poutanen* (Finland), *J. Torres* (Portugal) and *J. Zurutuza* (Spain) are regularly participating to the GB meetings as honorary members and invited guest, resp.

Activities during the period 2019-2021

EUREF Permanent GNSS Network (EPN) Tracking Network, network Coordination, and Central Bureau

Most of the activities covering the European GNSS Network (EPN) are reported on an annual basis in the Technical Reports of the International GNSS Service (IGS). In addition to the overview and summary given here, see Bruyninx et al. (2018) and Bruyninx et al. (2019) for more details.

The EPN Central Bureau (CB, managed by the Royal Observatory of Belgium - ROB) continued to monitor operationally EPN station performance in terms of data availability, correctness of metadata, and data quality (Bruyninx et al., 2019). Its "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^3G, *https://gnss-metadata.eu*, Bruyninx et al., 2020) allows now also to collect information on data licenses and Digital Object Identifiers (DOI), although only few EPN stations have provided this info so far. M^3G also introduced and Application Program (API) to retrieve and submit metadata from EPN and EPN densification stations and allows to upload and retrieve site pictures.

27 new stations were integrated in the EPN since July 2019 including the first EPN stations in Montenegro and Belorussia (see Figure 1.3a.1). Presently, 82% of the EPN stations are providing Galileo data and 69% provide BeiDou data.

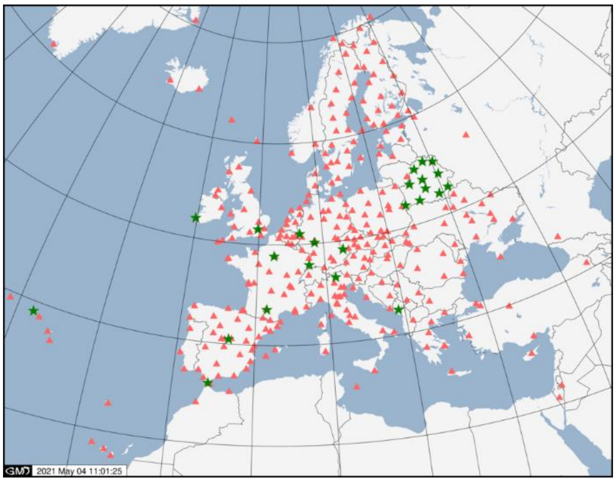


Figure 1.3a.1: EPN tracking stations (status May 2021).
* indicates new stations included in the network in since July 2019.

In November 2019, the EUREF Governing Board issued an update of the "Guidelines for EPN stations and Operational Centres":
see https://epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf.
With this update, from 2020 on, stations submitting RINEX 3 data can discontinue RINEX 2 uploads. Concerning the real-time data, submission of RTCM 3 is preferred over RTCM 2

and to ensure EPN stations can provide real-time access to the ETRS89, station managers are asked to insert the ETRS89 coordinates in their real-time streams.

EPN Real Time

During the period, the number of EPN stations providing real-time data was continuously growing. End of 2019, 54 % (188 stations) and end of 2020, 53 % (193 stations) established the so-called mount-points. Almost all varieties of RTCM messages (2.x to 3.3) are available from the three EPN broadcasters, with only few stations still providing RTCM 2.x. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) is still growing. The number of stations, which are delivering MSM4 (message type 1074 etc.) or MSM5 (message type 1075 etc.), increased to 66 whereas the MSM7 (1077 etc.) was available for 83 stations. Hence, the stations providing the “legacy” messages 1004 (GPS) and 1012 (GLONASS) significantly reduced to 27. Big improvement was made concerning the source of the data: only three stations remain which provide the data using an intermediate software. All other streams are coming (directly) from the receiver.

The introduction of long mount-point names on the three EPN broadcasters has been completed in 2019. The monitoring of the three EPN broadcasters at the EPN CB was extended, including the availability of data and product streams, the latency of the streams as well as the meta-data. Thanks to this, the consistency between the three EPN broadcasters improved very much.

EPN Analysis Centre Coordination

In years 2019-2021 EPN Analysis Centres Coordinator (ACC) continued to combine GNSS coordinate solutions (final, rapid and ultra-rapid) provided by 16 EPN Analysis Centres (AC). In 2019 11 EPN ACs started using Galileo observations (in addition to GPS and GLONASS) for the generation of the official products. Since August 2020 also SGO AC (Lechner Knowledge Center, Hungary) has started including Galileo observations in its solutions.

In October 2019 the EPN Analysis Centres Workshop was organized to discuss the topics relevant for GNSS data analysis within EPN. It was decided that ACs processing Galileo observations should switch from CODE IGS MGEX products (since November 2019 not consistent with the IGS14 framework) to CODE rapid products. Also, it was demonstrated by CODE AC that using chamber calibrations for Galileo may produce bias in station heights. It was therefore decided, that EPN CB will for the time being not include in the EPN ANTEX file the corrections for systems other than GPS or GLONASS for new individual receiver calibrations provided to EPN.

Since week 2106 (May 17, 2020) all EPN combined solutions have been aligned to the new IGS reference frame – IGb14, the updated version of the previously used IGS14. The IGb14 reference frame contains 15 more EPN reference stations (49 stations in total). After the switch, a slightly better agreement of EPN combined solutions with the IGS reference frame was observed, especially for the vertical component.

The ASI AC (Centro di Geodesia Spaziale G. Colombo, Italy) prepared test solutions using the new software - GipsyX, based on observations of three GNSS (GPS, GLONASS, Galileo). The new solutions have been tested by the ACC and showed good agreement with the combined solution. In January 2021, the solutions computed using GipsyX replaced the former ASI solutions (GPS-only) computed with the GIPSY-OASIS II software.

EUREF Reference Frame Product

EUREF releases each 15 weeks an update of EUREF Reference Frame Product in the latest ITRS/ ETRS89 realization (Bruyninx and Legrand, 2019, Legrand, 2021). Since May 2020, it is expressed in IGb14. The product is available from

https://epncb.oma.be/_productsservices/coordinates/,
ftp://epncb.eu/pub/product/cumulative/

and it consists of positions and velocities of EPN stations as well as a discontinuity list, and associated residual position time series. The EUREF Reference Frame Product agrees with the global IGb14 frame at the sub-mm, resp. 2 mm level for the horizontal and vertical positions and resp. at the 0.1mm/yr and 0.2 mm/yr for the horizontal and vertical velocities.

Not all stations in the EUREF reference frame product are suitable reference stations and therefore EUREF provides a new on-line web tool for assessing the suitability of EPN stations as reference stations (*http://epncb.oma.be/_productsservices/ReferenceFrame/*, Legrand and Bruyninx, 2021). It provides, for a specific input observation period, a restricted list of EPN stations which users can visualize on a map and interactively select the most suitable EPN reference stations to be included in their GNSS network processing. The web tool is based on a station categorization and also includes additional information and plots (position and velocity discontinuities, collocated stations, detrended position time series, selection criteria values (see Figure 1.3a.2), and velocity variability). Following the development of this tool, EUREF also revisited its "Guidelines for EUREF densifications" (Legrand et al., 2021).

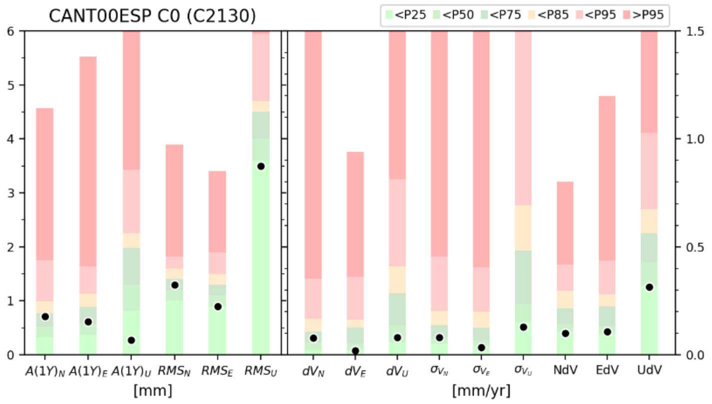


Figure 1.3a.2: Values of the criteria used to define the station categories. Example of the station CANT00ESP.

EPN Troposphere Product

For 341 EPN stations, Zenith Total Delay (ZTD) parameters and horizontal gradients were estimated by the 16 ACs and combined by the Troposphere Coordinator. In 2020, the conversion of the combined ZTD estimates to Integrated Water Vapour (IWV) has been implemented using the necessary auxiliary information, surface air pressure and weighted mean temperature of the atmosphere, from ECMWF operational products provided by the Technical University of Vienna. IWV has been tested against the Nevada Geodetic Laboratory (NGL) IWV estimates. For 2019 and 270 EPN stations the IVW bias ranges from -0,96 kg/m^2 to 0.41 kg/m^2 while the standard deviations are in the order of 0.4 kg/m^2 with maximum / minimum values of 0.91 kg/m^2 and 0.21 kg/m^2. Starting from 2021, the dissemination of the combined ZTD along with the derived IWV in SINEX_TRO v2.0 format is planned (Pacione and Dousa, 2019).

WG EPN Densification

The EPN Densification (EPND) WG is integrating the available national permanent GNSS networks on the product level. Daily/weekly position SINEX solutions from 28 EPND Analysis Centres are harmonized and combined on the weekly level and using the CATREF software a multi-year position/velocity solution is regularly generated. The EPND network consists of more than 3000 stations. A dedicated web portal had been developed to provide detailed information on EPND and allow access to the combination results (*https://epnd.sgo-penc.hu*). EPND is in close cooperation with EPOS, where the results are used for the generation of the European strain rate map (*https://doi.org/10.23701/sr.0001*) and EPND is also contributing to EGMS (European Ground Motion Service) providing reference for the InSAR analysis.

WG European Dense Velocities

Complementary to the EPN Densification, EUREF introduced a WG on dense velocities. The velocity estimates in ETRF2000, derived by currently 30 contributors, are the direct input to the generation process of a dense velocity field for Europe. In addition to results from GNSS permanent networks, densified solutions stemming from GNSS campaigns, InSAR or levelling are also included. In some countries, as e.g. in the Nordic countries, velocity models are already in use. They can be integrated to indicate possible differences between modelled and observed velocities. Also the results of the EPN Densification project are included. The alignment of the geodetic datum of each input is controlled by overlapping stations. More than 6000 individual station velocities are available for Europe. The description and detailed results are available on (*http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html*).

WG Deformation models

The precise knowledge of the crustal deformations within the EUREF area of interest is identified to be of vital importance from scientific perspective, for reference frame handling, and possibly as a tool for georeferencing of seamless ground motion products from InSAR (e.g. EGMS above). A first version of a European velocity model has been developed based on results from EPN Densification and European Dense Velocities (Steffen et al 2019) and the efforts towards a EUREF product continues.

European Vertical reference System (EVRS)

Since the last reporting period, the levelling data of Ukraine and North Macedonia have been added to the United European levelling network (UELN). Therefore, the network contains now the levelling data of 30 European countries. Furthermore, the measurements of Belgium, Bulgaria (partly), Czech Republic (partly), Italy and Slovenia have been updated. Since the release of EVRF2007, the UELN contains new data in 15 countries (Figure. 1.3a.3).

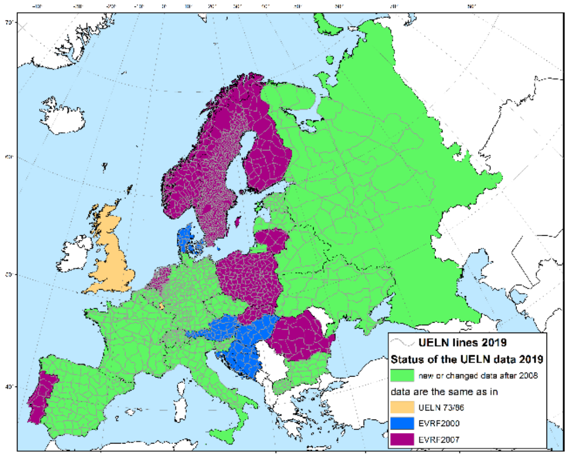


Figure 1.3a.3: UELN lines 2019.

Using these data, a new realization of EVRS has been calculated, which is named EVRF2019. Figure 1.3a.4 shows the differences to EVRF2007. The datum of EVRF2019 is realized by 12 datum points with their heights of the EVRF2007 adjustment. The measurements have been reduced to the epoch 2000 using the model of the land uplift for Fennoscandia and the Baltic region NKG2016LU_lev (Vestøl et al 2016) in Denmark, Sweden, Norway, Finland, Estonia, Latvia, Lithuania, Russia, Belarus and a velocity model for Switzerland. The heights of EVRF2019 are in the zero tidal system, according to IAG resolution No.16 adopted in Hamburg 1983 (Mäkinen, Ihde 2009). Additionally, the results of EVRF2019 have been provided in the mean-tide system – together with the recommendation to use these heights for tasks of oceanography as well as for clock rates. Furthermore, mean-tide heights can be used in the future for comparison with heights in the International Height System IHRS.

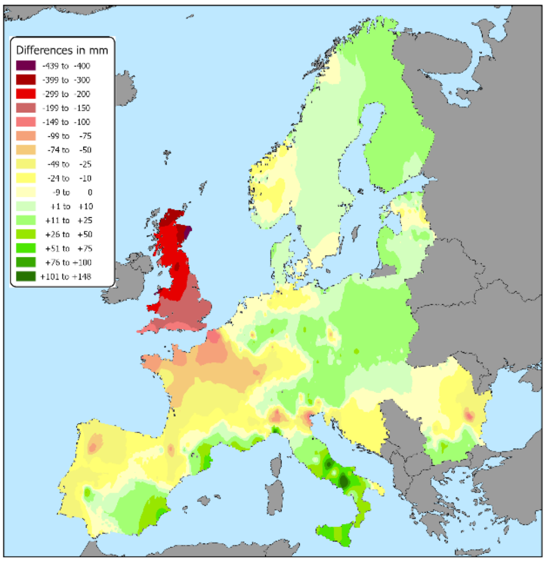


Figure 1.3a.4: Differences EVRF2019-EVRF2007

The mean value of the standard deviation of the adjusted heights is 19 mm. The accuracy of the heights varies in the individual countries between 7 mm and 47 mm. The heights of EVRF2019 are available at: *https://evrs.bkg.bund.de/Subsites/EVRS/EN/EVRF2019/evrf2019.html*. Transformation grids between national European vertical reference frames and EVRF2019 are available at *http://www.crs-geo.eu/*.

Organised Meetings

EUREF Governing Board meetings:

- October 15, 2019, in Warsaw, Poland, hosted by the Warsaw University of Technology
- February 26-27, 2020, in Munich, Germany, hosted by the Bavarian Academy of Sciences and Humanities
- May 28, 2020, virtual
- November 9 and 19, 2020, virtual
- February 16, March 2, 2021, virtual
- May 4 and 7, 2021, virtual

EUREF Annual Symposia:

- May 26-28, 2021 on-line from Ljubljana, Slovenia, (panned) (approx. 100 registered participants) EUREF Analysis Workshop:
- October 16-17, 2019 Warsaw, Poland (approx. 30 participants)

Publications

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E. (2019). GNSS metadata and data validation in the EUREF Permanent Network. GPS Solut 23:106, https://doi.org/10.1007/s10291-019-0880-9

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2019). EUREF Permanent Network. *IGS Technical Report 2018*, eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 95–106. https://doi.org/10.7892/boris.130408

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2020). EUREF Permanent Network. *IGS Technical Report 2019*, eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 111–124. https://doi.org/10.7892/boris.144003

Bruyninx, C., Fabian, A., Legrand, J., and Miglio A. (2020). GNSS Station Metadata Revisited in Response to Evolving Needs, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18634, https://doi.org/10.5194/egusphere-egu2020-18634

Fabian A., Bruyninx C., Legrand J., Miglio A., (2020). GNSS data quality check in the EPN network, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18634, https://doi.org/10.5194/egusphere-egu2020-21489, 2020

Kenyeres A., Bellet J.G., Bruyninx C., Caporali A., De Doncker F., Droscak B., Duret A., Franke P., Georgiev I., Bingley R., Huisman L., Jivall L., Khoda O., Kollo K., Kurt A.I., Lahtinen S., Legrand J., Magyar B., Mesmaker D., Morozova K., Nagl J. , Ozdemir S., Papanikolaouo X., Parseulinas E., Stangl G., Tangen O.B., Valdes M., Ryczywolski M., Zurutuza J., Weber M. (2019). Regional integration of long-term national dense GNSS network solutions. GPS Solut, 23:122, https://doi.org/10.1007/s10291-019-0902-7

Legrand J. (2021). EPN multi-year position and velocity solution C2130, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2130

Legrand J. and Bruyninx C. (2021). Station Classification and Reference Station Selection, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14190, https://doi.org/10.5194/egusphere-egu21-14190

Legrand J., Bruyninx C., Altamimi Z., Caporali A., Kenyeres A., Lidberg M. (2021). Guidelines for EUREF Densifications, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-Guidelines-DENS

Lidberg M., Söhne W., Kollo K. (2021). Advancing the geodetic infrastructure in Europe through EUREF, FIG Working Week 2021, 20-25 June

Mäkinen J. and Ihde, J. (2009).The Permanent Tide in Height Systems. In: Sideris M.G. (eds) Observing our Changing Earth. International Association of Geodesy Symposia, vol 133. Springer, Berlin, Heidelberg

Pacione R. and Dousa J. (2019). SINEX-TRO V2.00 format description, COST Action 1206 Final Action Dissemination Report, eds. J. Jones, G. Guerova, J. Douša, G. Dick, S. de Haan, E. Pottiaux, O. Bock, R. Pacione, R. van Malderen. 537-563

Vestøl O., Ågren J., Steffen H., Kierulf H., Lidberg M., Oja T., Rüdja A., Kall T., Saaranen V., Engsager K., Jepsen C., Liepins I., Paršeliūnas E., Tarasov L. (2016): NKG2016LU, an improved postglacial land uplift model over the Nordic-Baltic region. NKG meeting WG of Geoid and Height Systems. June 2016

Steffen R, Legrand J., Steffen H., Lidberg M., Kenyeres A., Brockmann E., Lutz S. (2019). Towards a Deformation Model for Europe using least square collocation, Presentation at the EUREF Symposia in Tallinn 22-24 May 2019. http://www.euref.eu/symposia/2019Tallinn/01-04-Steffen.pdf

Söhne W. (2019). EPN Real-Time Special Project – Status Report. Presented at the EUREF Symposium 2019.

Sub-Commission 1.3b: South and Central America

Chair: José Antonio Tarrío (Chile)
Vice-Chair: Demián Gomez (US)

Introduction and Structure

SIRGAS is the Geocentric Reference System for the Americas, in Spanish (Sistema de Referencia Geocéntrico para las Américas). Its definition corresponds to the International Terrestrial Reference System (ITRS), and it is realised by regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes the definition and realisation of a vertical reference system based on ellipsoidal heights as geometrical component and geopotential numbers (referred to a global conventional W_0 value) as physical component.

SIRGAS is a member of the Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and corresponds to a Working Group of the Cartography Commission of the PAIGH (Pan-American Institute for Geography and History). The Executive Committee manages the administrative issues, which depends on the Directing Council's main body. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed of one representative of each member country, one of IAG and one of PAIGH, it is also in charge of communicating the SIRGAS recommendations to the national bodies responsible for the local geodetic reference systems. The Working Groups coordinate the scientific and technical activities in close cooperation with the Scientific Council and the representatives of IAG and PAIGH.

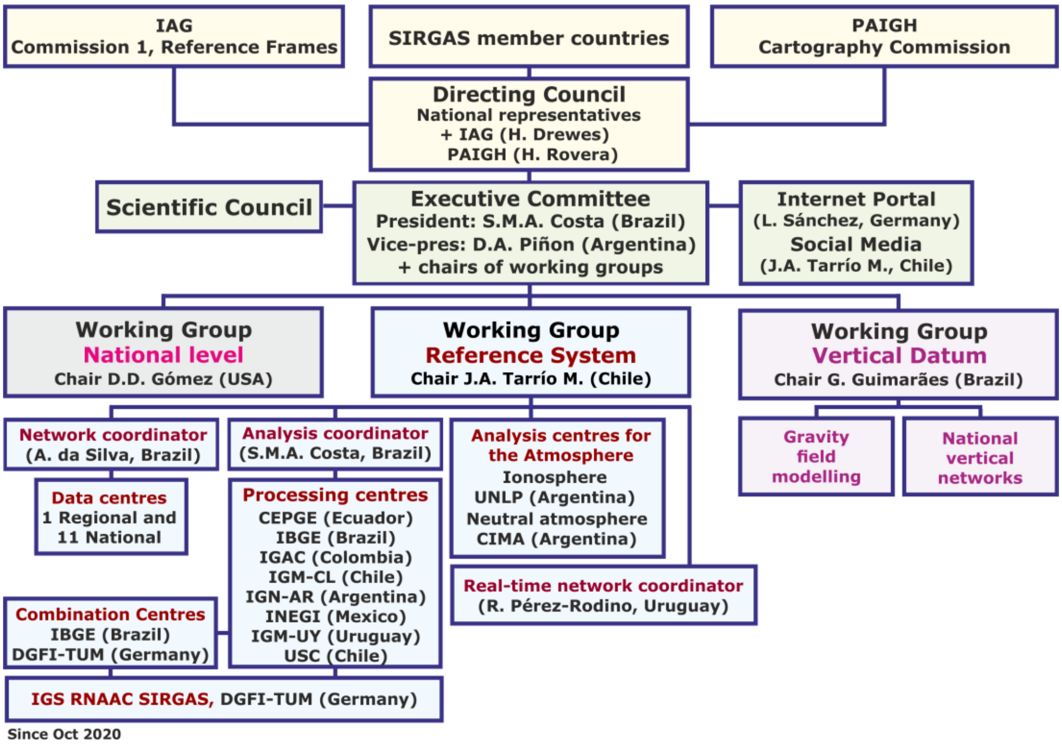


Figure 1.3b.1: Operational structure of SIRGAS

Members

SIRGAS Executive committee
- *Sonia María Alves Costa , Chair (Brasil).*
- *Diego Alejandro Piñón, Vice-Chair (Argentina)*
- *José Antonio Tarrío, SIRGAS-WG1 Chair (Chile)*
- *Demián Gomez, SIRGAS-WG2 Chair (US)*
- *Gabriel do Nascimento Guimarães, SIRGAS-WG3 Chair (Brazil)*

SIRGAS Directing council
- *Hermann Drewes, Representative of IAG*
- *Hector Carlos Rovera Di Landro, Representative of PAIGH*
- *Juan Francisco Moirano; Demian Gómez (Argentina)*
- *Arturo Echalar Rivera; Mario Sandoval Nava (Bolivia)*
- *Luiz Paulo Souto Fortes; Sonia Maria Alves Costa (Brazil)*
- *Juan Pedro Harms; Sergio Rozas Bornes (Chile)*
- *Jose Ricardo Guevara Lima; Francisco Javier Mora Torres (Colombia)*
- *Max Lobo Hernández; Álvaro Álvarez Calderón (Costa Rica)*
- *Alejandro Jiménez Reyes; José Leandro Santos (Dominican Republic)*
- *Edgar Fernando Parra Cárdenas; Jose Luis Carrión (Ecuador)*
- *Carlos Enrique Figueroa; Wilfredo Amaya Zelaya (El Salvador)*
- *Óscar Cruz Ramos; Fernando Oroxan Sandoval (Guatemala)*
- *Rene Duesbury; Hilton Cheong (Guyana)*
- *Bruno Garayt; Alain Harmel (French Guyana)*
- *Luis Alberto Cruz (Honduras)*
- *Enrique Muñoz Goncen, Francisco Medina (Mexico)*
- *Wilmer Medrano Silva, Ramón Aviles Aburto (Nicaragua)*
- *Javier Cornejo, Melquiades Dominguez (Panama)*
- *Daniel Ariar, Joel Roque Trinidad (Paraguay)*
- *Julio Enrique Llanos Alberca, Julio Sáenz Acuña (Peru)*
- *Daniel Piriz (Uruguay)*
- *Dana J. Caccamise II, Daniel R. Roman (USA)*
- *Jose Napoleón Hernández, Melvin Jesús Hoyer Romero (Venezuela)*

SIRGAS Scientific Council
- *Luiz Paulo Souto Fortes (Brazil)*
- *Laura Sanchez (Germany)*
- *Claudio Brunini (Argentina)*
- *María Virginia Mackern (Argentina)*

Activities during the period 2019-2021

During the period 2019-2021, the following achievements associated with maintaining the geodetic reference frame, SIRGAS, were obtained:

(a) Geocentric Reference Frame achievements

Network Processing

In 2020, SIRGAS incorporated 27 new GNSS stations, reaching close to 400 continuous stations (SIRGAS-CON) by the end of the year, of which 67 are included in the International GNSS Service (IGS) solution. This network realises the region's geodetic reference frame and is consistent with the International Terrestrial Reference Frame (ITRF). The network is operated and processed through the collaborative and continuous work of 13 data centres, 9 official processing centres, and two combination centres. Since august 2020 the Instituto Geográfico Nacional of Perú (IGN-PER) acts as a SIRGAS Experimental Processing Centre. With this new experimental processing centre, SIRGAS is approaching the goal of having a scientific GNSS processing centre in each region's country. Additionally, SIRGAS tropospheric products (tropospheric Zenith Path Delays (ZPD) with an hourly sampling rate) are computed by the SIRGAS Analysis Centre for the Neutral Atmosphere (CIMA), which is operated by the National University of Cuyo and UNCuyo / "Juan Agustín Maza" University.

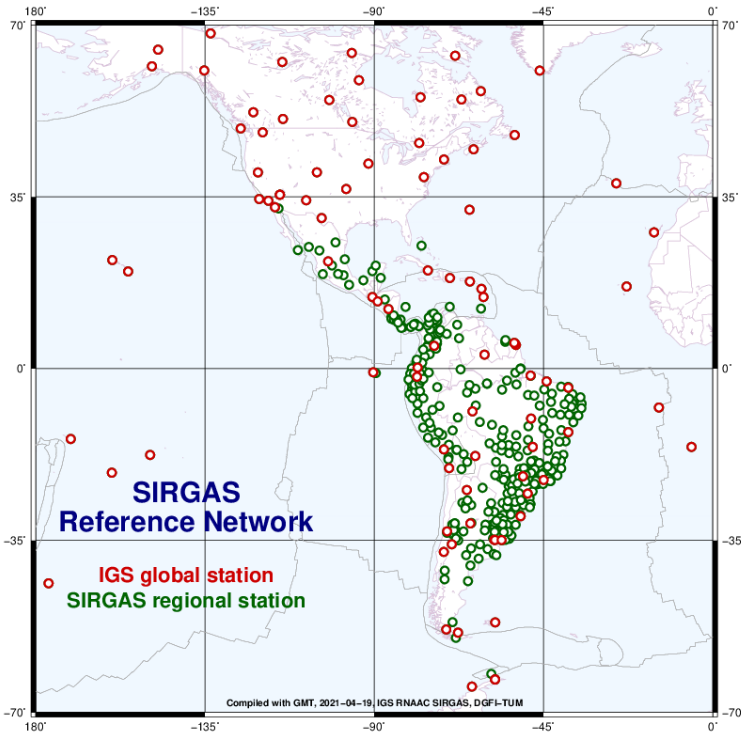


Figure 1.3b.2: Current SIRGAS Reference Network with expansion to North-America

Reprocessing in ITRF2014

To ensure the reliability and stability of the SIRGAS reference frame, in November 2018, the IGS RNAAC SIRGAS (DGFI-TUM) started the reprocessing of the historical data of SIRGAS (from January 2000 to July 2020) using IGS14 (ITRF2014) as the reference frame with antenna model igs14.atx and satellite orbits and clocks in IGS14 set by the Jet Propulsion Laboratory (JPL) of NASA.

Together with the 500 (approximately) SIRGAS stations, IGS global stations co-located with VLBI and SLR were added to support the SIRGAS initiative involving SLR data in the Implementation of the reference frame. This initiative started with a workshop at the SIRGAS2017 Symposium (Mendoza, Argentina) and continued making progress at a second SLR workshop at the SIRGAS2019 Symposium (Rio de Janeiro, Brazil). Further details in Sánchez L. (2020). SIRGAS Regional Network Associate Analysis Centre Technical Report 2019. Villiger A., Dach R. (eds.) International GNSS Service: Technical Report 2019, 125-136, 10.7892/BORIS.144003.

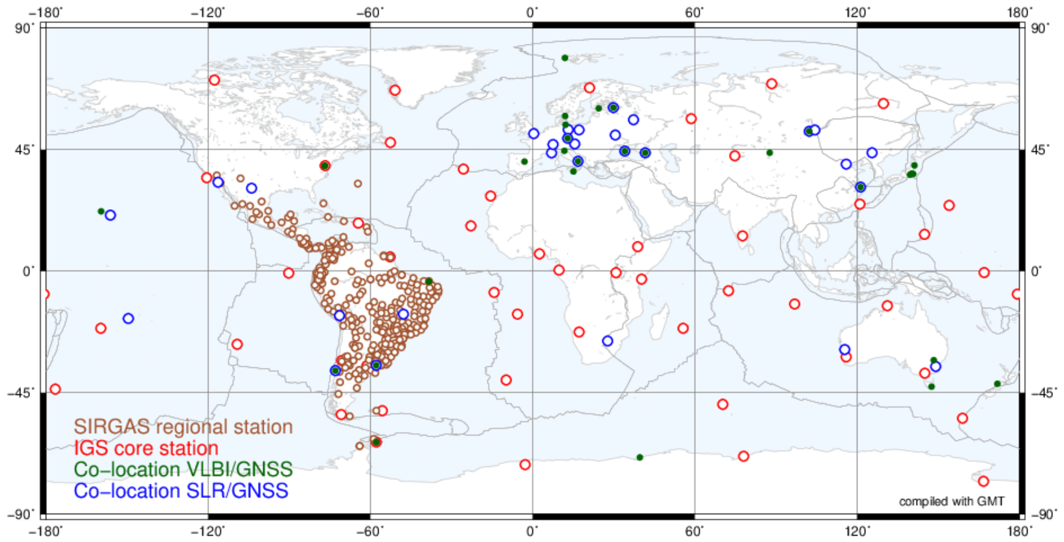


Figure 1.3b.3: GNSS network configuration for the combination of GNSS, SLR, and VLBI normal equations in the realisation of a geocentric geodetic datum in the regional reference frame SIRGAS. VLBI/GNSS (green dots) and SLR/GNSS (blue circles) co-located stations are necessary for the normal equation combination. IGS core stations (red circles) are necessary for a high-quality GNSS data processing

SIRGAS stations included in ITRF2020

The IGS started, in mid-2019, the third reprocessing of its network (1994 - 2020), applying the updated standards and conventions for determining a new version of the ITRF (ITRF2020). The IGS RNAAC SIRGAS (DGFI-TUM), by mutual agreement with the managers/owners of some SIRGAS stations, proposed to the IGS adding 30 additional SIRGAS stations for the region to have available more reference stations for the calculation of the regional frame. The IGS RNAAC SIRGAS (DGFI-TUM), in agreement with the managers/owners of some SIRGAS stations, proposed to IGS add more than 30 SIRGAS stations to the region has more fiducial stations to calculate the regional frame.

National densifications of SIRGAS

In the 2019-2021 period at the national level, several activities were reported, among which the installation of several GNSS stations in Ecuador and Colombia stand out (Fig. 1.3b.4).

Figure 1.3b.4: New GNSS stations in Ecuador and Colombia

The Instituto Geográfico Militar of Ecuador(ECU), through resolution No. 2019-037-IGM-JUR dated Dec 20, 2019, was resolved to adopt the Geocentric Reference System for the Americas (SIRGAS), in replacement of the PSAD56 Local Reference System, in order to provide support to cartographic and positional work in the country. In addition, 7 conversion parameters were made official for the transformation between systems.

This resolution can be found together with several legal documents generated by the IGM(ECU) through the following link:
http://www.geoportaligm.gob.ec/wordpress/?page_id=511

The Instituto Geográfico Agustin Codazzi in Colombia(IGA) densified its network in 15 stations to improve the geodetic infrastructure and the service provided to the community in general.

The Servicio Nacional de Geología y Minería de Chile, together with the geodetic analysis and processing centre of the University of Santiago, carried out the calculations and studies for the change from classical to modern datum (SIRGAS) in its mining cadastre. The above generates the first framework non-static reference for Chile; its name is REDGEOMIN(Red Geodésica para Minería) with EPSG CODE equal to 9694.

(b) Vertical Reference Frame achievements

Advances in IHRF

Concerning the SIRGAS Vertical Reference System (SVRS), there has been substantial progress made involving the incorporation of physical heights, the connection to the geometric components of SIRGAS, the integration of the national vertical networks, their links to the value of the reference potential W_0 of the IHRS, the definition for a specific epoch and the consistent connection with the ITRF.

In the context of the integration to the IHRS/IHRF, SIRGAS has proposed a set of 19 stations in Latin America and the Caribbean and has made progress in implementing these stations.

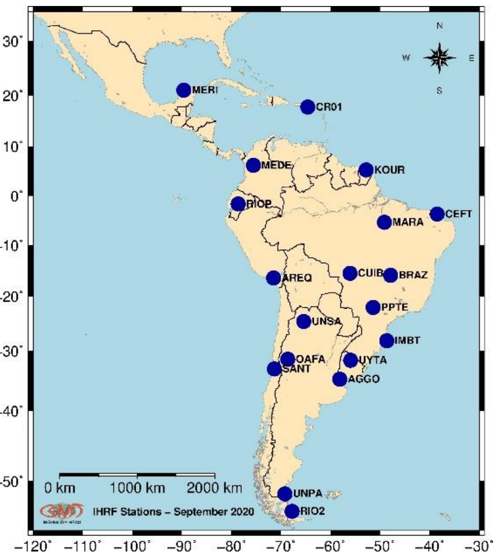


Figure 1.3b.5: Proposal for IHRF stations in the region

A diagnosis has been started in the IHRF stations from the calculation of the potential values using the global gravity models (comparison with the XGM2019 model). This diagnosis is essential to consider which station(s) should be concentrated efforts in terms of studies and improvements of the gravimetric distribution.

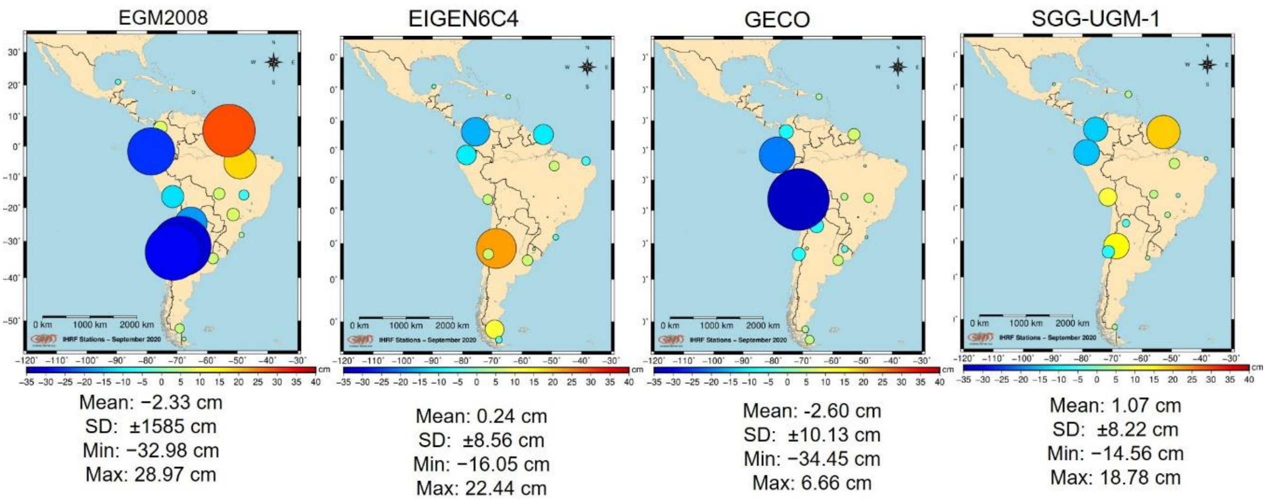


Figure 1.3b.6: Comparison of GGMs with XGM2019

Besides that, in 2021, the SIRGAS WG-III has been started the computation of geopotential values from the geoid or quasi geoid models available in the continent. Finally, the SIRGAS WG-III has been carrying out a scientific project together with the Technical University of Munich (TUM) called *Contributions of high-resolution gravity models in Latin America*. The goal of the project is to assess the geoid models and the levelling/GNSS stations available in Latin America using gravity field models of high resolution and of combining satellites to contribute to the potential calculation at the IHRF stations.

(c) Main contributions of the Centre for neutral atmosphere, CIMA

Tropospheric Products in the GNSS SIRGAS Network

Within the SIRGAS Continuously Operating Network (SIRGAS-CON) weekly processing, Latin-American Analysis Centres operationally estimate tropospheric Zenith Total Delays (ZTD) with an hourly sampling rate. These ZTD are the input data for the weekly SIRGAS combined tropospheric products, computed by the Analysis Centre for the Neutral Atmosphere (CIMA). The Internal precision of SIRGAS final ZTDs is 1mm. They are generated and available in daily SINEX TRO files since January 2014, with a latency of 30 days. They can be downloaded from ftp://ftp.sirgas.org/pub/gps/SIRGAS-ZPD/.

ZTD_{SIRGAS} validation concerning IGS products

A comparison was made between the tropospheric products of SIRGAS (ZTD_{SIR}) and the corresponding ones of the IGS (ZTD_{IGS}) in 60 stations (Figure 1.3b.), for a period of 7 years (2014 to 2020). The differences between both parameters (ZTD_{IGS}-ZTD_{SIR}) were calculated for each epoch, and the mean values of such differences (bias) were calculated (Figure 1.3b.8). The Mean Bias resulted 0.76 mm with 6.6 mm of mean RMS.

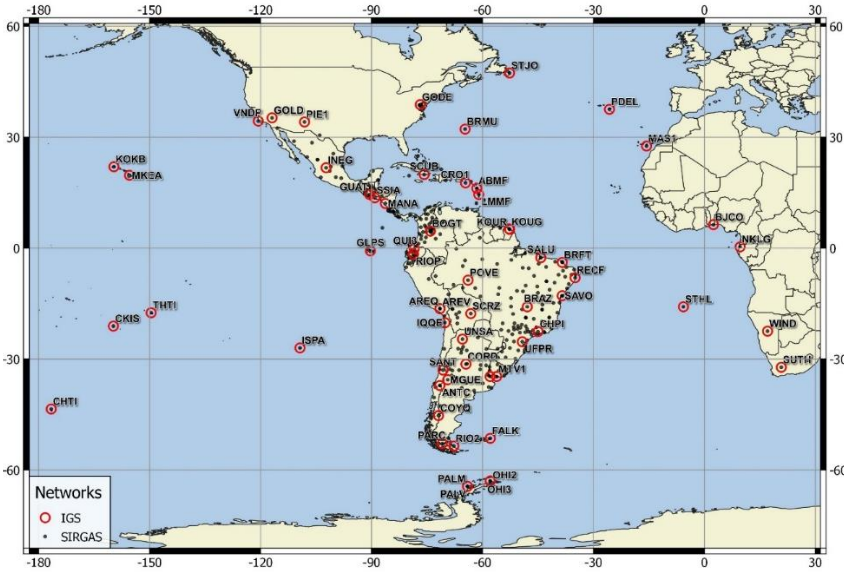


Figure 1.3b.7: $GNSS_{SIR}$ stations / IGS stations (distributed in different regions)

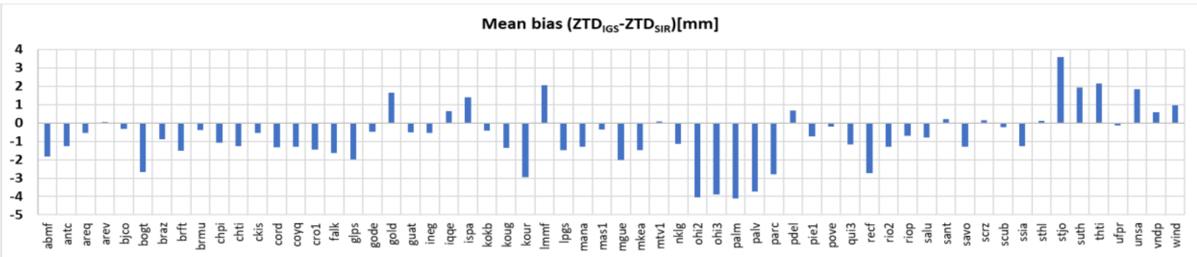


Figure 1.3b.8: Mean bias (ZTD_{IGS}-ZTD_{SIR}) for 60 GNSSSIR stations/IGS stations over a period of 7 years

ZTD_{SIRGAS} validation concerning Radiosonde data

Another comparison was made between the ZTD_{SIR} and the corresponding calculated from the Radiosonde data (ZTD_{Rs}). 42 $GNSS_{SIR}$ stations located within a maximum radius of 30 km from a radiosonde station were selected. This comparison could be performed for the 00 and 12 hrs UTC records due to limited availability of radiosonde records. The mean value and standard deviation were calculated as statistical indicators for the 7 years sampled (Figure 1.3b.9). The mean bias resulted - 8.6 mm with a mean standard deviation of ± 11.4 mm, Mackern et al. (2021).

These results show that the ZTDs estimated at the SIRGAS-CON stations, distributed from South America, Central America, and the Caribbean region, are consistent throughout the region and provide reliable time series of troposphere parameters, which can be used as a reference in future research.

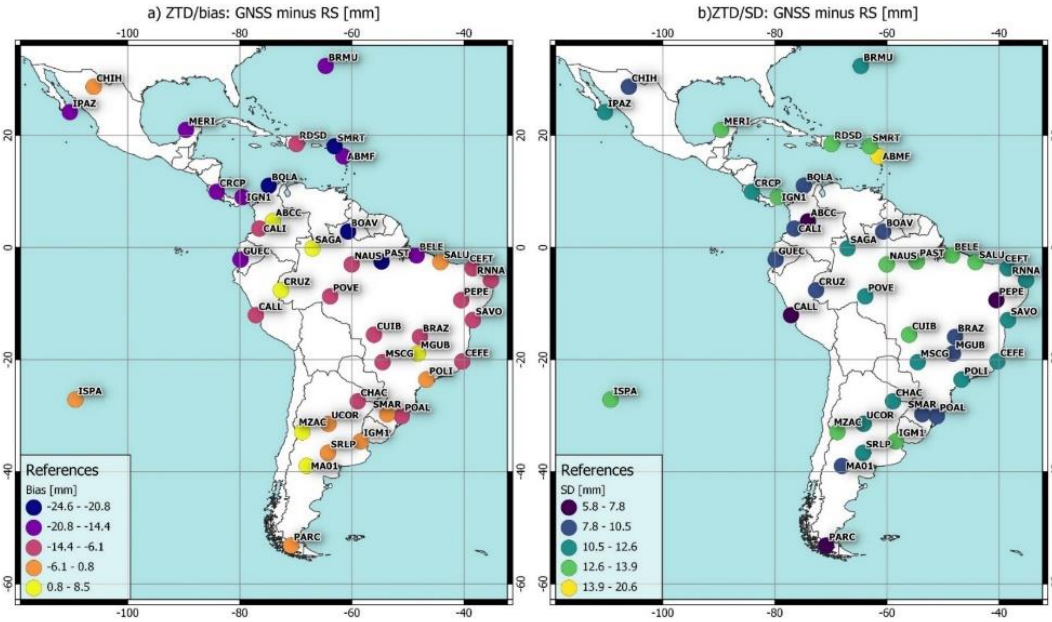


Figure 1.3b.9: a) Mean bias (ZTD_{SIR}-ZTD_{Rs}), b) Mean Standard deviation for 42 $GNSS_{SIR}$ stations/RS over period of 7 years

Time series of ZTD_{SIRGAS} parameters

The ZTD final SIRGAS products are available from 2014, with an hourly interval, with a latency of 28 days. There is a corresponding ZTD time series, from 2014 (or since its incorporation) to date (Figure 1.3b.10), for each of the SIRGAS-CON stations,

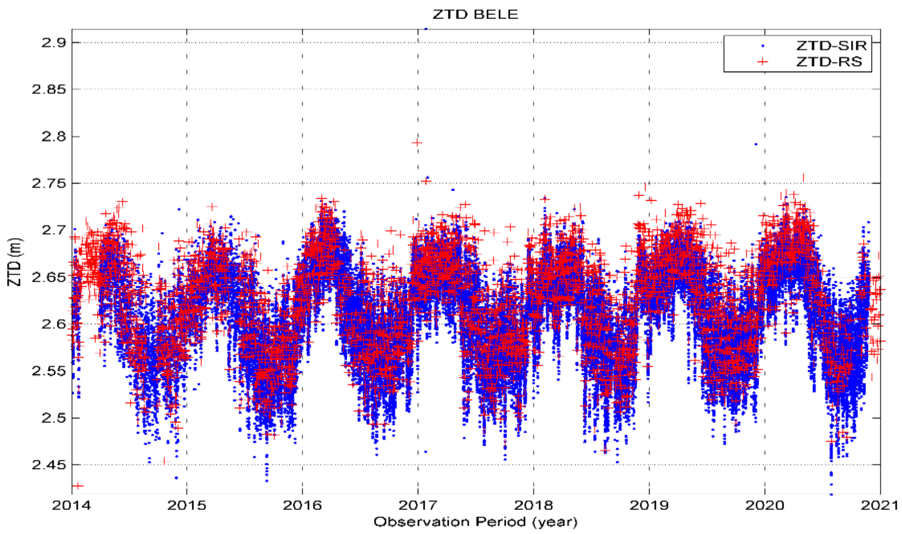


Figure 1.3b.10: ZTD time series (2014-2020) from BELE, Brasil

WG GRFA: "Geodetic Reference Frame for the Americas"

The Authorities of SIRGAS coordinated the development of the Terms of Reference of the new UN: GGIM: America's working group naming "Geodetic Reference Frame for the Americas" (GRFA). These terms were approved through Resolution 2019/6 of the Seventh Session of UN-GGIM: Americas.

Figure 1.3b.11: GRFA working group meeting

The main objectives of the GRFA are:

a) to support the Nations of the Americas so that they respond to the Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) resolution;

b) coordinate the efforts of the Member States to guarantee the sustainability and improvement of the regional geodetic reference frame, acting as a key facilitator of spatial data interoperability, the mitigation of hazards from disasters and sustainable development; and

c) to act as an interface between SIRGAS and the Member States to implement plans that push the development of the regional geodetic infrastructure, the geodetic reference frame of the Americas, and the geodetic capabilities of professional and technical specialists forwards. The Terms of Reference are published in the Spanish and English languages on the UN-GGIM: *http://www.un-ggim-americas.org/assets/modulos/grupoTrabajo.html?grupo=3*.

Organised Meetings

During the period 2019-2021, SIRGAS organised the following meetings:

Symposium SIRGAS2019
The current activities, advances, and new challenges of SIRGAS are reported, discussed, and evaluated in the annual SIRGAS Symposia, which have been held since 1993. This year, thanks to the kind invitation extended by the Brazilian Institute of Geography and Statistics (IBGE) and the Rio de Janeiro State University (UERJ), the SIRGAS 2019 Symposium was held in Rio de Janeiro, Brazil, between Nov 11 and 14, 2019. It was organised with the support of the International Association of Geodesy (IAG) and the Pan-American Institute for Geography and History (PAIGH). In the frame of this Symposium, two additional activities were programmed:

1. "GGOS Days 2019" (Global Geodetic Observing System) was held simultaneously in the same venue (Figure 1.3b.12), and a joint session between the SIRGAS community and GGOS expert representatives was developed on Nov 12 and;
2. The 2nd SLR (Satellite Laser Ranging) Workshop in Latin America took place from Nov 6 to 8, 2019. The main objective was to continue the integration between SIRGAS community (professionals and scientists) with the group of SLR experts. This effort was the continuation of actions initiated during the 1rst SLR SIRGAS workshop held in 2017 in Mendoza, Argentina; which aim was the promotion of the specialisation in the SLR technique, as well as data processing and its combination with GNSS (Global Navigation Satellite System) in the Latin American and international geodetic community context.

Figure 1.3b.12: Participants to GGOS Days 2019

Figure 1.3b.14: Participants of the SIRGAS Symposium 2019. Source: IBGE Rio de Janeiro, Brazil, Nov 11 to 14, 2019

The SIRGAS Symposium 2019 was attended by 164 participants (**Error! Reference source not found.**) from 16 countries (Argentina, Austria, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Germany, Mexico, Panama, Spain, United States, Uruguay and Venezuela). The main topics addressed during the Symposium included SLR in Latin America, colocation techniques (4 presentations); Studies of the Atmosphere and analysis of the Earth System based on SIRGAS Infrastructure (18 presentations); SIRGAS-GGOS Session (18 presentations); the improvement and maintenance of the SIRGAS reference frame (12 presentations); practical applications aimed at the adoption of SIRGAS at the sub-regional and national level and Infrastructure SIRGAS in Real-Time (12 presentations); advances in SIRGAS Unified Vertical Reference System (9 presentations); gravity and geoid (12 presentations); and general reports (4 presentations). In total, 75 oral contributions and 18 posters were presented.

During the meeting of Directing Council held on Nov 13 2019, the results of the elections for president and vice president were reported, who formally assumed at the closing ceremony of the Symposium (Fig. 1.3b.14). Other issues discussed during this meeting will be available on the SIRGAS webpage, section "SIRGAS: Resolutions."

Figure 1.3b.14: New Executive Committee: Sonia Costa from IBGE (Instituto Brasileiro de Geografia e Estatística), Brazil (president) and Diego Piñón from IGN (Instituto Geográfico Nacional), Argentina (vice president)

Workshop SLR SIRGAS 2019

The 2nd SLR Workshop in Latin America was attended by 25 participants (Fig. 1.3b.15) from 8 countries (Argentina, Brazil, Colombia, Costa Rica, Ecuador, Peru, Uruguay, and Venezuela). It was organised as an activity of the SIRGAS Working Group I. On this occasion, the instructor was Dr. Daniela Thaller from the BKG, Germany (Fig.5). The SIRGAS Executive Committee thanks the BKG for the possibility of Dr. Daniela Thaller qualifying SIRGAS community in the SLR data processing and analysis.

Figure 1.3b.15: Participants of the 2nd SIRGAS SLR Workshop, IBGE, Rio de Janeiro, Brazil, November 6 to 8, 2019

Figure 1.3b.16: Dr. Daniela Thaller teaching SLR data processing with Bernese software.

Symposium SIRGAS2020

Considering that all in-person activities in 2020 were cancelled due to the COVID-19 pandemic, SIRGAS promoted Webinars from May to September, 2020 with subjects related to geodetic activities in the region. The records and presentations from all Webinars are available on SIRGAS homepage (www.sirgas.org).

For October, SIRGAS organised a series of Webinars in the place of the annual SIRGAS Symposium, every Friday at 15 UTC. Each Webinar has 3 presentations with topics related to:

- Atmosphere studies and the Earth System analysis (Oct 2).
- SIRGAS reference frame's development and maintenance (Oct 9).
- Practical applications oriented to the adoption of SIRGAS at a sub-regional and national level (Oct 16).

- Height Systems (Oct 23).
- Gravimetry and geoid (Oct 30).

Figure 1.3b.17: SIRGAS 2020 Program

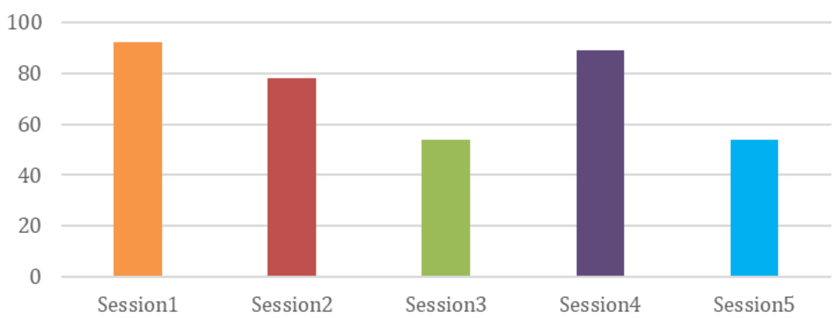


Figure 1.3b.18: Number of participants to SIRGAS2020 Symposium

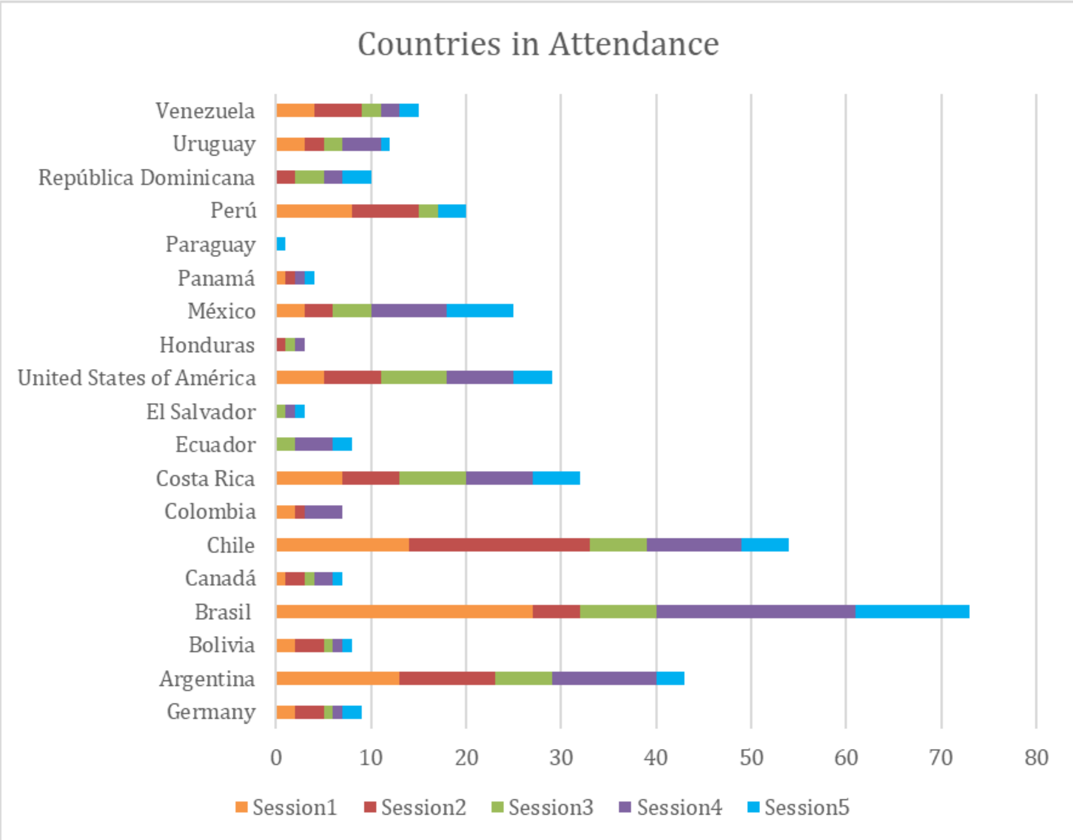


Figure 1.3b.19: Attendees for each country at SIRGAS2000 symposium

The Directing Council and Working Groups meeting were organised in the week between 16 to Nov 19 at 2020. The new SIRGAS Statute was approved during the Directing Council meeting, with the approval of all SIRGAS members, including all countries in North America. During the Working Groups meetings were presented the new structures and coordinators of GT II and GT III and future work for 2021.

Figure 1.3b.20: Working Group III meeting

The International Workshop for the Implementation of the Global Geodetic Reference Frame
The International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America was held in Buenos Aires, Argentina, from Sep 16 to 20, 2019. This workshop is a capacity building activity of the project "Implementation of the United Nations' Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America" of the International Union of Geodesy and Geophysics (IUGG) within the special grants program to celebrate in 2019 the centennial year of the IUGG foundation. The International Association of Geodesy (IAG) is the primary applicant of this project, and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the IUGG National Committees of Argentina, Brazil, Chile, Colombia, and Costa Rica supported it. In addition to the IUGG, IAG, and IASPEI support, the workshop counted on the sponsorship of the International Committee on Global Navigation Satellite Systems (ICG) of the United Nations Office for Outer Space Affairs (UNOOSA). Twenty-eight travel awards for colleagues from fourteen Latin American countries were covered with the money granted by the IUGG. ICG-UNOOSA provided six flight tickets for colleagues from Colombia, Peru, Chile, Brazil, Costa Rica, and Ecuador. The Instituto Geográfico Nacional (IGN) of Argentina and the Argentine-German Geodetic Observatory (AGGO) organised the logistics needed for the successful realisation of the meeting. The support of IUGG, ICG-UNOOSA, IGN, AGGO and all the experts participating in the workshop is highly appreciated.

In total, 130 participants from 20 countries (Argentina, Australia, Bolivia, Brazil, Chile, China, Colombia, Costa Rica, Dominican Republic, France, Germany, Guatemala, Italy, Mexico, Panama, Paraguay, Peru, United States of America, Uruguay, and Venezuela) attended the workshop. With 52 presentations distributed in eight sessions, the meeting brought together politics, international organisations promoting science, the highest level of expertise in Geodesy worldwide, and regional specialists in Geodesy. Jointly, they could provide the Latin American colleagues responsible for the national geodetic reference frames, the scientific and political arguments to convince policymakers about the necessity of investing in geodetic and geophysical infrastructure in their countries.

Figure 1.3b.21: Participants to the International Workshop for the Implementation of the Global Geodetic Reference Frame (GGRF)

This workshop convened for the first time politics (UN-GGIM, UN-GGIM Subcommittee on Geodesy, GEO, ICG-UNOOSA), international organisations promoting science (ICS, IUGG, IAG, IASPEI, FIG, PAIGH), the highest level of expertise in Geodesy worldwide (IAG, IAG Services, GGOS), and regional specialists in Geodesy (SIRGAS, gravity field modelling, geodetic observatories) to identify appropriate strategies to make real the objectives of the UN-GGRF initiative. The topics presented along the five days and the conclusions/recommendations arising from the discussions surely represent the appropriate start point to face the required activities to advance in the establishment of the GGRF in Latin America. Presentations, a list of participants and conclusions of the workshop are available at *http://www.sirgas.org/en/ggrf/*. Laura Sánchez (Deutsches Geodätsiches Forschungsinstitut Technische Universität München, Germany) and Claudio Brunini (Science Director of AGGO) were in charge of carrying out the event.

Outreach

During the 2019-2021 period, SIRGAS has carried out different outreach events, also has participated in the following international conferences:

2021

Establecimiento de la Red Argentina de Monitoreo Satelital Continuo (RAMSAC). D. Piñón. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS (RMBC): Complexidades e dasafios. A. Silva, G. Mantovani, M.A. de Almeida, N. Moura, S. Costa. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Red SIRGAS-CON en Costa Rica. A. Álvarez. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

REDGEOMIN: Red geodésica para la minería en Chile. J.A. Tarrío, J. Inzunza, F. Isla, M. Caverlotti, G. Jeldres, C. Ferraz, R. Urrutia, J. Ojeda. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Estado del Marco de Referencia SIRGAS: desarrollos recientes y nuevos desafíos. S. Costa, D. Piñón. Escuela Regional "Nuevas Técnicas Geodésicas para América Latina y El Caribe". Abril 6, 2021

Tropospheric products validation in the GNSS SIRGAS Network. M.V. Mackern, M.L. Mateo, M.F. Camisay, P. Rosell, G. Granados. Geodesy for Climate Research, Workshop of Inter-Commission Committee on "Geodesy for Climate Research" of the International Association of Geodesy. March 30, 2021 (video avaliable)

El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF). H. Wziontek, S. Bonvalot, E.D. Antokoletz. Webinar SIRGAS, 2021-03-05. Presentatuon also available in YouTube.

2020

Modelar el movimiento de la superficie terrestre: Velocidades continuas y coordenadas por etapas. H. Drewes, Webinar SIRGAS, agosto 20, 2020. Presentation also available in YouTube.

Procesamiento con NRCan PPP en entorno Windows Desktop. D. Gómez, Webinar SIRGAS, July 22, 2020. Presentation also available in YouTube.

Sistema internacional de Alturas IHRS. L. Sánchez, Webinar SIRGAS, June 25, 2020. Presentation also available in YouTube.

Procesamiento de datos GNSS con software libre, a partir de estaciones SIRGAS. B. Barraza, J.A. Tarrío, Webinar SIRGAS, May 29, 2020. Presentation also available in YouTube.

Actividades y productos de los centros de análisis SIRGAS. J.A. Tarrío, Universidad Santiago de Chile, Santigo de Chile. Webinar SIRGAS, May 14, 2020. Presentation also available in YouTube.

2019

Report from developing countries Americas and Caribbean Region. S. Costa. International Association of Geodesy (IAG) Executive Committee Meeting. San Francisco, USA, Dec 7, 2019

Vinculación del marco de referencia nacional de Argentina con el global, la red continental SIRGAS. M.V. Mackern. XII Congreso Nacional de Agrimensura. Mendoza, Argentina. October 9 - 11, 2019.

SIRGAS: The Geocentric Reference System for the Americas. W. Martínez, M.V. Mackern, V. Cioce, R. Pérez Rodino, S.R.C. de Freitas. Workshop for the Implementation of the GGRF in Latin America. Buenos Aires, Argentina. September 16-20, 2019.

Status of the SIRGAS reference frame: recent developments and new challenges. W. Martínez, M.V. Mackern, H. Drewes, H. Rovera, C. Brunini, L. Sánchez, L.P.S. Fortes, E. Laurıá, V. Cioce, R. Pérez, S.R.C. de Freitas, S.M.A. Costa, M. Hoyer, R.T. Luz, R. Barriga, W. Subiza. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

Tropospheric products from high-level GNSS processing in Latin America. M.V. Mackern, M.L. Mateo, M.F. Camisay, P.V. Morichetti. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

SIRGAS Social Media

SIRGAS has different accounts in social media:

- Facebook: https://www.facebook.com/SirgasAmericas/
- Twitter: https://twitter.com/SirgasAmericas/
- LinkedIn: https://www.linkedin.com/company/SirgasAmericas/
- a YouTube channel https://www.youtube.com/channel/UCHgFJJ6PPust08GKIlBtUAA

Publications

Sánchez L. (2019). SIRGAS Regional Network Associate Analysis Centre Technical Report 2018. Villiger A., Dach R. (Eds.), International GNSS Service Technical Report 2018 (IGS Annual Report), 109 - 125, 10.7892/boris.130408

Camisay M.F., Rivera J., Mateo, M.L., Morichetti, P.V., Mackern, M.V. (2020). Estimation of integrated water vapor derived from Global Navigation Satellite System observations over Central-Western Argentina (2015-2018). Validation and usefulness for the understanding of regional precipitation events. Journal of Atmospheric and Solar-Terrestrial Physics. 197. 105143, https://doi.org/10.1016/j.jastp.2019.105143

Drewes H. and Sánchez L. (2020). Velocity model for SIRGAS 2017: VEMOS2017, open access, https://doi.org/10.1594/PANGAEA.912350, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI-TUM), IGS RNAAC SIRGAS, 2020, in supplement to: Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi.org/ 10.1007/1345_2020_91

Mackern M.V., Mateo M.L., Camisay M.F., Morichetti P.V. (2020). Tropospheric Products from High-Level GNSS Processing in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi/org/10.1007/1345_2020_121

Sánchez L. (2020). SIRGAS Regional Network Associate Analysis Centre Technical Report 2019. Villiger A., Dach R. (eds.) International GNSS Service: Technical Report 2019, 125-136, https://doi.org/10.7892/BORIS.144003

Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi.org/10.1007/1345_2020_91

Sánchez L., Drewes H. (2020). SIRGAS 2017 reference frame realization SIR17P01, open access, DOI 10.1594/PANGAEA.912349, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI-TUM), IGS RNAAC SIRGAS, 2020, in supplement to: Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access,
https://doi.org/10.1007/1345_2020_91

Tarrío J.A., Soto C., González A., Barraza B., Isla F., and Caverlotti M. (2020). Geodesy in Chile (SIRGAS USC CENTRE): a Place Where the 4D Component Presents its Maximum Expression, GIM International May-June 2020:33, open acces: https://www.gim-international.com/magazine/may-june-2020.

Mackern M.V., Mateo M.L., Camisay M.F., Rosell P.A., Granados, G. (2021). Tropospheric Products validation in the GNSS SIRGAS Network. 1st ICCC "Geodesy for Climate Research "Workshop 2021, March 29-31, 2021.

Sub-Commission 1.3c: North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Daniel Roman (USA)

Introduction and Structure

In collaboration with the IAG community, its service organisations, and the national geodetic organizations of North America, the aims and objectives of this regional Sub-commission are to provide international focus and cooperation for issues involving the horizontal, vertical and three dimensional geodetic control networks of North America. Some of these issues include:

- Densification of the ITRF reference frame in North America and the promotion of its use;
- Definition, maintenance and future evolution of plate-fixed geometric reference frames for North America, including the North American Datum of 1983 (NAD83) and the forthcoming North American Terrestrial Reference Frame of 2022 (NATRF2022).
- Effects of crustal motion, including post-glacial re-bound and tectonic motions along, e.g., the western coast of North America and in the Caribbean;
- Standards for the accuracy of geodetic positions;
- Coordination of efforts with neighbouring IAG SC1.3b for Central and South America to ensure strong ties between each other's reference frames.
- Outreach to the general public through focused symposia, articles, workshops and lectures, and technology transfer to other groups.

Members

- *Michael Craymer (Canada)*
- *Daniel Roman (USA)*
- *Finn Bo Madsen (Denmark)*
- *Babak Amjadiparvar (Canada)*
- *Remi Ferland (Canada)*
- *Joe Henton (Canada)*
- *Mike Piraszewski (Canada)*
- *Dru Smith (USA)*
- *John Galetzka (USA)*
- *Phillip McFarland (USA)*
- *Theresa Damiami (USA)*
- *Lijuan Sun (USA)*
- *Don Haw (USA)*
- *Michael Bevis (USA)*
- *Geoff Blewitt (USA)*
- *Tom Herring (USA)*
- *Jeff Freymueller (USA)*
- *Corné Kreemer (USA)*
- *Richard Snay (USA)*

Activities during the period 2019-2021

The Sub-Commission is currently composed of three working groups:

- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Plate-Fixed North American Reference Frame
- SC1.3c-WG3: Reference Frame Transformations

The following summarizes the activities of each working group, followed by a report of other reference frame activities in Canada and the U.S., during the period 2019-2021. For more information and publications related to the working groups, see the regional Sub-Commission web site at *http://www.naref.org/*.

Note: the acronyms "NAD83" (as used in Canada) and "NAD 83" (as used in the U.S.) will be used interchangeably throughout this report.

WG 1.3c.1: North American Reference Frame Densification (NAREF)
Chair: Michael Craymer (Canada)

The objectives of this working group are to densify the ITRF reference frame in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the cur-rent IGS global network. A cumulative solution of coordinate and velocities will also be determined on a weekly basis. The working group will organize, collect, analyse and combine solutions from individual agencies, and archive and disseminate the weekly and cumulative solutions.

The Canadian Geodetic Survey (CGS) continues to produce weekly coordinate solutions of approximately 600 Canadian and northern U.S. public continuously operating Canadian Active Control System (CACS) stations in Canada, Greenland and the northern U.S. The data is processed using the Bernese GNSS Software v5.2 and final IGS orbits with about a 3 week latency. In addition, weekly solutions are also produced for over 750 commercial RTK stations in Canada. The time series of results for CACS and commercially operated stations are published online at *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php* for public stations and *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/rtk.php* for the commercial RTK stations.

CGS also continues to produce monthly-updated cumulative solutions of all of its weekly coordinate solutions using its own highly efficient combination software. A coordinates and velocities of nearly 900 current and discontinued public and over 1150 commercial stations are generated. In addition, periodic solutions with high accuracy campaign surveys of an additional 250 stations are included to densify the rather spare continuous network for generating an improved crustal deformation model for Canada. Figure 1.3c.1 gives a map of the vertical velocities from the last periodic solution with high accuracy campaign surveys. Several new CACS stations are planned for installation in strategic locations to improve network coverage but only a few new CACS stations could be installed due to COVID-19-related travel restrictions since early 2020.

Although NGS did not participate in the 2nd IGS reprocessing campaign, they have completed the reprocessing of their NOAA CORS Network (NCN) and IGS network stations. The newly reprocessed solution, called the Multi-Year CORS Solution 2 (MYCS2), is aligned to the ITRF2014 frame. MYCS2 supersedes the previous reference frame and realization, which was released in 2011 under the name MYCS1. The final alignment of the no-net-rotation SINEX files to ITRF2014 used 496 solutions from 194 ITRF2014 stations, not including any of the 26 IGS stations with post-seismic behavior. The MYCS2 generally implemented the IERS 2010 Conventions. Horizontal and vertical velocities from MYCS2 are shown in Figure 1.3c.2.

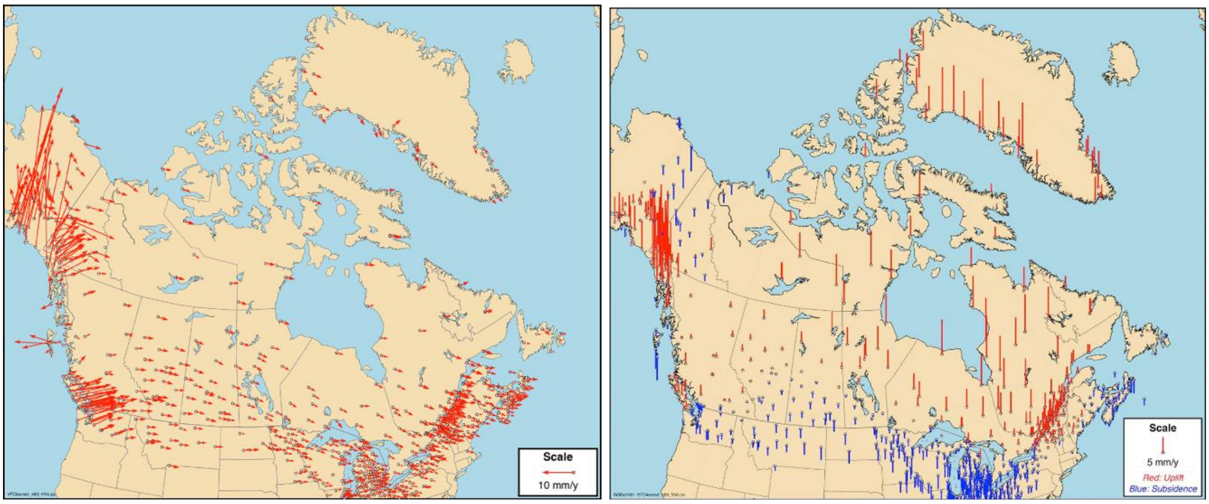


Figure 1.3c.1: Horizontal (left) and vertical (right) velocities for combined CACS and high accuracy campaign stations in Canada forming the current realization of NAD83(CSRS). Velocities are with respect to the NAD83(CSRS) v7 reference frame where a residual plate motion is apparent in the horizontal plot.

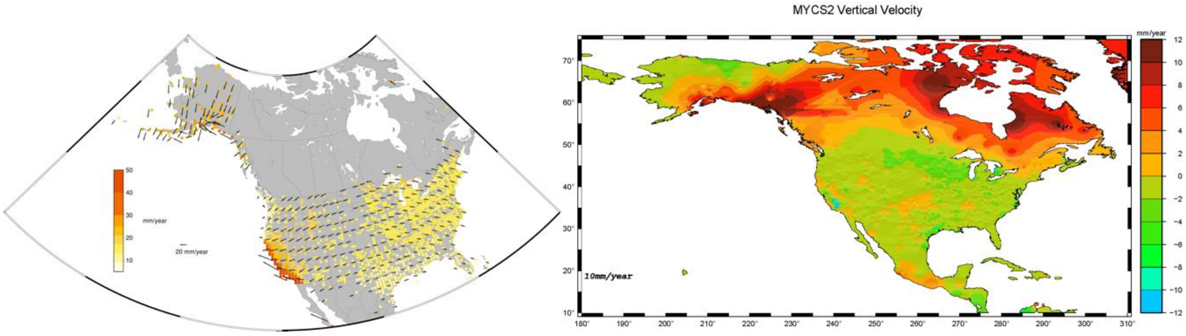


Figure 1.3c.2: Horizontal (left) and vertical (right) velocities in ITRF2014 from final MYCS2 cumulative solution of “repro2” weekly solutions to GPS week 1933. In the vertical plot, warm colors represent uplift and cool colors represent subsidence.

WG 1.3c.2: Plate-Fixed North American Terrestrial Reference Frame of 2022 (NATRF2022)

Chair: Daniel Roman

The objectives of this working group are to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace NAD83 and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared. In addition, similar plate-fixed reference frames will be established for U.S. states and territories on other tectonic plates in the Caribbean and Pacific regions.

Although NAD 83 was the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that it is offset from the actual geocentre (and thus ITRF) by about 2 meters. There is also a residual rotation with respect to North American tectonic plate of about 2 mm/yr at mid latitudes due to an inconsistency in the definition of the transformation from ITRF that now defines NAD 83. These problems make NAD 83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning systems. Additionally, the United Nations Global Geodetic Reference Frame (GGRF) also stipulates adoption of internationally accepted standards of which ISO 19161-1:2020 is the standard for the realization of the ITRS. Consequently, the U.S. has been making plans to replace NAD 83, along with its vertical datum, with a high accuracy geocentric reference frame called the North American Terrestrial Reference Frame of 2022 (NATRF2022). This high accuracy geocentric reference frame will likely be based on the forthcoming ITRF2020 at epoch 2020.0 and fixed to the North American plate. Discussions are also underway in Canada to adopt the same frame. Regardless whether or not the new frame is officially adopted in Canada, CGS will make coordinates and velocities available in both NAD83(CSRS) and NATRF2022, and provide a transformation between the two.

The new NATRF2022 reference frame will be defined by aligning it exactly with the latest realization of ITRF at an adopted reference epoch of 2020.0. It will then be kept aligned to the North American tectonic plate through an estimated Euler pole rotation. Discussions are presently underway on the selection of a set of reference frame stations representing stable North America and on the method of estimating an Euler pole rotation that either best represents the motion of the North American tectonic plate or that minimizes motions of stations outside the plate boundary zone. Investigations are also being made into methods of computing the Euler pole rotation, including a novel, robust approach developed by Kreemer et al. (2017). Remaining intra-frame motions will be modelled for propagating coordinates between epochs both horizontally and vertically.

In addition to defining a new regional reference frame for North America, the U.S. is also planning to define similar plate-fixed frames for the Caribbean and its territories on the Pacific and Mariana plates. The following names have been adopted for these reference frame:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MATRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PATRF2022)

WG 1.3c.3: Reference Frame Transformations in North America

Chair: Michael Craymer

The objectives of this working group are to determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed and to provide tools for implementing these relationships.

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 reference frame was re-defined in 1998 as a 7-parameter Helmert transformation from ITRF96 at epoch 1997.0. (Craymer et al., 2000) Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental time-dependent transformations between ITRF versions as published by the IERS (Soler and Snay, 2004). The NAD83-ITRF transformation was most recently updated to ITRF2014 in January 2017 just prior to adoption of ITRF2014 by the IGS. The updated transformation has been implemented in transformation software at the Canadian Geodetic Survey and U.S. National Geodetic Survey. The transformation will be updated to the forthcoming ITRF2020 once it is released.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a velocity model and transformation software for North America was developed by Snay and others in 2016. The model integrates velocity fields from various sources to provide North American coverage. The resulting interpolation grid of velocities has been implemented in TRANS4D, an update to the HTDP software that models and predicts horizontal motion for the U.S. Trans4D will likely serve as the initial Intra-Frame Velocity Model (IFVM) for NATRF2022 in the U.S. Investigation has also begun on use of InSAR-based surface deformation modelling tied to the NCN and CACS to serve as a follow on IFVM.

Canada has developed its own national velocity model that incorporates a GIA model to better predict vertical crustal motions in the central and northern regions where GNSS stations are sparse (Robin et al., 2019a, b, c, 2021). The model uses the latest Canadian cumulative solution discussed in SC1.3c-WG1 together with a blending of the ICE-6G and LAUR16 GIA models. The blended GIA model was effectively distorted to fit the GPS velocities thereby providing a more reliable velocity interpolation grid for GIA areas with sparse GNSS coverage. Figure 1.3c.3 illustrates the resulting vertical velocity grid in the NAD83(CSRS) reference frame.

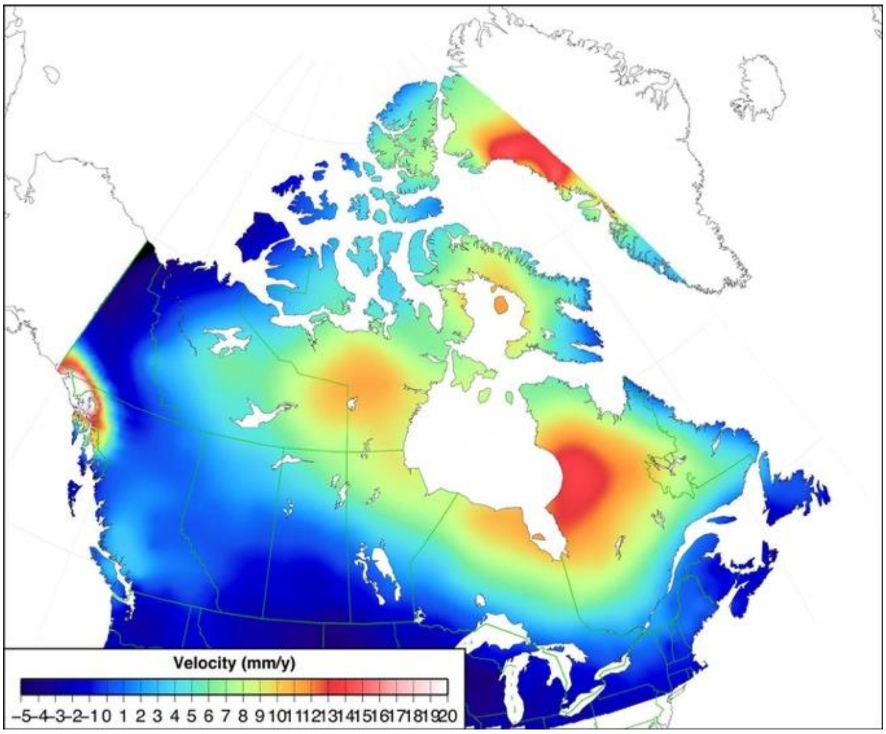


Figure 1.3c.3: Canadian vertical velocity model in NAD83(CSRS) v7 obtained from an integration of GNSS velocities with a GIA model.

Other Activities

NGS is creating a new high-level network of 36 highly stable, highly reliable GNSS tracking stations across the country at a spacing of approximately 800 km that will be contributed to the IGS and ITRF (see Figure 1.3c.4). These 36 stations include a minimum of 3 stations on each tectonic plate upon which the U.S. has significant populations (North American, Pacific, Caribbean, and Mariana) to enable computation of an Euler pole rotation (see SC1.3c-WG2). Of these 36, twenty six (26) are currently operational.

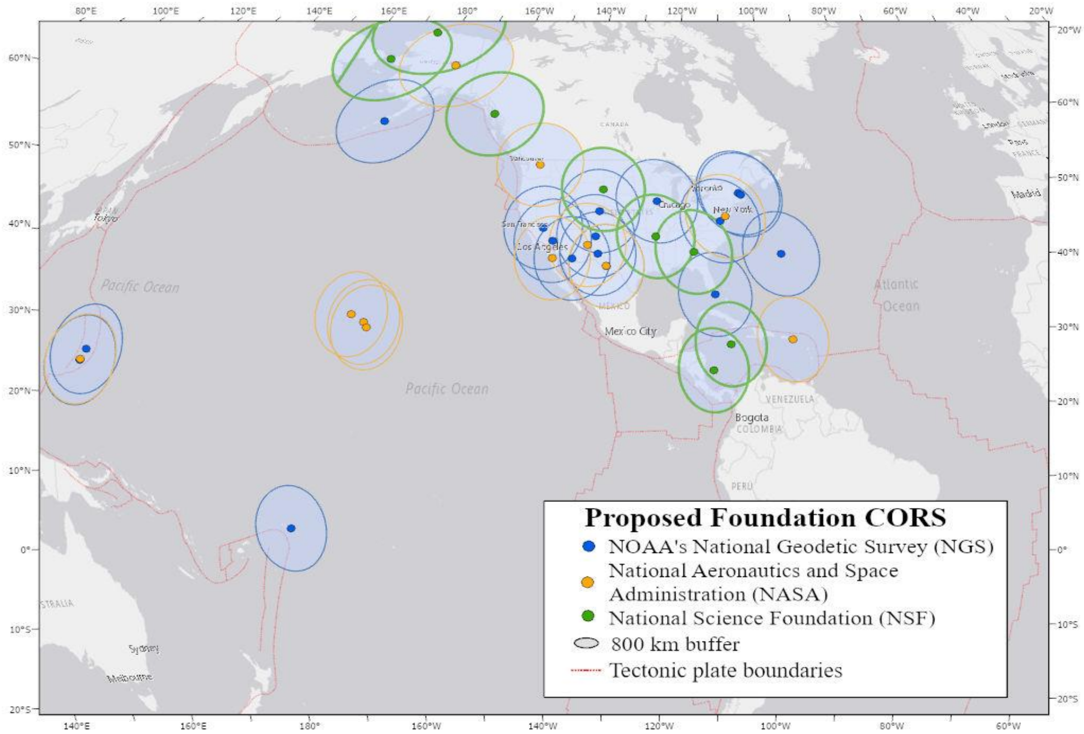


Figure 1.3c.4: Proposed locations for NOAA Foundation CORS (NFCN) sites to serve as IGS stations and link ITRF solutions to MYCS solutions. Of these twnety six (26) are currently operational).

Unlike most of the other stations in the NCN, these sites will be operated by the U.S. National Geodetic Survey (either through direct ownership or MOU's with other federal agencies) and will be built and operated to IGS standards. Referred to as the NOAA Foundation CORS Network (NFCN), this network is a subset of the larger NCN and will provide a more stable foundation for the reference frame in the U.S. Thirteen of these GNSS stations are already collocated with other techniques such as VLBI and SLR in order to create true GGOS stations. Another nine new collocated stations will be built at other GGOS sites lacking GNSS. The first of these sites was installed in Miami in late 2014 and the others will be built approximately two per fiscal year beginning the winter of 2019. When the project is completed, all NFCN stations will be fully GNSS capable, will support RINEX3, and will have local surveys ties between the different techniques performed to IERS standards about once every 5 years.

CGS has just recently received funding to enhance Canada's geodetic infrastructure to support future requirements for positioning services, the transportation industry (e.g., autonomous vehicle navigation) and weather modelling and forecasting. The primary objective of this five-year Space-Based Earth Observation (SBEO) project is to densify the existing network of continuously operating GNSS tracking station with about 22 or more real-time stations to support the work of the Canadian Geodetic Survey, Transport Canada and the meteorological branch of Environment and Climate Change Canada. Consideration will also be given to other non-geodetic uses of the GNSS data, such as reflectometry for determining snow depth and soil moisture.

Commercial real-time kinematic network (RTN) services and their networks of base stations have grown significantly over the years. They are effectively providing access to the NAD83 reference frame for many users independent of the public government networks in both Canada and the U.S. Because these networks are not always integrated into the same realization of NAD83, CGS began a program of validating the coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. CGS continues to provide on-going, monthly-updated multi-year cumulative solutions for 6 of the largest commercial RTN services in Canada; a total of nearly 900 stations (see Figure 1.3c.5). Compliance agreements have been signed with the five largest services where they have committed to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTN services are integrated into the latest realization of NAD83(CSRS). CGS is also monitoring the stability of RTN stations through time series of weekly coordinate solutions published on CGS's public website.

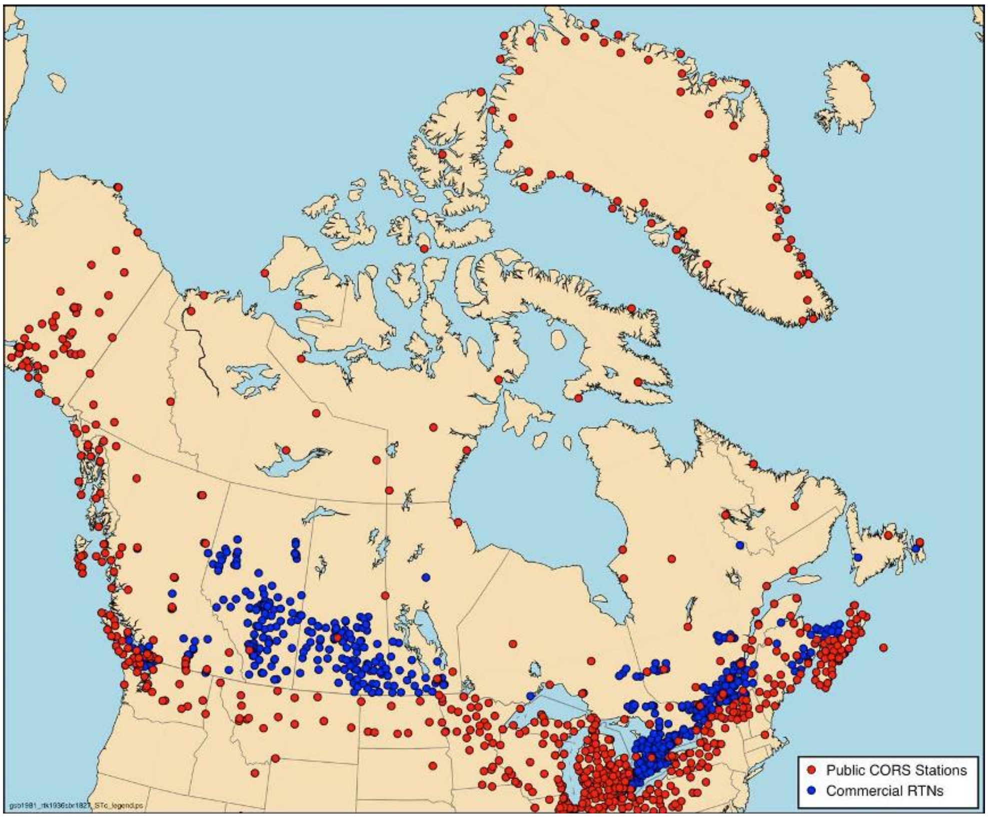


Figure 1.3c.5: Distribution of the six largest commercial RTK networks in Canada (blue dots) in relation to public federal and provincial networks of permanent GNSS stations (red dots). The commercial RTN stations significantly densify the public network in the Prairies.

NGS is also committed to developing an RTN Alignment Service (RAS) for RTN operators and users in the U.S. that will ensure RTN coordinates are consistent with the National Spatial Reference System (NSRS). This is intended to be a two-step procedure by first quantifying the alignment of base stations and then quantifying the alignment of rover positions relative to the NSRS.

Cooperation with other organizations and international integration

There has been much international coordination between NAREF and other groups. The most direct engagement has been with IAG 2.4c – gravity and geoid for Central and North America and the Caribbean. Canada has already adopted a geoid based vertical datum and the U.S. will soon do likewise. The North America-Pacific Geopotential Datum (NAPGD2022) is being jointly developed by Canada, the U.S. and Mexico to serve as a regional vertical datum, which will be accessed via the NATRF2022. As such, there is close cooperation between both 1.3c and 2.4c to ensure compatibility.

Additionally, NAREF is looking to foster closer cooperation and collaboration with the IAG Sub-Commission 1.3b for South and Central America (SIRGAS). Although SC1.3b is still referred to as SIRGAS within the IAG, the SIRGAS organization recently implemented new terms of reference that defines itself as more of a separate scientific non-governmental organization serving all of the Americas. SIRGAS WG I (Reference System) expanded its focus to developing a reference frame for all of the Americas in support of the regional implementation of the UN-GGIM Global Geodetic Reference Frame for all of the Americas. As such, IAG 1.3b and 1.3c members actively participated to ensure that the SIRGAS Reference Frame is tied to the ITRF throughout all of the Americas. And members of NAREF SC1.3c are now official members of both SIRGAS and its WG I and the newly formed UN-GGIM:Americas Working Group 4 of the Geodetic Reference Framework for the Americas (GRFA).

Members of NAREF have also been contributing to the UN-GGIM Sub-Committee on Geodesy (SCoG) and its working groups. NGS and CGS are members of the SCoG. M. Craymer has served as Chair of the SCoG Working Group on Policies, Standards and Conventions until 2020 and D. Roman has recently assumed duties as the Chair of the SCoG Working Group on Education Training and Capacity Building, renamed as the Working Group on Geodetic Capacity Development.

Related to the SCoG standards working group are NAREF contributions to the development of ISO standards and the ISO Geodetic Registry (ISOGR). The Registry is an authoritative collection of definitions of international reference frames and the transformations between them, similar to the privately run EPSG registry. The primary purpose of the ISOGR is to provide an authoritative source of such information for other registries, including EPSG, as well as GIS software developers and end users. Both CGS and NGS have made a significant effort to populate and update the Registry with all current and historical reference frame realizations used in Canada and the U.S. along with the many transformations among them. The Control Body that approves and facilitates the entry of data into the Registry is presently chaired on behalf of the IAG by M. Craymer (Canada) and L. Hothem (U.S.). Under their leadership, registry software has been developed and implemented by Ribose Group. More recently, CGS has funded the migration of the ISOGR to a new, more efficient software platform. The Registry is available at the following link: *http://registry.isotc211org*.

Organised Meetings

2021 Geospatial Summit, Virtual, May 4-5, 2021. https://geodesy.noaa.gov/geospatial-summit/

Geodesy Forum for UN-GGIM:Americas, Geodesy for Sustainable Americas, virtual, May 14, 2021

2021 Annual General Meeting of the Canadian Geodetic Reference System Committee (CGRSC), Virtual, May 26-28, 2021.

Publications

Craymer M., Hothem L. (2019). Geodetic Standards Activities in ISO and the UN-GGIM Sub-Committee on Geodesy. Presented at the 27th IUGG General Assembly, Montreal, July 8-18.

Craymer M., Lamothe P. (2021). NAD83(CSRS): From Static to Dynamic. Association of Canada Land Surveyors Webinar, May 18 (French) & 20 (English).

Donahue B., Lamothe P. (2021). Modernization of the North American Reference System – The U.S. Plan and the Considerations for Canada. Association of Canada Land Surveyors Webinar, January 19 (French) & 21 (English).

Dennis M.L. (2020). The National Adjustment of 2011: Alignment of Passive GNSS Control with the Three Frames of the North American Datum of 1983 at Epoch 2010.00: NAD83 (2011), NAD83 (PA11), and NAD83 (MA11), National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, July 29. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0065.pdf

Erickson C., Banham G., Berg R., Chessie J., Craymer M., Donahue B., Tardiff R., Thériault Y., Véronneau M. (2020). The U.S. is replacing NAD83 with NATRF2022: what this means for Canada. Geomatica, Vol. 73, pp. 74-80. https://doi.org/10.1139/geomat-2019-0021

Federal Register Notice (2020). Upcoming Changes to the National Spatial Reference System (NSRS), 85 FR 44864, 44864, 2020-16068, https://www.govinfo.gov/content/pkg/FR-2020-07-24/pdf/2020-16068.pdf.

Kinsman N., Scott G., Kanazir B., Jordan K., Jalbrzikowski J. (2021). Modernized NSRS Use Cases, webinar, April 08, 2021, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

McFarland P. (2020). Global Reference Frames: What they Are and How/Why NGS Aligns to Them, October 8, 2020, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 1: Geometric Coordinates and Terrestrial Reference Frames, NOAA Technical Report NOS NGS 62, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 2017, Revised April 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0062.pdf

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 2: Geopotential Coordinates and Geopotential Datum, NOAA Technical Report NOS NGS 64, National Geodetic Survey, National Oceanic and Atmospheric Administration, November 2017, Revised February 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0064.pdf

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 3: Working in the modernized NSRS, NOAA Technical Report NOS NGS 67, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 2019, Revised February 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0067.pdf

Robin C., Bremner M., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y. (2019a). An updated NAD83(CSRS) velocity field and hybrid crustal velocity model for Canada. AGU Fall Meeting, San Francisco, Dec. 9-13, Abstract No. G23C-0774

Robin C., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y. (2019b). NAD83(CSRS) v7: A New Realization of NAD83(CSRS) for Canada. Presented at the 27th IUGG General Assembly, Montreal, July 8-18

Robin C., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y., James T. (2019c). Comparing GIA models with an updated velocity field: Towards an improved Canadian Spatial Reference System. Workshop on workshop on Glacial Isostatic Adjustment, Ice Sheets, and Sea-Level Change – Observations, Analysis, and Modelling, Ottawa, September 26

Robin C., Craymer M., Ferland R., James T., Lapelle E., Piraszewski M., Zhao Y. (2021). NAD83v70VG: a new national crustal velocity model for Canada, Geomatics Canada, Open File 62. https://doi.org/10.4095/327592

Smith D. (2019). Blueprint for 2022, Part III: Working in the Modernized NSRS, July 25, 2019, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Smith D. (2020). Exploring and Quantifying the Contribution of Linear Coordinate Functions at NOAA CORS Network Stations to the 2022 Intra-Frame Velocity Model: An Experiment, NOAA Technical Memorandum NOS NGS 83, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, January 31. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0083.pdf

Smith D. (2020). A GPS Based Estimate of the Rotation of the Mariana Plate in both ITRF2008 and ITRF2014, NOAA Technical Report NOS NGS 74, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, August 11. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0074.pdf

Smith D. (2020). Delayed Release of the Modernized NSRS, August 27, 2020, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Smith D. (2020). Biquadratic Interpolation, NOAA Technical Memorandum NOS NGS 84, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, September 2. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0084.pdf

Smith D. (2020). On the Propagation of Formal Error Estimates of Euler Pole Parameters into Modernized NSRS Coordinates, NOAA Technical Memorandum NOS NGS 85, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, September 8. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0085.pdf

Smith D. (2020). Quantifying Systematic Error When Using Axial Rotation Rates Rather Than Geographic Euler Pole Parameters When Describing Tectonic Plate Rotation, NOAA Technical Memorandum NOS NGS 86, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, October 1. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0086.pdf

Smith D., Bilich A. (2019). NADCON 5.01, NOAA Technical Memorandum NOS NGS 81, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, July 30. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0081.pdf

Smith D., Dennis M. (2020). On the Use of Linear Units as a Companion to Horizontal Datum Transformations Performed on Curvilinear Coordinates (or "What does NGS mean when they provide NADCON transformations and error estimates for latitude and longitude in meters?"), NOAA Technical Memorandum NOS NGS 82, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, February 26. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0082.pdf

Smith D. (2021). Working in the Modernized National Spatial Reference System, March 11, 2021, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Sub-Commission 1.3d: Africa (AFREF)

Chair: Elifuraha Saria (Tanzania)

No report was submitted

Sub-Commission 1.3e: Asia-Pacific

Chair: Basara Miyahara (Japan)

Introduction and structure

The objective of sub-commission 1.3e is to improve the regional cooperation that supports the realization and densification of the International Terrestrial Reference frame (ITRF). Its work is carried out in close collaboration with the Geodetic Reference Frame Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP).

The specific objectives of the Sub-commission 1.3e are:

- The densification of the ITRF and promotion of its use in the Asia Pacific region;
- To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- To develop a better understanding of crustal motion in the region;
- To promote the collocation of different measurement techniques, such as GNSS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
- To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Members

- *John Dawson (Australia)*
- *Yamin Dang (China)*
- *Shyam Veer Singh (India)*
- *Basara Miyahara (Japan)*
- *Yi Sang Oh (Republic of Korea)*
- *Mohd Yunus (Malaysia)*
- *Dalkhaa Munkhtsetseg (Mongolia)*
- *Graeme Blick (New Zealand)*

National geospatial information agencies of the Asia-Pacific region are listed here: *https://www.un-ggim-ap.org/content/members*.

Activities during the period 2019-2021

The sub-commission 1.3e has three focuses in the period; densification of ITRF, collaboration with global geodetic community, and geodetic capacity development in the region.

Asia-Pacific Reference Frame (APREF) Project

The purpose of the Asia-Pacific Reference Frame (APREF) project is to create and maintain an accurate geodetic framework to meet the growing needs of society including industries, science programs and the general public using positioning applications in the Asia-Pacific region. The project specifically is:

- Encouraging the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;

- An authoritative source of coordinates, and their respective velocities, for geodetic stations in the Asia-Pacific region;
- Establishing and maintaining a dense velocity field model in Asia and the Pacific for scientific applications and the long-term maintenance of the Asia-Pacific reference frame.

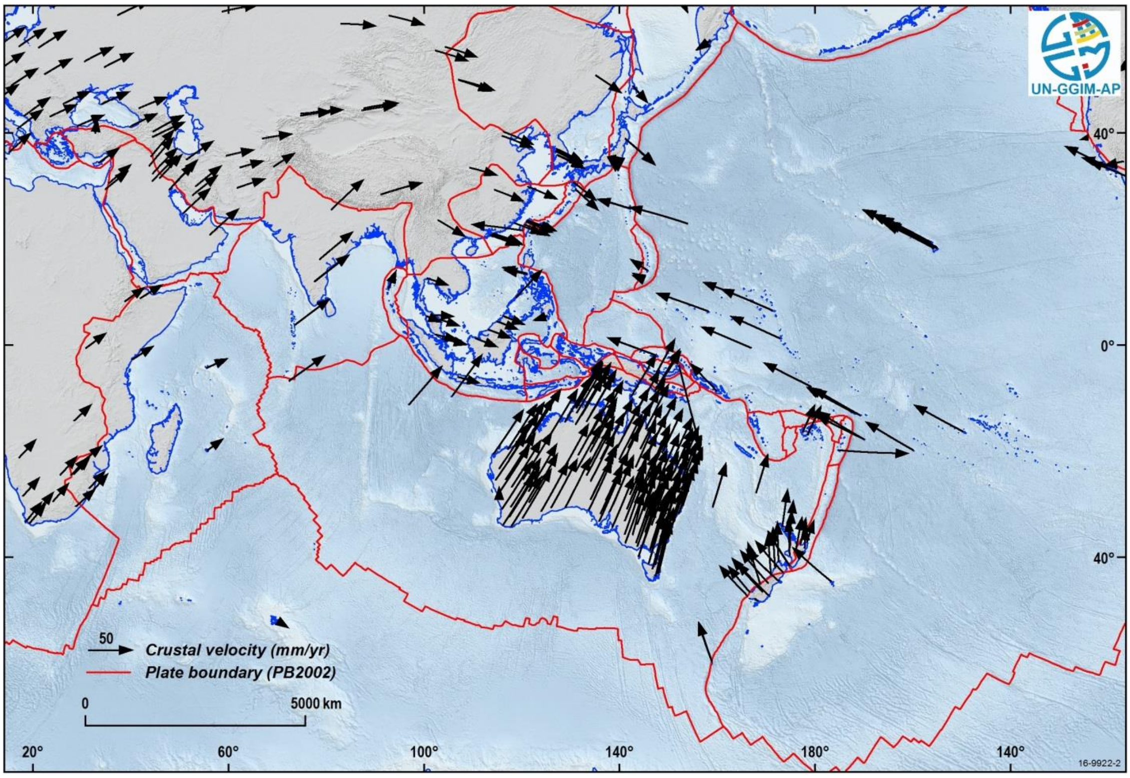


Figure 1.3e.1: APREF GNSS stations

A large number of agencies have and are participating in APREF, the following table summarizes commitments and contributions by member nations/organizations.

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
Afghanistan	National Geodetic Survey (USA)			2
Alaska, USA	National Geodetic Survey (USA)			7
American Samoa	National Geodetic Survey (USA)			1
Australia	Geoscience Australia	✓	✓	139
Australia	Curtin University	✓		1
Australia	Department of Natural Resources, Mines and Energy, QLD			8
Australia	Department of Environment, Land, Water and Planning	✓		107
Australia	Department of Infrastructure, Planning and Logistics, Northern Territory			5
Australia	Department of Primary Industries, Parks, Water & Environment, Tasmania			2
Australia	Department of Finance, Services & Innovation, New South Wales			170

Country/Locality	Responding Agency	Contribution		
Australia	RTK NetWest			12
Australia	IPS Radio and Space Services			3
Australia	Department of Transport and Main Road, Queensland			17
Brunei	Survey Department, Negara Brunei Darussalam			1
China	The Institute of Geodesy and Geophysics, Chinese Academy of Sciences	✓		
Cook Islands	Geoscience Australia and Lands Department of Cook Islands			1
Cook Islands	Geospatial Information Authority of Japan			1
Federated States of Micronesia	Geoscience Australia and Weather Service of the Federated States of Micronesia			1
Fiji	Geoscience Australia and Lands Department of Fiji			1
French Polynesia	Geospatial Information Authority of Japan			1
Guam, USA	National Geodetic Survey (USA)			1
Hong Kong, China	Survey and Mapping Office			14
India	Survey of India			3
Indonesia	Bakosurtanal			8
Iran	National Cartographic Center, Iran			6
Iraq	National Geodetic Survey (USA)			6
Japan	Geospatial Information Authority of Japan			8
Japan	Japan Aerospace Exploration Agency			1
Kazakhstan	Kazakhstan Gharysh Sapary			2
Kiribati	Geoscience Australia and Weather Service of Kiribati			1
Kiribati	Geospatial Information Authority of Japan			2
Macau, China	Macao Cartography and Cadastre Bureau			3
Marshall Islands	Geoscience Australia and Weather Service of Marshall Islands			1
Malaysia	Department of Survey and Mapping Malaysia, JUPEM			7

Country/Locality	Responding Agency	Contribution		
Mongolia	Administration of Land Affairs, Construction, Geodesy and Cartography (ALACGaC)			8
Nauru	Geoscience Australia and Lands Department of Nauru			1
New Zealand	Land Information New Zealand	✓	✓	38
Northern Mariana Islands	National Geodetic Survey (USA)			1
Papua New Guinea	National Mapping Bureau, Papua New Guinea, and Geoscience Australia			2
Philippines	Department of Environment and Natural Resources, National Mapping and Resource Information Authority	✓	✓	4
Samoa	Geoscience Australia and Lands Department of Samoa			1
Solomon Islands	Geoscience Australia and Weather Service of Solomon Islands			1
Tonga	Geoscience Australia and Lands Department of Tonga			1
Tuvalu	Geoscience Australia and Weather Service of Tuvalu			1
Vanuatu	Geoscience Australia and Lands Department of Vanuatu			1

APREF data and products are provided with an open access data policy via the internet, following the practice of the International GNSS Service (IGS).

- Daily GNSS RINEX data, see ftp://ftp.data.gnss.ga.gov.au/daily/
- Station log files, see ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/logs/
- Weekly coordinate estimates in SINEX format, see ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/solutions/apref/

Asia Pacific Regional Geodetic Project

For further densification and improvement of access to the ITRF, the group has continued to support the annual Asia Pacific Regional Geodetic Project (APRGP), which is a week-long GNSS campaign throughout the region (see Fig. 1.3e.2). Campaigns were undertaken in 2019 and 2020. A campaign is planned for 2021.

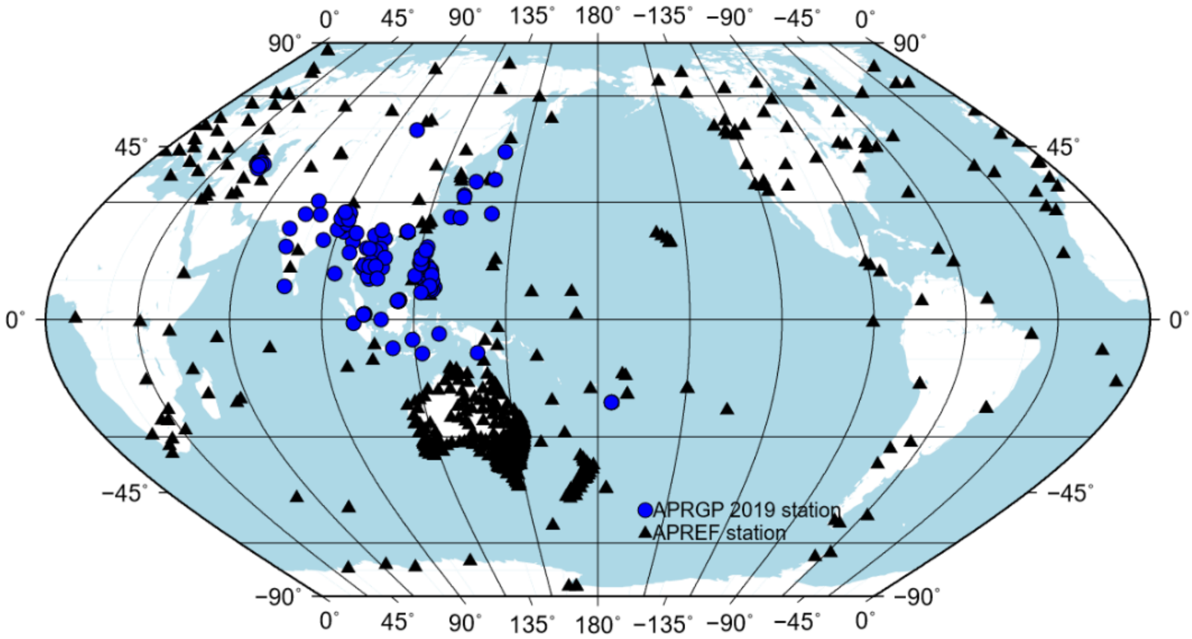


Figure 1.3e.2: Participating stations of the APRGP 2019 GNSS campaign.

Cooperation with other organizations and international integration

Sub-Commission 1.3e made a contribution towards the development of two documents of the UN-GGIM Subcommittee on Geodesy reported to the Tenth Session of UN-GGIM which was held in virtual format.

Outreach and capacity development

Several capacity development events were originally planned, but all of them are cancelled or postponed because of COVID-19 pandemic.

- UN-GGIM-AP, FIG, IAG "Positioning and Datum Modernisation Forum" in 3 November 2019 in conjunction with UN-GGIM-AP 8th Plenary Meeting. It was also the first opportunity to welcome a presentation from the geodetic working group of the UN-GGIM Arab States. Modernization of geodetic reference frames and its issues and challenges were discussed from global, regional and national perspectives. Countries in the region reported their progress, issues and challenges in your geodetic datum.

Figure 1.3e.3: Positioning and Datum Modernisation Forum

- Inaugural "Geodesy4Sendai" Session in 5 November 2019 in conjunction with UN-GGIM-AP 8th Plenary Meeting and GEO Week 2019. It was the first meeting jointly organized by the GEO Geodesy for the Sendai Framework Community Activity and UN-GGIMAP. This session addressed the first project of Geodesy4Sendai – a GNSS-enhanced Tsunami Early Warning "Shield Consortium" whose components are aligned to specific Sendai and SDG targets/indicators and geodesy contribution to Disaster Risk Reduction from regional perspective.

- FIG Technical Seminar on Reference Frame in Practice: Reference Frames, Progress and Challenges in the Asia-Pacific Region, 10 December 2020.

Organized Meetings

Sub-commission 1.3e usually has its annual session at the UN-GGIM-AP Plenary meeting in collaboration with the UN-GGIM-AP Working Group on Geodetic Reference Frame.

- The sub-commission 1.3e held its annual session at the 8th Plenary Meeting of UN-GGIM-AP on 3 November 2019. The national/regional/global issues and challenges on geodetic reference frame were discussed and resolution to tackle them were developed to table them to the Plenary Session.

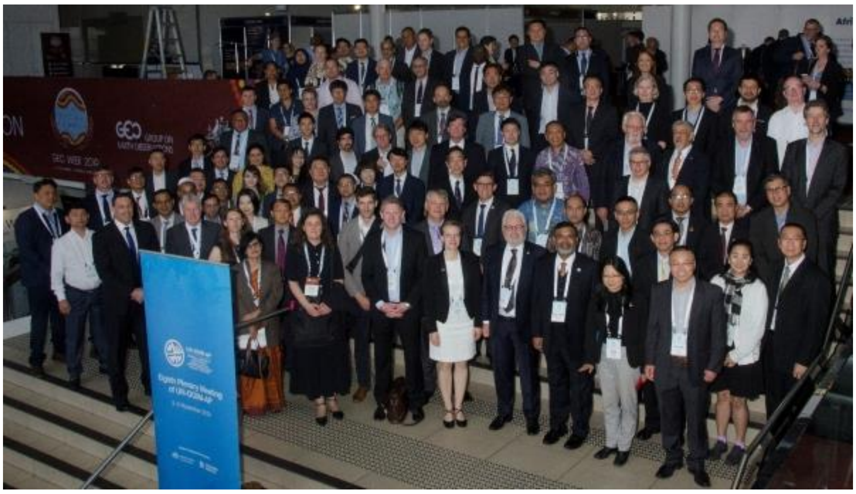


Figure 1.3e.4: 8th Plenary Meeting of UN-GGIM-AP

- The annual session of sub-commission 1.3e was held on 3 November 2020 in virtual format in conjunction with UN-GGIM-AP 9th Plenary Meeting. Although this was the first online session, the session has a larger number of participants than the past sessions and around 70 people participated in it.

Publications

Hu, G. (2019). Report on the Analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2019. Record 2020/27. Geoscience Australia, Canberra.

Hu G., Jia M., Dawson J. (2019). Report on the Asia Pacific Reference Frame (APREF) Project. Record 2019/17. Geoscience Australia, Canberra, https://doi.org/10.11636/Record.2019.017

Sub-Commission 1.3f: Antarctica

Chair: Martin Horwath (Germany)

Introduction and Structure

SC 1.3f deals with the densification of the ITRF in Antarctica and the application of geodetic GNSS measurements for geoscientific investigations, especially in geodynamics, geophysics, and glaciology. For this, the SC 1.3f promotes and supports all activities to realize geodetic GNSS measurements on bedrock sites in Antarctica. Therefore, a close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR), especially to the SCAR Expert Group (EG) "Geodetic Infrastructure in Antarctica" (GIANT).

In terms of geodetic infrastructure Antarctica is a special case because it is not subject to sovereignty of any state. Instead, the Antarctic Treaty ensures freedom of research. Thus, geodetic markers and GNSS installations have been set up and are being maintained by a great number of different national Antarctic programs.

Members

The membership is mostly identical with that of SCAR EG GIANT. In that way, cooperation and coordination can best be pursued since all nations are represented who are involved geodetic GNSS activities in Antarctica.

- *Martin Horwath (Germany)*
- *Alessandro Capra (Italy)*
- *Mirko Scheinert (Germany)*
- *Manuel Berrocoso (Spain)*
- *Graeme Blick (New Zealand)*
- *Jan Cisak (Poland)*
- *Beata Csatho (USA)*
- *John Dawson (Australia)*
- *Giorgiana De Franceschi (Italy)*
- *Koishiro Doi (Japan)*
- *Rene Forsberg (Denmark)*
- *Angelo Galeandro (Italy)*
- *Brendan Hodge (USA)*
- *Larry Hothem (USA)*
- *Erik Ivins (USA)*
- *Thomas James (Canada)*
- *Aspurah Kamburov (Bulgaria)*
- *Matt King (Australia)*
- *Christoph Knöfel (Germany)*
- *Jeronimo Lopez-Martinez (Spain)*
- *Jaakko Mäkinen (Finland)*
- *Kenichi Matsuoka (Norway)*
- *Alexey Matveev (Russia)*
- *Gennadi Milinevsky (Ukraine)*
- *Monia Negusini (Italy)*
- *Elizabeth Petrie (United Kingdom)*
- *Markku Poutanen (Finland)*
- *Goncalo Prates (Portugal)*
- *Yves Rogister (France)*
- *Kazuo Shibuya (Japan)*

- *Lars Sjoberg (Sweden)*
- *Norbertino Suarez (Uruguay)*
- *Terry Wilson (USA)*
- *Andres Zakrajsek (Argentina)*

Activities during the period 2019-2021

SCAR GNSS Database

In close linkage with SCAR EG GIANT a database on geodetic GNSS in Antarctica (SCAR GNSS Database) is being maintained at TU Dresden. This is an ongoing activity (see data1.geo.tu-dresden.de/scar) and provides an important background support for the GIANT-REGAIN project (see below).

Geodetic observations (non-exhaustive list)

Space geodetic observations (VLBI, DORIS, GNSS) and sea level observations at Syowa Station were continued.

Continuous observation of gravity by the superconducting gravimeter at Syowa Station was suspended from September 2018 to the end of October 2020 due to the distortion of the refrigerator support frame.

From November to December 2019, absolute gravity measurements using FG-5 were carried out at two Antarctica Stations, Jang Bogo Station (South Korea) and Mario Zucchelli Station (Italy).

Reprocessing of GNSS data in Antarctica (GIANT-REGAIN)

At the SCAR Meeting 2016 in Kuala Lumpur an initiative was launched by Mirko Scheinert (Germany) and Matt King (Australia) entitled "Geodynamics in Antarctica based on Reprocessing GNSS Data Initiative" (GIANT-REGAIN). This project aims to provide a consistent solution of coordinates and coordinate changes for the most complete set of GNSS bedrock stations in Antarctica for further applications in geodesy, geophysics and geodynamics (especially studies on glacial-isostatic adjustment). It was a huge task especially to collect and homogenize the necessary metadata. The project comprises now about data from about 250 bedrock sites in Antarctica over a time span from 1995 to the end of 2017. The progress and first results of GIANT-REGAIN were reported at the 27th IUGG General Assembly in Montreal, 2019.

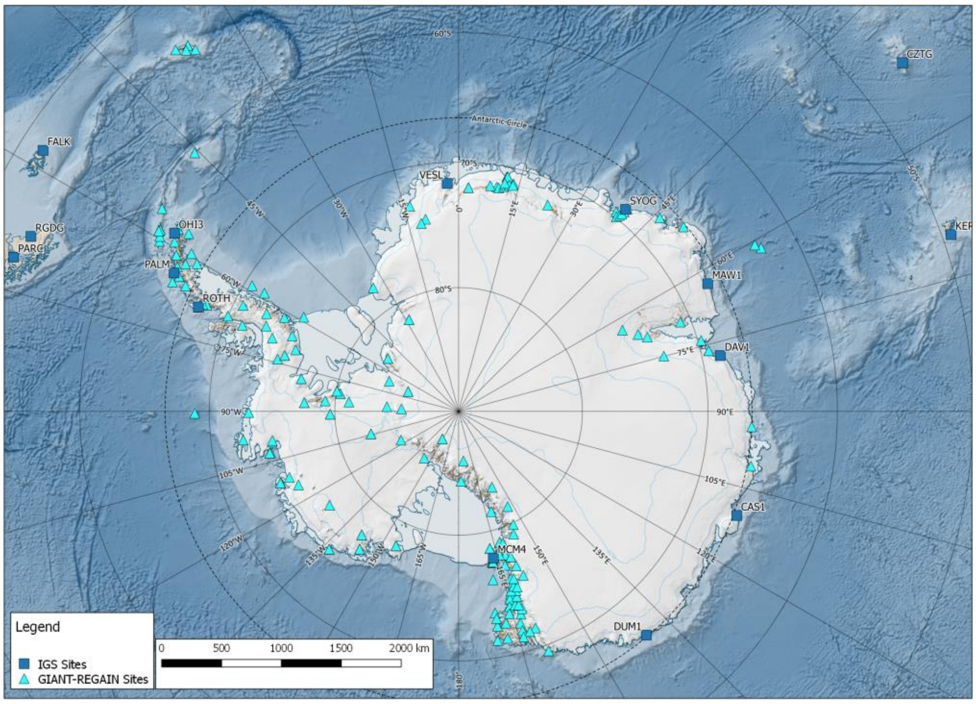


Fig. 1.3.f.1: Overview of geodetic GNSS sites on bedrock in Antarctica utilized for the GIANT-REGAIN project, © TU Dresden / SCAR EG GIANT. See text for explanations. Map source: Quantarctica 3, QGIS 2.18.

Participation in related meetings, conferences and workshops

Group members took part in relevant meetings, conferences and workshops although due to the Corona crisis most meetings took place in an online format or had to be cancelled at all. Besides the annual EGU General Assemblies and AGU Fall Meetings, the following meetings shall especially be mentioned:

- IUGG General Assembly, Montreal (Canada), 08 – 18 July 2019
- International Symposium on Antarctic Earth Sciences (ISAES) XIII, Incheon (South Korea), 28 July – 02 August 2019
- XXXVI SCAR Meeting and Open Science Conference (online, originally to take place in Hobart, Australia), August 2020

Organised Meetings

Caused by the Corona crisis a special group meeting (like on occasion of preceding SCAR meetings) could not take place in 2020.

Publications

Rosado B., Fernández-Ros A., Berrocoso M., Prates G., Gárate J., de Gil A., and Geyer A. (2019). Volcano-tectonic dynamics of Deception Island (Antarctica): 27 years of GPS observations (1991–2018). *Journal of Volcanology and Geothermal Research*, *381*, 57-82.

Samrat N. H., King M. A., Watson C., Hooper A., Chen X., Barletta V. R., and Bordoni, A. (2020). Reduced ice mass loss and three-dimensional viscoelastic deformation in northern Antarctic Peninsula inferred from GPS. *Geophysical Journal International*, *222*(2), 1013-1022.

Turner R. J., Reading A. M., and King M. A. (2020). Separation of tectonic and local components of horizontal GPS station velocities: a case study for glacial isostatic adjustment in East Antarctica. *Geophysical Journal International*, *222*(3), 1555-1569.

Whitehouse P.L., Gomez N., King M.A. et al. (2019). Solid Earth change and the evolution of the Antarctic Ice Sheet. Nat Commun 10, 503. https://doi.org/10.1038/s41467-018-08068-y

Zanutta A., Negusini M., Vittuari L., Martelli L., Cianfarra P., Salvini F., Mancini F., Sterzai P., Creati N., Dubbini M., and Capra A. (2021). Victoria Land, Antarctica: An Improved Geodynamic Interpretation Based on the Strain Rate Field of the Current Crustal Motion and Moho Depth Model. *Remote Sensing*, *13*(1), 87.

Working Groups of Sub-commission 1.3

WG 1.3.1: Time-dependent transformations between reference frames in deforming regions

Chair: Richard Stanaway (Australia)

Introduction and Structure

The main aim of the WG is to develop strategies to enable time-dependent transformations in deforming regions to support positioning and geodetic applications. The WG is reviewing the different approaches currently used to enable transformation between reference frames within plate boundary zones and regions affected by glacial isostatic adjustment (GIA). These transformations are necessarily time-dependent to account for secular plate motion, interseismic strain and episodic seismic deformation. In these instances conformal transformations do not adequately model the complexity of the deformation field and other approaches are required to enable high precision transformations between source and target reference frames at different epochs. Deformation and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for positioning, land surveying, mapping and GIS.

Since May 2020, the WG has been closely collaborating with the Open Geospatial Consortium (OGC) Coordinate Reference System (CRS) Domain Working Group and other regional reference frame working groups to develop a functional model for non-conformal time-dependent transformations, deformation models and a standarised open-source geodetic grid exchange format (GGXF). The functional model and grid format will be supported by registries of geodetic parameters such as those hosted by ISO/TC 211 and IOGP/EPSG to assist geodetic agencies, positioning services and software developers. The WG is also working closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members comprise of a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying, GIS and IT. The WG has attempted to be as inclusive as possible with the aim of involving geodesists from most countries that deal with and manage significant crustal deformation.

Members

- *Richard Stanaway (Australia)*
- *Wan Anom Wan Aris (Malaysia)*
- *Elmar Brockmann (Switzerland)*
- *Miltiadis Chatzinikos (Greece)*
- *Yingyang Cheng (China)*
- *Michael Craymer (Canada)*
- *Chris Crook (New Zealand)*
- *Nic Donnelly (New Zealand)*
- *Kristian Evers (Denmark)*
- *Jeff Freymueller (USA)*
- *Pasi Häkli (Finland)*
- *Muzaffer Kahveci (Turkey)*
- *Kevin Kelly (USA)*
- *Martin Lidberg (Sweden)*
- *Roger Lott (UK)*

- *Niraj Manandhar (Nepal)*
- *Basara Miyahara (Japan)*
- *José Antonio Tarrío Mosquera (Chile)*
- *Chris Pearson (New Zealand)*
- *Susilo (Indonesia)*

Corresponding Members
- *Stylianos Bitharis (Greece)*
- *Graeme Blick (New Zealand)*
- *Carine Bruyninx (Belgium)*
- *Xavier Collileux (France)*
- *Paul Denys (New Zealand)*
- *Patrick Forster (South Africa)*
- *Mark Greaves (UK)*
- *Leonid Lipatnikov (Russia)*
- *Craig Roberts (Australia)*
- *Hagi Ronen (Israel)*
- *Yoshiyuki Tanaka (Japan)*
- *Tatsuya Yamashita (Japan)*
- *Norman Teferle (G.-D. Luxembourg*

Activities during the period 2019-2021

(a) Developing a functional model and grid format for time-dependent transformations

Conformal time-dependent transformations are already in widespread use typically to accommodate secular plate rotation within a no-net-rotation (NNR) global frame. Plate motion models (PMM) can be simply represented within a 14 parameter model as rotation rate parameters with zeros for the other parameters. The 14 parameter Helmert transformation method is widely used for transformation between different realisations of ITRF, other TRF and plate-fixed RF such as the ETRF, NAD83 and GDA2020. This approach enables time evolution of parameters (rotation, translation and scale) from a defined reference epoch. PMM and time-dependent conformal transformations are suitable for transformation of points within stable portions of a tectonic plate but fail to accommodate intraplate (e.g. GIA) localised and plate boundary zone deformation. Conformal transformation models alone are not suitable for countries straddling plate boundaries. In these instances, geophysical, grid or triangulated velocity models can be used to estimate secular interseismic displacement of a crust-fixed RF as a function of time. Considerable work has been done to develop velocity grids for this purpose.

In addition to secular displacement, episodic seismic displacement models are required for transformation of spatial data (points, point clouds, vectors, strings, polygons and raster data) displaced by earthquakes. Local reference frames used for surveying and mapping often need to be updated to account for coseismic and postseismic deformation where displacements are significant and exceed certain positioning and dimensioning tolerances. Interseismic strain accumulation resulting in distortion of a crust-fixed RF can also require updates to the RF when the strain exceeds certain dimensional tolerances (e.g. across a locked fault). Displacement grids can be used transform spatial data within a consistent reference frame across these events (for example transformation of pre-earthquake spatial data sets to a post-earthquake epoch). A combination of secular velocity and episodic displacements is required to enable transformation between RF in seismically active areas and is especially important with the rapid uptake of GNSS-PPP, particularly by users with limited geodetic expertise. The combination of models is broadly termed a "deformation model" or "trajectory model" and is typically comprised of a suite of velocity grids, coseismic displacement and postseismic amplitude grids. The functional model approach dictates how the grid models are populated, aggregated and used to estimate time-dependent displacements and transformations within and between reference frames.

In June 2020, the Open Geospatial Consortium (OGC) Coordinate Reference System Domain Working Group (OGC CRS DWG) co-chaired by Keith Ryden (ESRI, USA) and Mark Hedley (UK Met Office) commenced biweekly virtual meetings to develop a deformation model functional model and associated geodetic grid format for eventual development as a standard. This activity has been chaired by Roger Lott (IOGP, UK). The considerable overlap with the membership and aims of this OGC DWG project and the IAG WG has provided an ideal opportunity for these meetings to be mutually beneficial.

Chris Crook (LINZ, New Zealand) and Kevin Kelly (ESRI, USA) have co-chaired the deformation model functional model (DMFM) project of the OGC CRS DWG with monthly meetings since June 2020. The following github web-page has full details of this work to date: *https://github.com/opengeospatial/CRS-Deformation-Models.*

Concurrently, Roger Lott is chairing the complementary OGC CRS DWG project that is continuing work with the development of a geodetic grid exchange format (GGXF). One of the main impediments to the uptake of time-dependent transformation models is the lack of an accessible open-source grid format that can accommodate all of the requirements of the grids used in time-dependent transformations. The GGXF format is intended to support not only displacement and velocity grids but also a wider range of geodetic applications, for example as a standard format for geoid, quasi-geoid and hydroid models. The following github web-page has more details: *https://github.com/opengeospatial/CRS-Gridded-Geodetic-data-eXchange-Format.*

The DWG work is nearing finalisation with the next step to promulgate the functional model and grid format and to develop standards and guidance notes to assist implementation with RF used in practice. The importance of this work for datum modernisation, better alignment of GNSS positioning and data frames and the contribution by members of this IAG cannot be understated.

(b) Velocity models for kinematic to static/semi-kinematic RF transformations

In addition to the 14 parameter model, a gridded velocity model is now widely used for time-dependent transformations. Velocities (typically represented in a topocentric format) within a given reference frame are tabulated in a grid format and may be 1D (vertical or single component only), 2D (horizontal only) or 3D. Ideally, uncertainties and covariance information are also assigned to each node value in order to provide users of the model indicative uncertainties at different epochs. For any given point within the model coverage area, velocities and uncertainties can be estimated using a suitable interpolation method and variance propagation. This approach is ideal for transformations of GNSS-PPP positions (currently in the ITRF2014/IGS14 RF) to a local RF at a specific epoch.

A velocity grid is RF specific and provides a means of estimating displacements of points within a RF as a form of intraframe kinematic transformation or propagation. It could also be used directly for interframe transformations (e.g. between ITRF and a crust-fixed RF at a specific epoch) if there is a null-transformation between the velocity model RF and the target RF at the interframe transformation reference epoch. The velocity model alone has no episodic component, so any displacement of the target frame due to earthquakes or other phenomena would be implicit in the transformation for any epoch after a deformation event (assuming that the target frame is updated for these deformation events). Where uncorrected pre-earthquake spatial data is used with this approach, then a seismic displacement model (reverse sense) needs to be applied in addition to the velocity model to align post-earthquake positioning with pre-earthquake datasets.

Recent national and regional velocity model studies by WG members are now summarised. The WG also recognises the substantial efforts made recently by other geodesists in developing models to enable time-dependent transformations.

(c) National and regional velocity grids

Mike Craymer (NRCan, Canada) reports that Canada has recently updated its 3D velocity grid NAD83v70VG (Fig. 1.3.1.1) to support transformation of GNSS PPP positions (currently in the kinematic IGS14 RF) to the Canadian spatial reference system NAD83(CSRS)v7 (Robin, *et al*., 2021). The velocity grid is comprised of 3 grids with 0.25° spacing for each topocentric velocity component and associated uncertainties. The velocities are modelled in the IGS14 RF to enable kinematic PPP solutions in that RF to be transformed to NAD83(CSRS)v7 at the interframe transformation epoch.

The US is in the process of implementing a new national RF to supersede NAD83 and four intraframe velocity models (IFVM) will be an integral part of the new RF. The IFVM will model intraframe velocities within the four major plate-fixed reference frames within US jurisdiction (North America, Pacific, Caribbean and Marianas). Each plate-fixed frame will have a PMM and associated 14 parameter transformation to enable IGS14 (or later) transformations to each plate-fixed frame at a specified epoch.

Latin America has a long established geodetic framework SIRGAS. The current SIRGAS velocity grid (1 degree spacing), VEMOS2017 has evolved significantly since its first realisation in 2003. VEMOS2017 is defined in three reference frames (IGS14, South American Plate and Caribbean Plate). In the most tectonically active country in South America, Chile, José Antonio Tarrío (Universidad de Santiago de Chile) has indicated that the proposed new national dynamic datum for the resource sector REDGEOMIN will incorporate a denser velocity grid to better model interseismic secular velocities along the South America, Nazca and Antarctic Plate boundaries where a 1 degree resolution is insufficient to model the variability of plate boundary deformation along these highly active plate boundaries.

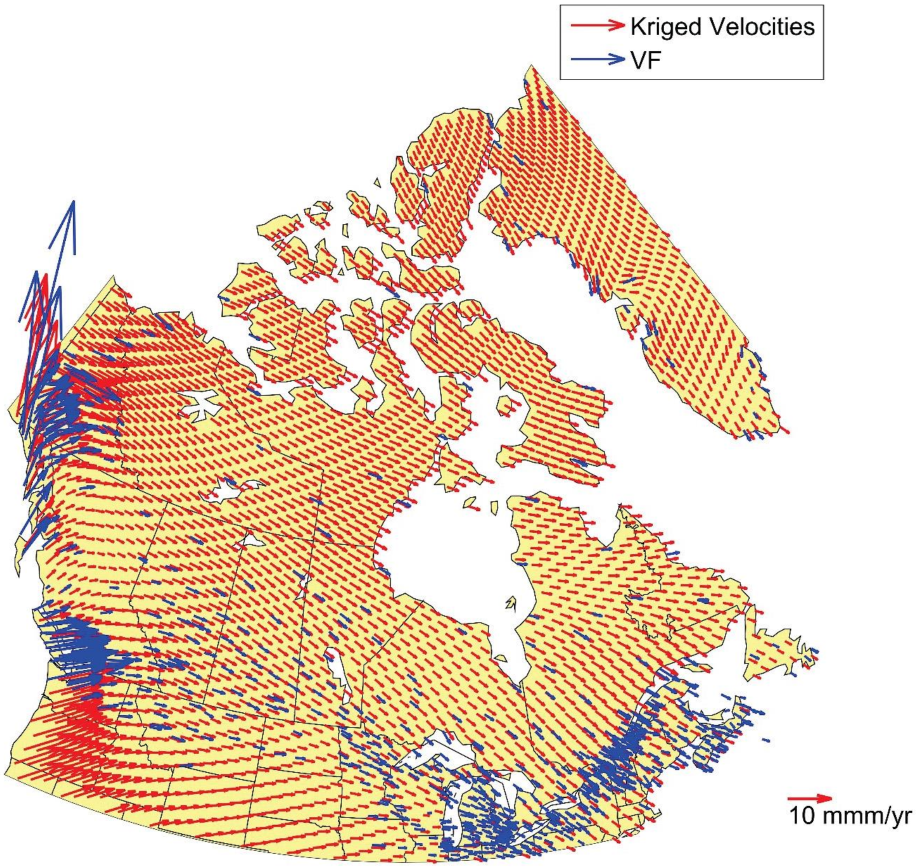


Figure 1.3.1.1(a): NAD83v70VG, horizontal component, in NAD83(CSRS). The gridded model (red arrows) is decimated for easier visualisation. The model is estimated from the measured horizontal component of the velocity field (blue arrows) (Robin *et al*., 2020)

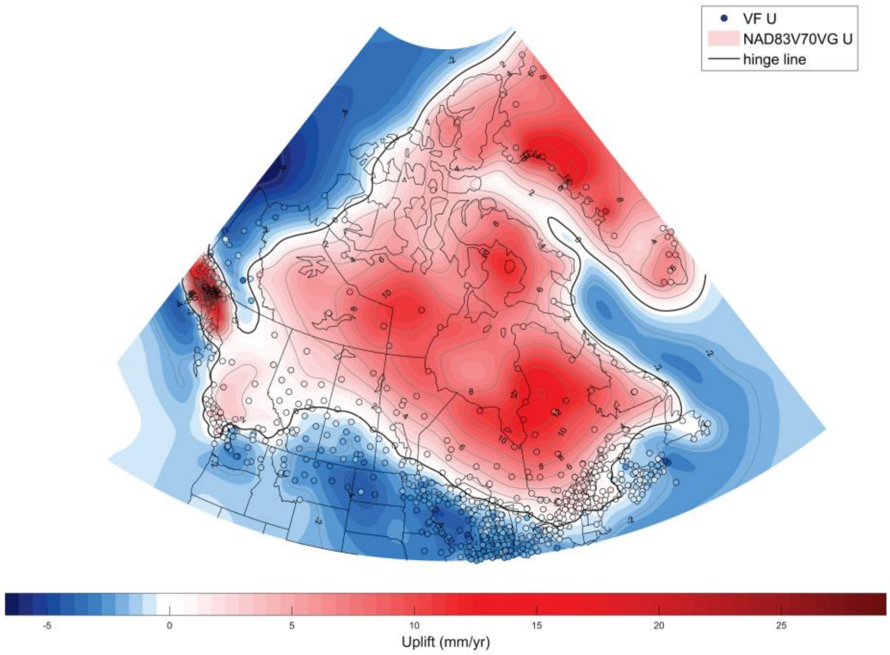


Figure 1.3.1.1(b): NAD83v70VG, vertical component, in NAD83(CSRS). The observed velocity field is shown with coloured circles and shaded contours represents the hybrid velocity model which integrates both the observed velocity field and a combined geophysical model. (Robin *et al*., 2020).

Yingyang Cheng (Chinese Academy of Surveying and Mapping) and colleagues have a developed gridded horizontal velocity model (1° grid interval overall with up to 0.25° interval denser grids in complex deformation zones) to model secular displacements within the Chinese Reference Frame CGCS2000 (Cheng *et al.*, 2021). China has a diffuse but nevertheless complex deformation field and 20 microplates have been identified within China. Tatsuya Yamashita (GSI, Japan) has reported that Japan was improving their secular deformation model (Fig. 1..3.1.2) to support PPP to JGD transformations (POS2JGD) to be precise enough for autonomous navigation tolerances (<3 cm). POS2JGD is a significant improvement on the current approach with a step-function applied at periodic intervals. Recent studies (Takagi *et al*. 2020) and (Tanaka *et al*. 2020) have tested the performance of an approach with a piecewise linear function and found that the new approach could be adequate for applications that require precision alignment of positioning with earlier (static) spatial data (e.g. autonomous driving, precision agriculture, and machinery control). In addition to improving the secular deformation model, Tatsuya has recently collaborated with WG colleagues Chris Crook and Nic Donnelly (LINZ, NZ) developing coseismic displacement grids after large earthquakes from SAR controlled by GNSS ground-truthing (Yamashita, 2020).

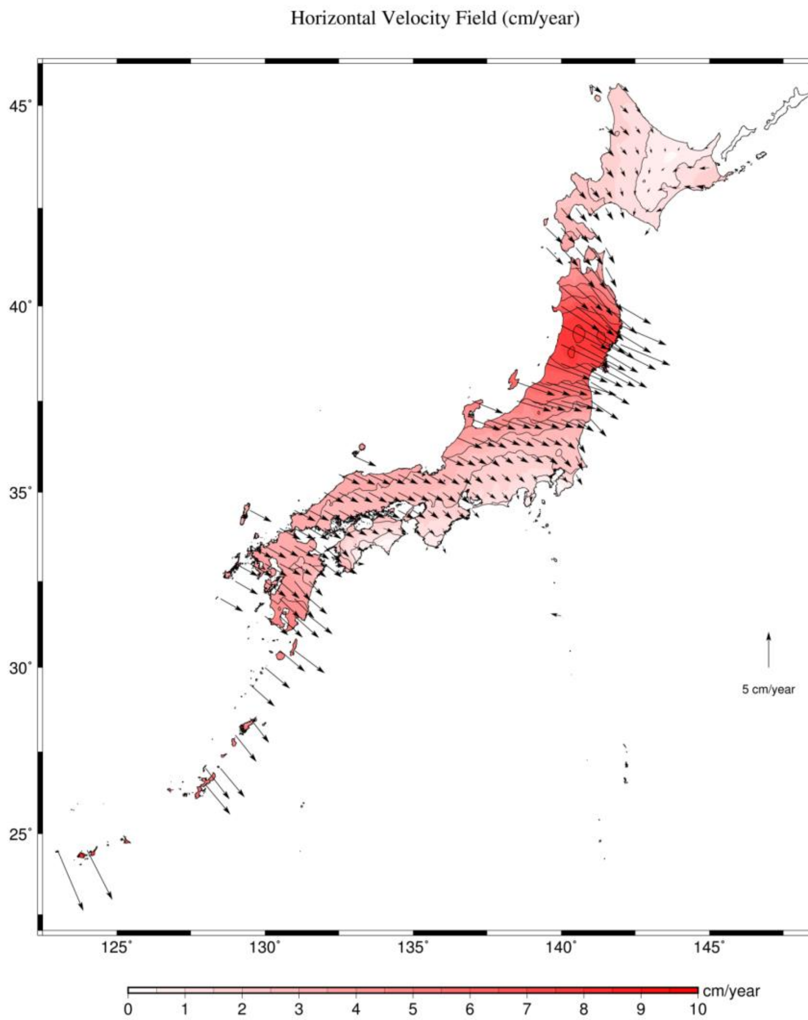


Figure 1.3.1.2(a): The Japanese POS2JGD horizontal secular velocity field (in the IGS14 RF). The postseismic velocity correction after the Tōhoku 2011 earthquake is still significant (up to 8 cm/yr).

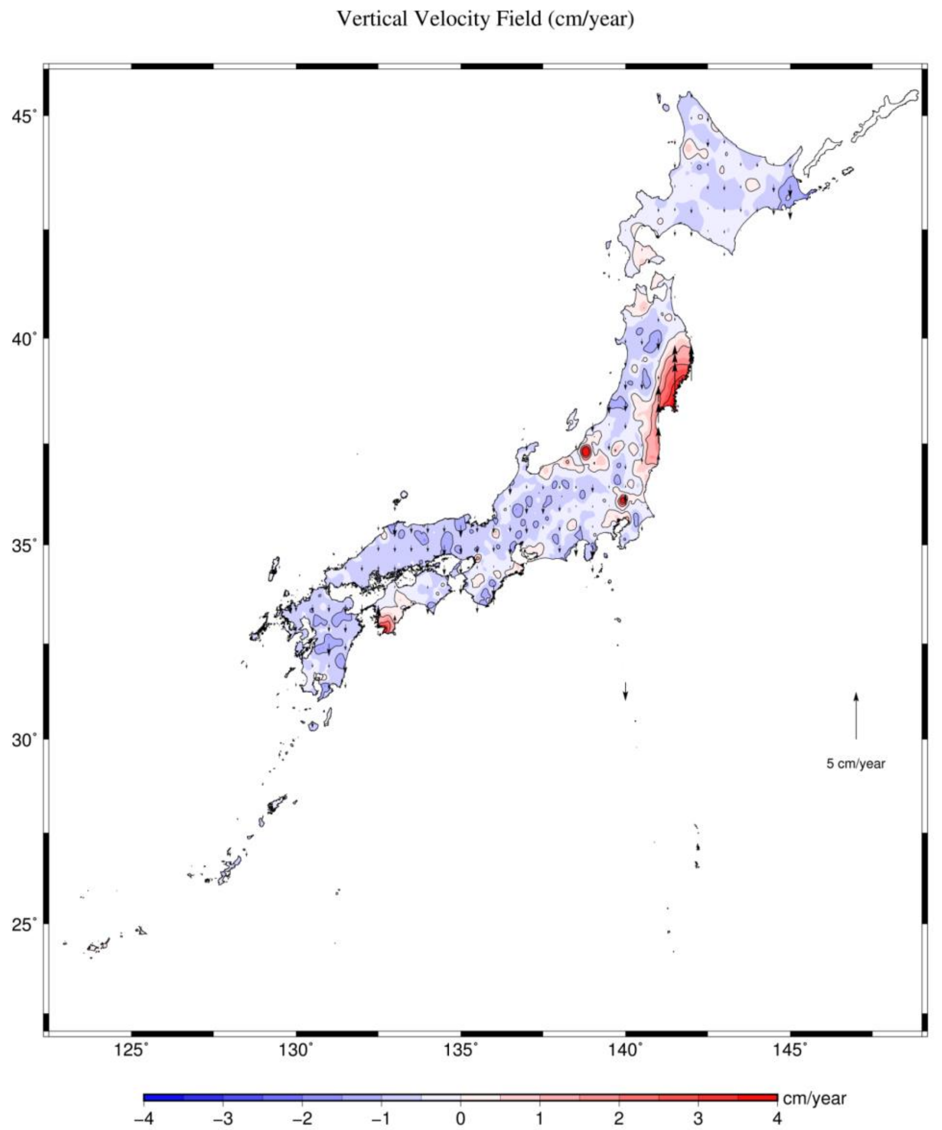


Figure 1.3.1.2(b): The Japanese POS2JGD vertical secular velocity model. The postseismic uplift velocity correction after the Tōhoku 2011 earthquake is still significant (up to 4 cm/yr).

Wan Anom Wan Aris (UTM, Malaysia) and colleagues have developed coseismic displacement and postseismic amplitude grids to support maintenance of the GDM2000 datum in Malaysia and integrity of the MyRTK active geodetic network to account for deformation of the network due to recent large earthquakes in Sumatra (Wan Aris *et al.*, 2018).

Australia is fortunate not to have to deal with significant intraplate deformation apart from isolated intraplate earthquakes, far-field coseismic/postseismic deformation and localised deformation (e.g. from resource extraction, water abstraction and regolith creep). A 14-paramater transformation which embeds the Australian PMM (APMM) is used for ITRF2014 to GDA2020 (Australian plate-fixed) time-dependent transformations to support positioning services such as AusPOS (ICSM, 2020). Since January 2020, a time-dependent Australian Terrestrial Reference Frame (ATRF2014) has also been in use, providing Australia with a dual-frame geodetic reference system that accommodates the requirements of users of both kinematic and plate/crust-fixed reference frames. ATRF2014 is fully aligned with ITRF2014. A national deformation model to support ATRF is being considered to account for any intraplate and localised deformation.

The development of the European velocity model has been significant over the last two years. The EUREF WG on European Dense Velocities chaired by Elmar Brockmann (swisstopo, Switzerland) has currently compiled ~7000 estimated velocities over continental Europe, Turkey and Israel with half of these validated independently by at least 2 analysis centers. This work has been a very substantive collaborative effort involving input from geodetic researchers and agencies from most European countries, Turkey and Israel. This dense velocity field has been used to generate a grid model of velocities (Fig. 1.3.1.3) (swisstopo, 2021). The rapid increase in observed velocities has improved the uncertainty of modelled velocities across Europe. This work ties in closely with the goals of the EUREF WG on Deformation Models chaired by Martin Lidberg (Lantmäteriet, Sweden).

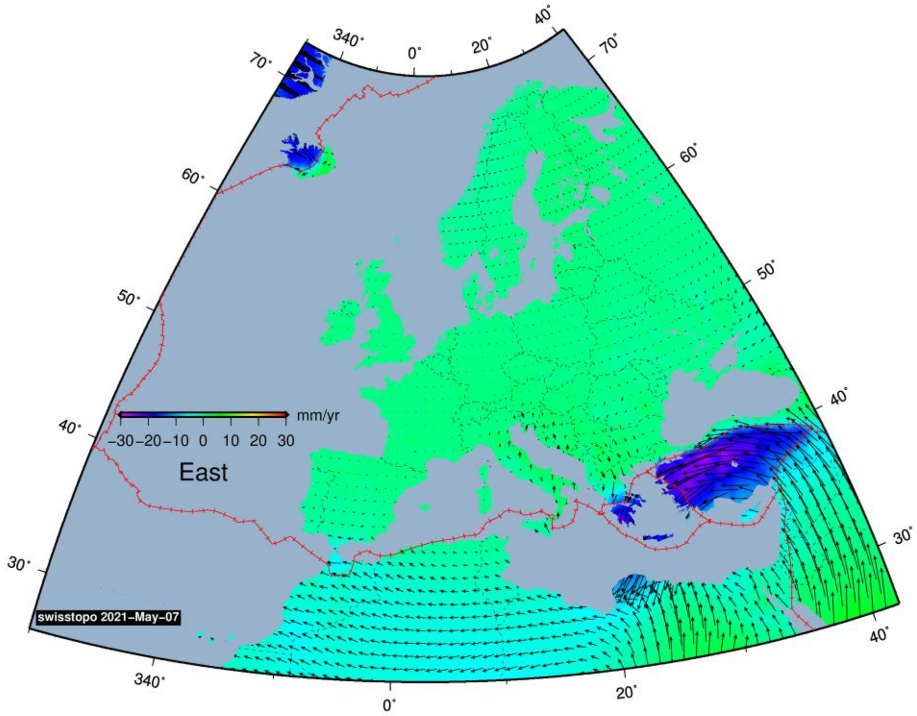


Figure 1.3.1.3(a): European velocity field (East) in a stable Eurasian plate frame (swisstopo, 2021)

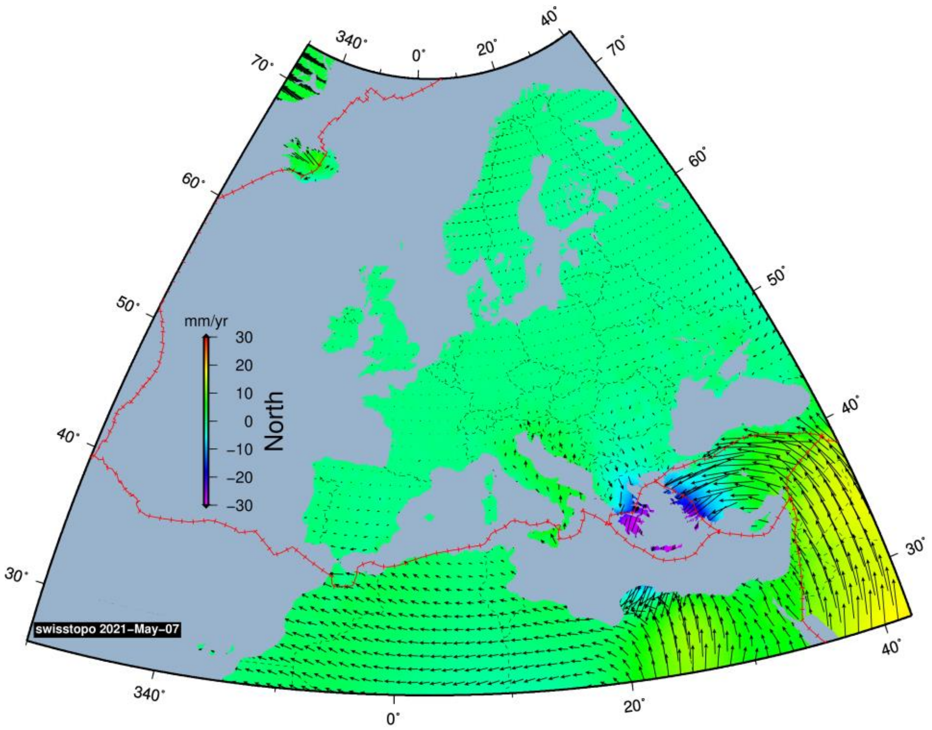


Figure 1.3.1.3(b): European velocity field (North) in a stable Eurasian plate frame (swisstopo, 2021)

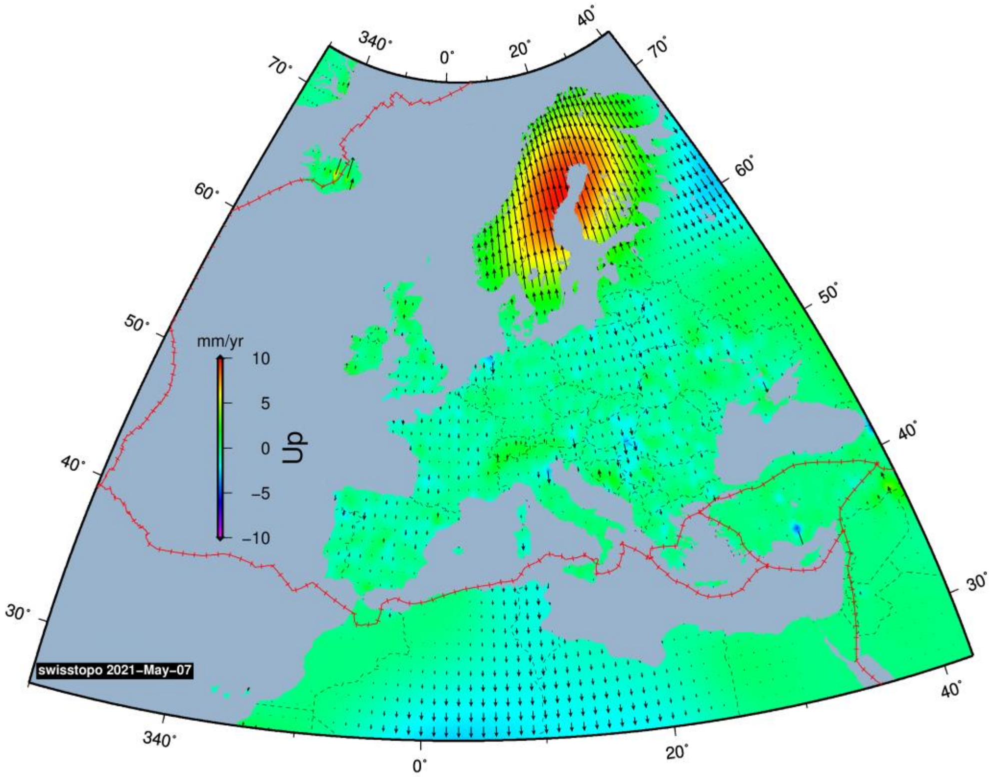


Figure 1.3.1.3(c): European velocity field (Up) in a stable Eurasian plate frame (swisstopo, 2021)

Pasi Häkli (NLS, Finland) along with many collaborators from the Nordic Geodetic Commission (NKG) has developed a horizontal intraplate (Eurasian plate fixed) velocity model for the Nordic and Baltic region (Häkli *et al.,* 2019). The model accounts for the crustal extension component of GIA in the Fennoscandian/Baltic region. The current Nordic vertical velocity model (NKG2016LU) largely attributable to GIA is also used for reference (Vestøl et al., 2019).

Stylianos Bitharis (AUTh, Greece) and colleagues have undertaken considerable development of a velocity model for Greece (Bitharis *et al*., 2019) which has the most complex and active tectonic setting in Europe. This research has been provided to the EUREF WG.

Turkey shares the complex tectonic setting with Greece and Muzaffer Kahveci (KTUN, Turkey) has cited recent work on an update on velocity modelling in Turkey (Kurt *et al.*, 2020).

(d) Questionnaire on usage of time-dependent transformation and deformation models

In 2020, a questionnaire was distributed through the IAG WG and OGC CRS DWG to ascertain how different agencies and research institutions were defining, distributing and using deformation models and velocity grids. The response to the questionnaire was very encouraging with agencies from 29 countries providing information on their respective approaches. The questionnaire and supplied responses can be viewed at this GitHub link (*https://github.com/opengeospatial/CRS-Deformation-Models/blob/master/survey/Deformation%20survey%20responses.xlsx*). The responses have assisted the IAG WG and OGC CRS DWG in developing a functional model and grid format that has flexibility to suit existing approaches to handling RF deformation and to support migration to a more standardised format.

(e) Glossary

A glossary of terms relevant to the WG or aide-memoire is being compiled to provide a useful reference for researchers, developers of standards, guidance notes and working documents. There is no full consistency between key organizations including the ISO, IERS, IOGP/EPSG with regard to terminology and this can to lead to confusion and misunderstandings. The aim of the glossary is to enable groups of users familiar with a specific terminology to translate definitions using plain English.

(f) Complex time-dependent transformations and velocity models in positioning services

Chris Pearson (University of Otago, NZ) has provided significant input into the improvement of Trimble's positioning products with the application of deformation models within the Trimble geodetic library (TGL) used by Trimble Access 2020.20 and Trimble Business Center 5.40 (Pearson, 2020). This work is of very great importance and it is expected that other positioning services will adopt a similar approach to enable more robust, consistent and repeatable localization of GNSS positioning with an established local reference frame to enable better alignment with spatial data.

Organized Meetings

The covid-19 pandemic has effectively ruled out face-to-face international meetings at least until 2022. A WG meeting had been planned to coincide with the FIG Working Week in Amsterdam in May 2020. Fortuitously, the OGC initiated open-access biweekly webinars in June 2020 to develop a functional model for time-dependent transformations and a geodetic grid exchange format (GGXF) for the representation of time-dependent grid models (and geodetic data in general) in a more platform independent and standardized way. The considerable overlap of the goals and membership of the two WG and the opportunity to meet virtually every fortnight has been very collaborative and beneficial. A special note of thanks goes to Keith Ryden (ESRI), Roger Lott (IOGP), Chris Crook(LINZ) and Kevin Kelly (ESRI) for their support and impetus for these regular meetings.

Publications

Bitharis S., Papadopoulos N., Pikridas C., Fotiou A., Rossikopoulos D., and Kagiadakis V. (2019). Assessing a new velocity field in Greece towards a new semi-kinematic datum, Survey Review, 51:368, 450-459, https://doi.org/10.1080/00396265.2018.1479937

Cheng P., Cheng Y., Wang X. and Xu Y. (2021). Update China geodetic coordinate frame considering plate motion. Satellite Navigation, 2, 2 https://doi.org/10.1186/s43020-020-00032-w

Häkli P, Lidberg M., Jivall L., Steffen H., Kierulf H., Ågren J., Vestøl O., Lahtinen S., Steffen R., Tarasov L, New Horizontal Intraplate Velocity Model for Nordic and Baltic Countries, FIG Article, 2019.

ICSM, GDA2020 Technical Manual (2020). https://www.icsm.gov.au/sites/default/files/2020-2/GDA2020%20Technical%20Manual%20V1.5_4.pdf

Kurt A.I., Cingöz A., Özdemir S., Peker S., Özel Ö., and Simav M. (2020). Estimation of the Updated Coordinates and Velocities of Turkish National Fundamental GNSS Network within the Context of GNSS Data Reprocessing (in Turkish), Harita Dergisi; 164: 1-17

Pearson, C., Deformation models in Trimble Access 2020.20 and Trimble Business Center 5.40 (2020). Trimble White Paper

Robin, C.M.I., Craymer, M., Ferland, R., James, T.S., Lapelle, E., Piraszewski, M., Zhao, Y. (2021). NAD83v70VG: A new national crustal velocity model for Canada. Geomatics Canada Open File 0062, Natural Resources Canada. https://doi.org/10.4095/327592

Swisstopo (2021), EUREF WG on Dense Velocities, Results, http://pnac.swisstopo.admin.ch/divers/dens_vel/000.html

Takagi, Y., Kokado, K., Koso, Y., Yamao, H., Tsutsumi, T., and Iwata, M (2020)., Accuracy evaluation of a crustal deformation model with velocity in terms of maintaining the Japanese geodetic datum, JpGU-AGU joint meeting 2020, 2020/07/12-16 (SGD01-12)

Tanaka M., Koso Y., Yamashita T., Yamao H., Takagi Y., and Iwata M. (2020). Towards sophistication of Crustal Deformation Correction System (POS2JGD) - Evaluation of deformation model with linear velocity -, 134th Meeting of the Geodetic Society of Japan, 2020/10/23 (in Japanese)

Vestøl O., Ågren J., Steffen H., Kierulf H., and Tarasov L. (2019). NKG2016LU a new land uplift model for Fennoscandia and the Baltic Region. J Geod 93, 1759–1779, https://doi.org/10.1007/s00190-019-01280-8, 2019.

Yamashita T. (2020). Updating a national geodetic datum based on SAR and GNSS CORS after a large scale earthquake, Report on the visiting research at LINZ, 49 pp

Wan Anom W. A., Musa T. A., Omar K. M., Rasisi S., Omar A. H., (2018). Non-Linear Crustal Deformation Modeling For Dynamic Reference Frame: A Case Study in Peninsular Malaysia, Proceedings of the FIG Working Week, Istanbul, Turkey

Sub-commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

Chair: Zinovy Malkin (Russia)

Overview

International terrestrial and celestial reference frames, ITRF and ICRF, respectively, as well as the tie between them expressed by the Earth Orientation parameters (EOP) are key products of geodesy and astrometry. The requirements to all the components of this triad grow steadily and the mm/µas level of accuracy is the current goal of the astronomic and geodetic community.

The current computation procedures for ITRF and ICRF are based on multi-stage processing of observations made with several space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Not all of them provide equal contributions to the final products. The latest ITRF realizations have been derived from combination of normal equations obtained from all four techniques, whereas the ICRF is a result of a single global VLBI solution. The latter is tied to the ITRF using an arbitrary set of reference stations. However, VLBI relies on the ITRF origin provided by satellite techniques and shares responsibility with SLR for the ITRF scale. Finally, all the techniques contribute to positions and velocities of the ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated to improve the accuracy of both reference systems and the consistency between each other and EOP. The subject becomes more and more complicated when moving to millimeter accuracy in all components of this fundamental triad. Consequently, we face systematic errors involving the connection between the ICRF and ITRF realizations, which cannot be fixed by datum correction during the current solution.

There are several issues currently preventing the consistent realization of the terrestrial and celestial reference systems (TRF and CRF, respectively) at the mm/µas level of accuracy:

- Insufficient number and non-optimal distribution of active and stable stations (VLBI and SLR in the first place) and radio sources.
- Technological (precision) limitations of existing techniques.
- Incompleteness of the theory and models.
- Not fully consistent models applied during data analysis.
- Not fully understood and agreed-upon details of the processing strategy.
- Not fully understood and accounted for the systematic errors of different techniques.

The above issues are subject of research activity within the IAG SC 1.4. All three WGs of the IAG SC 1.4 are working in close cooperation with each other because there is clear interaction among their topics. To provide this, it was decided that each WG chair becomes a member of two other working groups, and the SC chair if a member of all the three groups.

SC 1.4 Meetings

Due to the pandemic situation, no SC 1.4 meeting was held in 2020–2021.

Other related meetings

At the following meetings, the problems related to the IAG SC 1.4 topics were discussed:
– 27th IUGG General Assembly, Montreal, Canada, 08–18 Jul 2019;
– Journées 2019 "Astrometry, Earth Rotation and Reference Systems in the Gaia era", Paris Observatory, 7-9 Oct 2019.
– Solid Earth Team Meeting, La Jolla, CA, USA, 4–6 Nov 2019;
– EGU General Assembly (online), 4–8 May 2020;
– European VLBI Group for Geodesy and Astrometry (EVGA) 25th Working Meeting (online), 15-18 Mar 2021;
– EGU General Assembly (online), 19–30 Apr 2021.

Working Groups of Sub-commission 1.4

WG 1.4.1: Improving and unification of geophysical and astronomical modeling for better consistency of reference frames

Chair: Dan MacMillan (USA)

Members
- *Robert Heinkelmann (Germany)*
- *Hana Krásná (Austria, Czech Republic)*
- *Sébastien Lambert (France)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Lucia McCallum (Plank) (Australia)*
- *Tobias Nilsson (Sweden)*
- *Stanislav Shabala (Australia)*

Activities during the period 2019-2021

WG 1.4.1 is concerned with the modeling of geophysical and astronomical effects and how they affect the consistent determination of the terrestrial and celestial reference frames. The work of the group generally falls into the following categories: 1) analysis and solution parametrization, 2) external models, and 3) internal inconsistencies within the VLBI technique. There clearly are overlaps between work done by the three Working Groups of IAG 1.4. Several of the group members (D. MacMillan, S. Lambert, H. Krásná, and Z. Malkin) also were in the IVS Aberration Working Group, which worked on a recommendation for a galactic aberration model for VLBI analysis and for use in the ICRF3 solution. S. Lambert, R. Heinkelmann, and Z. Malkin were also in the IAU ICRF3 working group.

(a) Modeling Source Structure Variation

In recent years, there has been considerable work done on the effect source structure in VLBI analysis. In the first significant investigation, Anderson, and Xu (2018) analyzed the VLBI CONT14 continuous 2-week observing campaign data and concluded that source structure error amounts to half the VLBI error budget. Research continues how best to correct via imaging techniques the source structure error in the historical S/X data set (1980-present) as well as into the future and for next generation VGOS broadband observing.

Petrov et. al (2019) showed that the distribution of VLBI(S/X)-Gaia (optical) source position offset angles is nearly uniform over the sky. The offset directions were shown to be correlated with source jet direction; the distribution of the offset directions is correlated with the jet direction. Lunz et al. (2019) investigated the VLBI frequency dependence of the offsets and found similar behavior for K-band but not for X/Ka.

In an analysis of closure delays of 3417 celestial reference frame sources, Xu et al. (2019) found that the closure amplitude root mean square (CARMS) is a measure of how far away a source is from being compact and how much structure error contributes to residual delay errors in geodetic analysis.

Xu et al. (2021a) found that CARMS increases with the radio-optical distance, indicating that the structure is generally associated with a significant radio-optical offset. They also confirmed, for a reduced sample of sources, the finding of Y. Kovalev and his colleagues in earlier studies (e.g., Petrov et. al, 2019) that the radio-optical offset vectors are generally aligned with the direction of the radio jet.

(b) ICRF3 and Other ICRF Accuracy/Precision Investigations

In 2018, the IAU ICRF3 working group created this new realization of the ICRS, which was then described in detail in Charlot et al. (2020). ICRF3 contains radio source positions for three different realizations of the ICRS at S/X-bands, X/Ka-bands, and K-band.

The IVS Working Group on Galactic Aberration completed its investigation and recommended a galactic aberration constant of 5.8 µas/yr for the ICRF3 solution. This constant was derived from a Calc/Solve solution using all data (1979 to 2018) that was to be used for the ICRF3 solution. Galactic aberration with this constant and with a reference epoch of 2015.0 was applied as an *a priori* model in the final ICRF3 solution. Applying the model has the effect of removing the decades long effect of aberration on VLBI source positions thus allowing better comparisons between VLBI and Gaia positions. The work of the IVS WG is summarized in MacMillan et al. (2019).

Mayer and Böhm (2020) investigated whether one can reduce the deformation between the VLBI CRF and the GAIA CRF by using different models (e.g., tropospheric raytracing, galactic aberration) and analysis strategies (gradient parameterization).

(c) Modeling Troposphere Noise in VLBI Analysis

Nilsson and Balidakis (2021) investigated the impact of using tropospheric delays in the VLBI analysis obtained from raytracing though ERA5 model atmospheres. The results show that fixing the tropospheric delays to ERA5 makes the results (in terms of baseline length repeatability) much worse, except for the EURO sessions where a slight improvement could be seen in this case. However, when using a priori delays from ERA5, the tropospheric gradients can be fixed in the analysis without making the results worse and sometimes improving the results slightly.

(d) Gravitational Antenna Deformation

A type of model that has recently been introduced into VLBI geodetic analysis is gravitational deformation of VLBI antennas, which mainly affects the height of the stations, typically at the centimeter level. At this time, deformation models have only been derived for six antennas, but there are efforts within the IVS to perform measurements of more antennas in the VLBI networks.

(e) CONT17

Nilsson et al. (2019) investigated the precision and accuracy of Earth orientation parameters (EOP) from the CONT17 campaign.

MacMillan (2019) analyzed the differences between EOP estimated from the CONT17 simultaneous observing sessions of the two legacy (S/X) networks and the VGOS network. The EOP biases between the legacy networks were at the 1-sigma level. Based on the wrms differences of the EOP, the polar motion and UT1 precisions of the two networks were 20 µas and 2.3 µsec. Baseline length precision of the VGOS network was about 0.4 ppb compared with 0.8 ppb for the Legacy 1 network and 0.5 ppb for the Legacy 2 network.

(f) Reference Frame Investigations

Karbon et al. (2019) examined the impact of using different TRF realizations on the CRF and the EOP. They found that using JTR2014, there were yearly signals and other artifacts in the EOP, compared to the EOP obtained using ITRF2014 or DTRF2014. However, the effect on the source coordinates were small.

Glaser et al. (2019) investigated the effect of local ties on the realization of terrestrial reference frames by performing simulations of VLBI, SLR, and GPS observations. VLBI is most affected by the size local tie uncertainties because of the inherent insensitivity of VLBI to the geocenter. In addition, local ties in the southern hemisphere were shown to be important for the realization of TRF scale.

(g) VGOS Observing

Nilsson analyzed the performance of the VGOS sessions and compared their results to those obtained from simultaneous S/X sessions. The results show that the baseline length repeatability is slightly better for VGOS compared to the simultaneous R/R4 sessions. However, the EOP estimates were worse; this was probably due to the non-optimal network geometry of VGOS sessions.

T. Nilsson, E. Varenius, R. Haas at Onsala Space Observatory analyzed the local short-baseline experiments performed at Onsala (2019-2020) to determine the local tie vectors between the VGOS telescopes and the legacy S/X telescope (the ONETIE experiments). In this analysis, they investigated the impact of varying some of the modelling and parametrization, like thermal and gravitational deformation and the estimation interval of the tropospheric and clock parameters. There was a clear difference in the vertical components of about 5 mm when gravitational deformation of the ONSALA60 S/X antenna was not applied.
Xu et al. (2021b) evaluated the quality of VGOS broadband observations. Because the measurement noise of the VGOS system is so much less than for the S/X system, source structure effects are clearly visible in VGOS observations. Xu et al. (2021c) shows that it is

possible to derive images directly from VGOS observations and to then derive structure corrections from these images. Applying the corrections can reduce CARMS by 80%.

Publications

J. Anderson and M. H. Xu, Source structure and measurement noise are as important as all other residual sources in geodetic VLBI combined, J. Geophys. Res, 123(11), 10162, 2018. doi: 10.1029/2018JB015550

P. Charlot, C. S. Jacobs, D. Gordon, S. Lambert, A. de Witt, J. Bohm, A. L. Fey, R. Heinkelmann, E. Skurikhina, O. Titov, E. F. Arias, S. Bolotin, G. Bourda, C. Ma, Z. Malkin, A. Nothnagel, D. Mayer, D. S. MacMillan, T. Nilsson, R. Gaume. The third realization of the International Celestial Reference Frame by very long baseline interferometry, Astronomy and Astrophysics, 644, A159, 2020. doi.org/10.1051/0004-6361/202038368.

S. Glaser, R. Konig, K.H. Neumayer, T. Nilsson, R.Heinkelmann, F. Fletchner, H. Schuh. On the impact of local ties on the datum realization of global terrestrial reference frames, Journal of Geodesy, 93:655-667, 2019.

M. Karbon, S. Belda, and T. Nilsson. Impact of the terrestrial reference frame on the determination of the celestial reference frame. Geodesy and Geodynamics, 10(1):58-71, 2019. https://doi:10.1016/j.geog.2018.11.001

S. Lunz, J. Anderson, R. Heinkelmann, M.H. Xu, S. Gong, H. Schuh. Radio source position offsets among various radio frames and Gaia. In R. Haas, S. Garcia-Espada, and J. A. Lopez Fernandez, editors, Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, pages 204{208, Las Palmas de Gran Canaria, Spain, 2019.

D. S. MacMillan, A. Fey, J. M. Gipson, D. Gordon, C. S. Jacobs, H. Krasna, S. B. Lambert, Z. Malkin, O. Titov, G. Wang, M. H. Xu. Galactocentric acceleration in VLBI analysis – Findings of IVS WG8, Astronomy and Astrophysics, 630, A93, 2019. doi.org/10.1051/0004-6361/201935379.

D. S. MacMillan, Comparison of EOP and scale estimated from the three simultaneous CONT17 observing networks, Journal of Geodesy, 2019 (submitted).

D. Mayer, J. Böhm. Comparing Vienna CRF solutions to Gaia-CRF2, International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345-2020_99.

T. Nilsson, K Balidakis, and T. Ning. An assessment of the tropospheric parameters estimated from the CONT17 campaign. In R. Haas, S. Garcia-Espada, and J. A. Lopez Fernandez, editors, Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, pages 204{208, Las Palmas de Gran Canaria, Spain, 2019. Available from: http://www.oso.chalmers.se/evga/24_EVGA_2019_Las_Palmas.pdf.

T. Nilsson, K. Balidakis, R. Heinkelmann, and H. Schuh. Earth orientation parameters from the CONT17 campaign. Geophysica, 54(1):19-25, 2019.

T. Nilsson and K. Balidakis: Calibrating the Tropospheric Delays of VLBI Observations using Numerical Weather Prediction Models, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11956, https://doi.org/10.5194/egusphere-egu21-11956, 2021

L. Petrov, Y. Y. Kovalev, A. V. Plavin, 'A quantitative analysis of systematic differences in the positions and proper motions of Gaia DR2 with respect to VLBI', Monthly Notices of the Royal Astronomical Society, 502, Issue 3, 3023-3031, 2019. https://doi.org/10.1093/mnras/sty2807.

E. Varenius, R. Haas, and T. Nilsson. Short-baseline interferometry local-tie experiments at the Onsala Space Observatory. J. Geodesy, 95:54, 2021. doi:10.1007/s00190-021-01509-5.

M. H. Xu, J. M. Anderson, R. Heinkelmann, S. Lunz, H. Schuh, and G. L. Wang. Structure effects for 3417 celestial reference frame radio sources. The Astrophysical Journal Supplement Series, 242(1):5, 2019.

M. H. Xu, S. Lunz, J. M. Anderson, T. Savolainen, N. Zubko, H. Shuh. Evidence of the Gaia-VLBI position differences being related to radio source structure, Astronomy and Astrophysics, 647, A189, 2021a.

M. H. Xu, J. M. Anderson, R. Heinkelmann, S. Lunz, H. Schuh, and G. L. Wang. Observable quality assessment of broadband very long baseline interferometry system. Journal of Geodesy, 95:51, 2021b.

M. H. Xu, T. Savolainen, N. Zubko, M. Poutanen, S. Lunz, H. Schuh,G. L. Wang. Imaging VGOS observations and investigating source structure effects, Journal of Geophysical Research: Solid Earth, Volume 126, Issue 4, article id. e21238.

WG 1.4.2: Improving VLBI-based ICRF and comparison with Gaia-CRF

Chair: Sébastien Lambert (France)

Members
- *Maria Karbon (Germany, now France)*
- *Daniel MacMillan (USA)*
- *Zinovy Malkin (Russia)*
- *François Mignard (France)*
- *Jacques Roland (France)*
- *Manuela Seitz (Germany)*
- *Stanislav Shabala (Australia)*

Activities during the period 2019-2021

Since 2018, the ICRF3 (Charlot et al. 2020) constitutes the new reference and the most precise realization of the ICRS. For the first time, it is a multiwavelength CRF. For the first time also, a 'brother' CRF was produced by an independent technique in a different wavelength domain (optical) with a comparable precision, that is Gaia (Prusti et al. 2016) and its Data Release 2 (DR2) realization (Gaia-CRF2, Brown et al. 2018, Mignard et al. 2018). This optical catalog meets the requirements of the ICRS and constitutes, therefore, an optical realization of the ICRF. Both CRFs (one should, actually, say 'all four CRFs') were extensively compared in independent studies: including Mignard et al. (2018) who compared Gaia DR2 against the prototype ICRF3, whereas Charlot et al. (2020) and Liu et al. (2020) compared the final ICRF3 against Gaia DR2. All studies raised similar conclusions that the S/X realization of the ICRF has no large-scale systematics compared to Gaia-CRF2 (i.e., within 0.05 mas), although the K and X/Ka realizations need improvements in terms of systematics (precision lower by a factor of 2 in declination than in right ascension and systematic distortion of ~0.2 mas in declination for the latter). Comparisons between recent (post-ICRF3) VLBI solutions were led by the ICRS-PC team at Paris Observatory (Lambert and Arias 2020) in the frame of annual campaigns of comparison of VLBI catalogs produced by the various IVS analysis centers. The aim of such campaigns is (i) to provide some feedback to the analysts on how well their CRF realize the ICRS and (ii) to get a view of the up-to-date VLBI solutions with respect to the latest (i.e., current) ICRS realizations. Since 2018, the annual comparisons are done against the ICRF3 and Gaia DR2. The results are published in the IERS annual reports. The conclusions of the 2019 campaign are the axes of the submitted CRF are generally consistent with ICRF3 at S/X and with Gaia DR2 at the level of 50 μas, although some solutions show significant zonal deformation and some are still aligned onto the old reference ICRF2.

Liu et al. (2020) noted that, with the improved accuracy of the ICRF3 S/X positions, the radio-to-optical offsets at sub-mas level become an accessible product for further studies, well beyond the question of reference frames: one thinks about the core-shift effect, that is the frequency-dependence of the apparent position of the 'core' due to synchrotron self-absorption and external absorption. And, indeed, a fascinating field of research is now open thanks to the arrival of Gaia DR2 (and now EDR3; Brown et al. 2021, Klioner et al. 2021a). This field of research aims at understanding what astrophysical causes are at the origin of the radio-optical and radio-radio offsets. An important drawback is to provide astrometric constraints to the relativistic jet models. In return, this knowledge can provide a mean to perfect the linking between catalogs at different wavelengths. Several recent results and ongoing research are related to this field.

Based on VLBI and Gaia DR2 solutions, Plavin et al. (2019) and Kovalev et al. (2020) showed that the significant parsec-scale radio-optical offsets found between VLBI and Gaia positions happen preferentially parallel to the jet direction. Radio-to-optical offsets point downstream the jet and the optical centroids appear to have, generally, a higher optical polarization. This suggests that the optical emission is dominated by optically thin jet features in the downstream region of the jet. Such regions of synchrotron emission are expected to have a more organized magnetic field and, accordingly, a higher linear polarization. In contrast, upstream offsets suggest the signature of the accretion disk (low optical polarization). Xu et al. (2021) derived closure amplitude root mean square (CARMS; see also Xu et al. 2019) for ICRF3 sources, which quantifies the magnitudes of source structure effects in the VLBI observations. They found that CARMS increases with the radio-optical distance, indicating that the structure is generally associated with a significant radio-optical offset. They also confirmed, for a reduced sample of sources, the finding of Y. Kovalev and his colleagues in several earlier studies that the radio-optical offset is generally aligned with the direction of the radio jet. In December 2020, the Gaia Early Data Release 3 (EDR3) was released with more source in common with the ICRF3 and recent VLBI solutions. The optical counterpart of the ICRF sources now have positional precisions at the same level as VLBI. Comparisons between VLBI and Gaia DR3, including the pc-scale structure and polarization information of the MOJAVE data base (Lister et al. 2019) are ongoing at the time this report is being written (Lambert et al. 2021, in revision), supporting previous results of alignment between pc-scale radio-jet and radio-optical offset and, additionally, a recurrent coincidence between the optical centroid and (preferably stationary) radio knots with a high fractional polarization (indicating synchrotron self-absorption).

Ongoing efforts are made by several teams to improve the accuracy of the current CRFs and the ability to link them with the highest accuracy. Cite the dedicated astrometric observing programs of sources at mid-and southern declinations (de Witt et al. 2021) with increased data rate and pool of sources, and improved uv-coverage of the network. Jacobs et al. (2021) mentions that a new X/Ka antenna in Misasa, Japan (54-m diameter) is expected to reduce both the random error limiting precision and the systematic distortions vs. declination limiting accuracy of the current X/Ka network. The K-band network is also making efforts both in improving the network itself (e.g., in East Asia; Xu et al. 2021) and by imaging the ICRF sources (de Witt et al. 2021). Imaging efforts are also led at USNO, via the new Fundamental Reference Image Data Archive (FRIDA; Hunt et al. 2021). FRIDA will be public soon and will replace the Radio Reference Frame Image Database, providing positional, structure and polarization information. USNO and Paris Observatory are also conducting the Fundamental Reference AGN Monitoring Experiment (FRAMEx; Dorland et al. 2020) project that includes observations of reference radio sources in the radio, infrared, and visible, as well as with other ground- and space-based telescopes (e.g., in the X-ray) in order to better understand astrometric and photometric variability at multiple timescales, complementing efficiently the existing MOJAVE data base (which is, however, at 15 GHz). Both these works will be precious, if not crucial, for improving the understanding on the basic questions of 'what are the reference points in VLBI?' and therefore improving the CRF themselves.

Publications

A. G. A. Brown, A. Vallenari, T. Prusti, J. H. J. de Bruijne, F. Mignard, R. Drimmel, C. Babusiaux, C. A. L. Bailer-Jones, U. Bastian et al. Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties. Astronomy & Astrophysics, 595:A2, Nov. 2016.

A. G. A. Brown, A. Vallenari, T. Prusti, J. H. J. de Bruijne, C. Babusiaux, C. A. L. Bailer-Jones, M. Biermann, D. W. Evans, L. Eyer et al. Gaia Data Release 2. Summary of the contents and survey properties. Astronomy & Astrophysics, 616:A1, Aug. 2018.

A. G. A. Brown, A. Vallenari, T. Prusti, J. H. J. de Bruijne, C. Babusiaux, and M. Biermann. Gaia Early Data Release 3. Summary of the contents and survey properties. Astronomy & Astrophysics, 2021.

P. Charlot, C. S. Jacobs, D. Gordon, S. B. Lambert, J. Boehm, A. de Witt, A. Fey, R. Heinkelmann, E. Skurikhina, O. Titov, E. F. Arias, S. Bolotin, G. Bourda, C. Ma, Z. Malkin, A. Nothnagel, R. A. Gaume, D. Mayer, and D. S. MacMillan. The third realization of the International Celestial Reference Frame by very long baseline interferometry. Astronomy & Astrophysics, 644:A159, 2020.

B. Dorland, N. Secrest, M. Johnson, T. Fischer, N. Zacharias, J. Souchay, S. Lambert, C. Barache, and F. Taris. The Fundamental Reference AGN Monitoring Experiment (FRAMEx). In C. Bizouard, editor, Astrometry, Earth Rotation, and Reference Systems in the Gaia era, pages 165–171, Sept. 2020.

L. Hunt, P. Cigan, D. Gordon, M. Johnson, J. Spitzak. Update on VLBA Imaging of ICRF3 Sources. European VLBI network for Geodesy and Astrometry (EVGA) 2021 working meeting, March 2021.

S. A. Klioner et al. Gaia Early Data Release 3. The celestial reference frame (Gaia-CRF3). Astronomy & Astrophysics, 2021.

Y. Y. Kovalev, D. I. Zobnina, A. V. Plavin, and D. Blinov. Optical polarization properties of AGNs with significant VLBI–Gaia offsets. Monthly Notices of the Royal Astronomical Society: Letters, 493(1):L54– L58, 01 2020.

S. Lambert and E. F. Arias, Maintenance of the International Celestial Reference Frame, IERS Annual Report 2019, DOI: 10.13140/RG.2.2.16364.08323, 2020

M. L. Lister, D. C. Homan, T. Hovatta, K. I. Kellermann, S. Kiehlmann, Y. Y. Kovalev, W. Max-Moerbeck, A. B. Pushkarev, A. C. S. Readhead, E. Ros, and T. Savolainen. Mojave. XVII. Jet kinematics and parent population properties of relativistically beamed radio-loud blazars. Astrophysical Journal, 874(1):43, 2019.

N. Liu, S. B. Lambert, Z. Zhu, and J. C. Liu. Systematics and accuracy of VLBI astrometry: A comparison with Gaia Data Release 2. Astronomy & Astrophysics, 634, 2020.

F. Mignard, S. A. Klioner, L. Lindegren, J. Hernandez, U. Bastian, A. Bombrun, D. Hobbs, U. Lammers, D. Michalik et al. Gaia Data Release 2. The celestial reference frame (Gaia-CRF2). Astronomy & Astrophysics, 616:A14, 2018.

A. V. Plavin, Y. Y. Kovalev, and L. Y. Petrov. Dissecting the AGN disk–jet system with joint VLBI-Gaia analysis. The Astrophysical Journal, 871(2):143, jan 2019.

A. de Witt, S. Basu, P. Charlot, D. Gordon, C. Jacobs, M. Johnson, H. Krasna, K. Le Bail, F. Shu, O. Titov, M. Schartner. Improving the S/X Celestial Reference Frame in the South: A Status Update. European VLBI network for Geodesy and Astrometry (EVGA) 2021 working meeting, March 2021.

A. de Witt, C. Jacobs, D. Gordon, M. Nickola, A. Bertarini. K-band Imaging of 732 ICRF3 sources. European VLBI network for Geodesy and Astrometry (EVGA) 2021 working meeting, March 2021.

M. H. Xu, J. M. Anderson, R. Heinkelmann, S. Lunz, H. Schuh, and G. L. Wang. Structure effects for 3417 celestial reference frame radio sources. The Astrophysical Journal Supplement Series, 242(1):5, May 2019.

M. H. Xu, S. Lunz, J. M. Anderson, T. Savolainen, N. Zubko, and H. Schuh. Evidence of the Gaia–VLBI position differences being related to radio source structure. Astronomy & Astrophysics, 647:A189, 2021.

S. Xu, T. Jike, T. Jung, F. Shu, L. Cui, A. Melnikov, J. McCallum, S. Yi, B. Zhang, N. Sakai, X. He, H. Imai, N. Kawaguchi, D. Sakai, C. Oh, P. Jiang, M. Xu, G. Wang. The K Band Geodesy with the East Asian VLBI Network. European VLBI network for Geodesy and Astrometry (EVGA) 2021 working meeting, March 2021.

JWG 1.4.3: Consistent Realization of TRF, CRF, and EOP

Chair: Robert Heinkelmann (Germany)
Vice-Chair: Manuela Seitz (Germany)

Members
- *Claudio Abbondanza (US)*
- *Sabine Bachmann (Germany)*
- *Liliane Biskupek (Germany)*
- *Christian Bizouard (France)*
- *Xavier Collilieux (France)*
- *Aletha de Witt (South Africa)*
- *Anastasia Girdiuk (Germany)*
- *David Gordon (US)*
- *Robert Heinkelmann (Germany)*
- *Christopher Jacobs (US)*
- *Shuanggen Jin (China)*
- *Hana Krásná (Austria)*
- *Sebastien Lambert (France)*
- *Karine Le Bail (Sweden)*
- *Daniel MacMillan (US)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Manuela Seitz (Germany)*
- *Benedikt Soja (Switzerland)*
- *Nicholas Stamatakos (US)*

Corresponding Members:
- *Grzegorz Bury (Poland)*
- *Alberto Escapa (Spain)*
- *Jose Ferrandiz (Spain)*
- *Juan Getino (Spain)*
- *Richard Gross (US)*
- *Florian Seitz (Germany)*
- *Krzysztof Sosnica (Poland)*
- *Jean Souchay (France)*
- *Daniela Thaller (Germany)*
- *Radoslaw Zajdel (Poland)*

Overview

The International Astronomical Union / International Association of Geodesy / International Earth Rotation and Reference Systems Service (IAU/IAG/IERS) Joint Working Group (JWG) on the Consistent realization of TRF, CRF and EOP was created by IAU Commission A2, IAG Sub-Commission 1.4 and IERS to continue the activity of the previous IAG Working Group 1.4.1 on 'Consistent Realization of ITRF, ICRF, and EOP that operated in the period 2015-2019.

Its purpose is to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. The JWG strives to achieve this purpose through the computation of multi-technique CRF-TRF solutions together with EOP in one step, which can serve as reference solutions for comparisons. The JWG will investigate the impact of different analysis options, model choices and combination strategies on the consistency between TRF, CRF, and EOP. It will study the differences between multi-technique and VLBI-only solutions, study the possible contributions to EOP and frame determination by the LLR technique, study the differences between EOP derived by VLBI solutions at different radio wavelengths in cooperation with the IAU Division A WG on 'Multi-waveband Realizations of International Celestial Reference System', study the differences between EOP derived by VLBI solutions improved through Gaia (optical) data in cooperation with potential future IAU Division A WG(s) on VLBI – Gaia topics, study the effects on the results, when different data time spans are considered, compare the practically achievable consistency with the quality requirements deployed by IAG GGOS; and derive conclusions about future observing systems or analysis procedures in case the quality requirements cannot be met with the current infrastructure and approaches.

The webpage of the working group with an external and an internal area can be found here *https://www.iers.org/IERS/EN/Organization/WorkingGroups/ConsistentRealization/consistentRealization.html*.

Current and ongoing activity

The kick-off meeting of the JWG was held as a video conference on June 9, 2020. Several presentations were made at the meeting including the Chair's introductory talk and reports on the latest activity of the group members and the plans for the nearest future.

The IERS ITRS Center, IGN, France, is working on the next ITRF release, ITRF2020, computed as a consistent TRF+EOP solution.

IERS Rapid Service/Prediction Center (RS/PC), USNO (team leader N. Stamatakos), is planning to participate in the JWG activity to provide consistency between the JWG finding and recommendations and users of RS/PC products, including development of procedures and software used in the RS/PC.

Research team of the Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany (DGFI-TUM, M. Seitz, M. Bloßfeld, D. Angermann, M. Glomsda) is working on the problems of consistent realization of ITRS and ICRS in the framework of ITRF2020. The analysis is performed making use of the normal equations provided by the IVS Analysis Centers. The goal is to estimate for the first time EOP series and CRF solution consistent with DTRF (ITRS realization of DGFI-TUM). Two DTRF2020 solutions are planned: the first one will be EOP+TRF solution computed with the source coordinates fixed to ICRF3, and second one will be EOP+TRF+CRF solution. Several details of the analysis strategy is under investigation.

The joint research team of Eidgenossische Technische Hochschule, Zürich, Switzerland, and Jet Propulsion Laboratory, USA (B. Soja, C. Abbondanza, T.M. Chin, R. Gross, M. Heflin, J. Parker, X. Wu) is working on the project aimed at joint consistent determination of EOP, TRF, and CRF. Two kinds of software are used. KALREF based on Kalman filtering is used for joint determination of EOP and TRF for JTRF2014. Software SREF based on square-root information filter is used for JTRF2020 and is capable of jointly estimating EOP, TRF, and CRF. SREF is currently under intensive development, so no definite EOP+TRF+CRF solution is available yet. Nevertheless, JPL plans to contribute a joint TRF/CRF solution to ITRF2020.
Research team of the Institute for Geodesy of Leibniz Universität, Hannover (L. Biskupek and J. Müller) is working on the implementation of lunar laser ranging (LLR) to the joint solution.
Research team of the Federal Office of Metrology and Surveying, Austria, is working on testing of models and analysis options on the TRF, EOP, and CRF with particular emphasis on new models included in the ITRF2020 and ray-tracing troposphere modeling.

Joint international team (A. de Witt, C. Jacobs, D. Gordon, J. Quick, J. McCallum, H. Krasna, B. Soja, K. Le Bail, S. Horiuchi) is working on extending and improvement of the K-band CRF solution with further perspective of computing independent K-band CRF+TRF+EOP solution. Collocation of GNSS receivers at all VLBA sites would allow a direct comparison of VLBI and GNSS TRF realizations.

The IVS Combination Center at Federal Agency for Cartography and Geodesy (BKG), Germany, (S. Bachmann, A. Girdiuk, D. Thaller) is working on consistent realization of CRF, TRF, and EOP as an IVS combined products. The main activities of this group include:

– Setting up BKG 2020 solution for IVS products w.r.t. ITRF2020 requirements;
– Extending routine IVS combination by source parameters for consistent determination along with station positions and EOP;
– Multi-technique combined solutions (VLBI, GNSS, and potentially SLR) with the full set of parameters related to the reference systems, i.e., TRF, CRF and EOP.

Publications

Bachmann, S. and Thaller, D. Adding source positions to the IVS combination - First results, J. Geod (2016) 91: 743. DOI: 10.1007/s00190-016-0979-5

Baenas, T., Escapa, A., Ferrándiz, J.M. 2021, Secular changes in length of day: Effect of the mass redistribution, A&A 648, A89, doi: 10.1051/0004-6361/202140356

Baenas, T., Escapa, A., Ferrándiz, J.M. 2020, Forced nutations of a two-layer Earth in canonical formulation with dissipative Hori-like kernel, Advances in Space Research 66, 2646, doi: 10.1016/j.asr.2020.08.023

Baenas, T., Escapa, A., Ferrándiz, J.M. 2020, Nutation of the non-rigid Earth: Effect of the mass redistribution, A&A 159, A159, doi: 10.1051/0004-6361/202038946

Bury G., Sośnica K., Zajdel R., Strugarek D., Hugentobler U. (2021) Determination of precise Galileo orbits using combined GNSS and SLR observations. GPS Solutions, Vol. 25 No. 11, Berlin - Heidelberg 2021, pp. 1-13. https://doi.org/10.1007/s10291-020-01045-3

P. Charlot, C. S. Jacobs, D. Gordon, S. Lambert, A. de Witt, J. Bohm, A. L. Fey, R Heinkelmann, E. Skurikhina, O. Titov, E.F. Arias, S. Bolotin, G. Bourda, C. Ma, Z. Malkin, A. Nothnagel, D. Mayer, D. S. MacMillan, T. Nilsson, R. Gaume, `The Third Realization of the International Celestial

Reference Frame by Very Long Baseline Interferometry', in Astronomy & Astrophysics, 2020, vol 644, article A159, https://doi.org/0.1051/0004-6361/2020238368

Escapa, A., Getino, J., Ferrándiz, J.M., Baenas, T. 2020, Second-order effects in IAU2000 nutation model, in: Ch. Bizouard (ed.) Journées 2019 Astrometry, Earth Rotation, and Reference Systems in the GAIA era, Observatoire de Paris, 221, https://syrte.obspm.fr/astro/journees2019/LATEX/JOURNEES2019.pdf

Ferrándiz J.M., Gross R.S., Escapa A. Getino J., Brzezinski A., Heinkelmann R. 2020, Report of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation, IAG Symposia, doi: 10.1007/1345_2020_103

Ferrándiz, J.M., Al Koudsi, D. Escapa, A. Belda, S. Modiri, S. Heinkelmann, R., Schuh, H. 2020, A First Assessment of the Corrections for the Consistency of the IAU2000 and IAU2006 Precession-Nutation Models, IAG Symposia, doi: 10.1007/1345_2020_90

Krasna H, Gordon D, de Witt A, Jacobs CS, Soja B (2019) Earth Orientation Parameters Estimated From K-band VLBA Measurements. In: Haas R, Garcia-Espada S, Lopez Fernandez J (eds) Proceedings of the 24th EVGA Working Meeting, Chalmers University of Technology, vol 24, pp 238-242, DOI 10.7419/162.08.2019

Kwak Y., Bloßfeld M., Schmid R., Angermann D., Gerstl M., Seitz M.: Consistent realization of celestial and terrestrial reference frames. Journal of Geodesy, 10.1007/s00190-018-1130-6, 2018

D. S. MacMillan, A. Fey, J. M. Gipson, D. Gordon, C. S. Jacobs, H. Krasna, S. B. Lambert, Z. Malkin, O. Titov, G. Wang, M. H. Xu, `Galactocentric Acceleration in VLBI Analysis: Findings of IVS WG8', in Astronomy & Astrophysics, 2019, vol 630, article A93, https://doi.org/10.1051/0004-6361/201935379

D. Mayer & J. Böhm (2020) Comparing Vienna CRF solutions to Gaia-CRF2. International Association of Geodesy Symposia. https://doi.org/10.1007/1345_2020_99

Seitz M., Steigenberger P., Artz T.: Consistent adjustment of combined terrestrial and celestial reference frames. Earth on the Edge: Science for a Sustainable Planet, IAG Symposia, Vol.139, 2012

Seitz M., Steigenberger P., Artz T.: Consistent realization of ITRS and ICRS. In: Behrend D., Baver K.D. (Eds.), IVS 2012 General Meeting Proceedings, 314-318, NASA/CP-2012-217504, 2012

V. V. Singh, L. Biskupek, J. Müller, M. Zhang (2021) Impact of non-tidal station loading in LLR. Advances in Space Research, https://doi.org/10.1016/j.asr.2021.03.018

B. Soja, T.M. Chin, R. Gross, C. Abbondanza, M. Heflin, J. Parker, X. Wu (2019): "Consistent determination of terrestrial and celestial reference frames"; Poster: Solid Earth Team Meeting 2019, La Jolla, California, USA; 2019-11-04 – 2019-11-06. doi: 10.13140/RG.2.2.31215.38562

B. Soja, R. Gross, C. Abbondanza, T.M. Chin, M. Heflin, J. Parker, X. Wu (2019): "The impact of jointly determining TRF and CRF on the EOP"; Talk: 27th IUGG General Assembly, Montreal, Canada; 2019-07-08 – 2019-07-18; in: "IUGG2019 Abstracts", IUGG19-3618. doi: 10.13140/RG.2.2.11024.15363

B. Soja, R. Gross, C. Abbondanza, T.M. Chin, M. Heflin, J. Parker, X. Wu (2019): "Chasing consistency: joint determination of terrestrial and celestial reference frames"; Talk: European Geosciences Union General Assembly 2019, Vienna, Austria; 2019-04-07 – 2019-04-12; in: "Geophysical Research Abstracts", Vol. 21, EGU2019-10211. doi: 10.13140/RG.2.2.18414.25920

Zajdel R., Sośnica K., Bury G., Dach R., Prange L. (2020) System-specific systematic errors in earth rotation parameters derived from GPS, GLONASS, and Galileo. GPS Solutions, Vol. 24 No. 74, Berlin - Heidelberg 2020, pp. 1-15. https://doi.org/10.1007/s10291-020-00989-w

Zajdel R., Sośnica K., Bury G., Dach R., Prange L., Kaźmierski K. (2021) Sub-daily polar motion from GPS, GLONASS, and Galileo. Journal of Geodesy, Vol. 95 No. 3, Berlin Heidelberg, Germany 2021, pp. 1-27. https://doi.org/10.1007/s00190-020-01453-w

Commission 2 – Gravity Field

https://com2.iag-aig.org/

President: Adrian Jäggi (Switzerland)
Vice President: Mirko Reguzzoni (Italy)

Structure

Sub-Commission 2.1:	Land, Marine and Airborne Gravimetry
Sub-Commission 2.2:	Geoid, Physical Height Systems and Vertical Datum Unification
Sub-Commission 2.3:	Satellite Gravity Missions
Sub-Commission 2.4:	Regional Geoid Determination
Sub-Commission 2.4a:	Gravity and Geoid in Europe
Sub-Commission 2.4b:	Gravity and Geoid in South America
Sub-Commission 2.4c:	Gravity and Geoid in North and Central America
Sub-Commission 2.4d:	Gravity and Geoid in Africa
Sub-Commission 2.4e:	Gravity and Geoid in Asia-Pacific
Sub-Commission 2.4f:	Gravity and Geoid in Antarctica
Sub-Commission 2.5:	Satellite Altimetry
Sub-Commission 2.6:	Gravity Inversion and Mass Transport in the Earth System
Study Group 2.1.1:	Developments in Gravity Instrumentation, Analysis and Applications
Study-Group 2.4.1:	Downward Continuation of Airborne Gravity Data for Local Geoid Improvement
Joint Working Group 2.1.1:	Establishment of the International Gravity Reference Frame
Joint Working Group 2.1.2:	Unified file formats and processing software for high-precision gravimetry frame
Joint Working Group 2.2.1:	Error assessment of the 1 cm geoid experiment
Working Group 2.6.1:	Geodetic observations and physical interpretations in the Tibetan Plateau

Overview

This report presents the activities of the entities of Commission 2 for the reporting period 2019- 2021. As shown above, Commission 2 consists of 6 sub-commissions (SC), whereby SC 2.4 is composed of 6 regional sub-commissions, and several Working Groups, Joint Working Groups and Study Groups. Most of these entities were very active and made significant progress in their specifically stated objectives and program of activities despite the severe impacts of Covid-19. The corresponding reports can be found below, and the main achievements are summarized in the end of this overview section.

Activities during the reporting period 2019-2021

Commission 2 fostered and significantly supported main tasks and objectives of the present IAG period, such as the establishment of the International Height Reference Frame (IHRF; cf. IAG 2019 resolution no. 3), and the establishment of the Infrastructure for the International Gravity Reference Frame (IGRF, cf. IAG 2019 resolution no. 4).

Commission 2 was also very active in advocating mass transport from space by establishing the Combination Service of Time-variable Gravity Fields (COST-G) at the 2019 IUGG General Assembly as new Product Center of the IGFS that now operationally provides consolidated monthly global gravity models with improved quality, robustness, and reliability. Moreover, Commission 2 initiated a new Horizon 2020 project to increase the visibility towards EU/Copernicus by developing a prototype for a groundwater product based on the COST-G products as a new cross-cutting application of the existing product portfolio of in total three Copernicus core services.

Commission 2 also actively contributed to GGOS-related activities. As a voting member of the GGOS Executive Committee (EC) the president of the Commission 2 was participating in the monthly GGOS EC telecons.

Commission 2 was involved in the organization of several scientific conferences and workshops, as well as sessions at EGU and AGU. Naturally, however, all these activities were severely limited due to the Covid-19 pandemic situation.

Conferences and Meetings

Gravity, Geoid and Height Systems (GGHS) 2020, Austin, Texas

The official Commission 2 symposium was originally planned as a joint symposium with the IGFS that should have been held in September 2020 in Austin, Texas, at the premises of the University of Texas. Due to the Covid-19 pandemic situation two telecons have been held with the GGHS convenors in April and May 2020 to discuss potential options for a replanning of the GGHS 2020. A first concept for a potential online meeting has been worked out until June 10. A final vote on June 17 clearly showed, however, that a majority of the GGHS convenors was in favor to postpone the GGHS to 2022. The current planning foresees that the GGHS will be held in the second week of September 2022, again at the premises of the University of Texas at Austin.

IAG General Assembly 2021, Beijing, China

Commission 2 was also deeply involved in the preparation of the scientific program of the virtual IAG General Assembly 2021, Beijing, China. The organization of the two main gravity- related sessions have been coordinated by the president ("Temporal gravity field") and vice-president ("Static gravity field") of Commission 2, and it also supported the preparation of several joint sessions.

Further theme-specific events

During the reporting period 2019-2021, commission 2 also fostered and supported several theme-specific conferences, meetings and workshops, which are presented in detail in the following individual reports of the respective entities of Commission 2.

Activities of the Sub-Commissions

SC 2.1 Land, Marine and Airborne Gravimetry

Though COVID-19 has slowed down field activities, as well as in-person meetings and workshops, SC 2.1 together with its associated joint working and study groups, JWG 2.1.1, JWG 2.1.2, and SG 2.1.1, can still report on a sizeable number of activities among its members. In particular, we highlight the efforts of JWG 2.1.1, "Establishment of the International Gravity Reference Frame", whose proposal was formally presented to the IAG Executive Committee by the President of Commission 2 in April of 2021.

SC 2.2 Methodology for Geoid and Physical Height Systems

During the reporting period, SC2.2 activities focused mainly on the publication of the results of the “1 cm geoid experiment”, the realization of the International Height Reference System (IHRS) through the Implementation of the International Height Reference Frame (IHRF), the organization of a dedicated sessions within the 2021 European Geosciences Union, the 2021 IAG Scientific Assembly and the organization of the next Gravity Geoid and Height Systems (GGHS) conference. The SC2.2 JWG2.2.1 "Error assessment of the 1 cm geoid experiment" has already started work to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

SC 2.3 Satellite Gravity missions

The main activities of SC 2.3 include the promotion of scientific investigations regarding current and future gravity field missions. A new combination service for Level-2 and Level-3 time-variable gravity field solutions (https://cost-g.org), with the purpose to provide unique and user-friendly gravity products to a wider user community, originally developed in the frame of the Horizon 2020 Framework Program of the European Commission, has now become an integral component of the IGFS infrastructure. In the hydrological branch, one of the already established Essential Climate Variables (ECVs) of the Global Climate Observing System (GCOS) is groundwater. The Steering Committee of GCOS recommended in December 2020 to establish also Total Water Storage (TWS), the prime output of GRACE and GRACE-FO, as an additional ECV. This process was strongly supported by SC 2.3 members. Various SC 2.3 members are also involved in activities to realize future mass change missions which are currently discussed at various space agencies to guarantee gapless observations after GRACE-FO and to increase spatial and temporal resolution of mass transport data by dedicated future mission constellations.

SC 2.4 Regional Geoid Determination

SC 2.4 coordinates the activities of the 6 regional sub-commissions on gravity and geoid determination and supports the organization of conferences, workshops and schools. The focus of the reporting period was the collection, validation, and inclusion of new global and regional elevation models in the European database, the organization of outreach events like the SIRGAS webinar on the International Gravity Reference System (IGRS) and its realization (IGRF)”, and the determination of a recent precise geoid model for the whole continent of Africa. Further highlight were the release of the first North American geoid model that was jointly computed by NGS, NRCan, and INEGI, the organization of the first Asia Pacific geoid workshop, and investigations about the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic models.

SC 2.5 Satellite Altimetry

Over the period of 2019-2021, the IAG sub-commission 2.5 mainly focused on the following research activities:

- New international team on mean sea surface (MSS) topography and marine gravity field for upcoming SWOT and existing missions.
- Significant publication contributions to ESA’s “25 Years of Progress in Radar Altimetry” Symposium.
- Integrated use of altimetry and space geodetic techniques in monitoring global and coastal sea levels, inland surface water levels, and elevation changes over mountain

glaciers.

- New applications that use altimeter-derived gravity to detect undersea volcano eruptions and submarine plate tectonic motions.
- New developments in data processing algorithms, validation and calibration.

SC 2.6 Gravity and Mass Transport in Earth System

Sub-commission 2.6 promotes and supports scientific research concerning spatial and temporal variations of gravity related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. A new international team supported by ISSI the International Space Science Institute (ISSI) and ISSI-Beijing was established in 2020 for gravity field modelling and its applications in the Earth system. Another important activity of SC2.6 was the initiation of WG2.6.1, aiming at the study on mass transport, geodynamic, and climate change of the Tibetan Plateau based on multiple geodetic observations.

Activities of Study Groups

Two SGs (SG 2.1.1 and SG 2.4.1) reporting to Commission 2 via SC 2.1 and SC 2.4, and Commission 2 is involved in ten JSGs as a partner, but none of these report directly to Commission 2. Their reports can be found in the ICCT section, and the Commission 1 and 3 sections.

Activities of Working Groups

One WG (WG 2.6.1) and 3 JWGs (JWG 2.1.1, 2.1.2, 2.2.1) are reporting to Commission 2. Their reports can be found in the corresponding chapters. Commission 2 is involved in nine further JWGs as a partner, but none of these report directly to Commission 2.

Sub-commission 2.1: Land, Marine and Airborne Gravimetry: Standards, Observations, and Innovation

Chair: *Derek van Westrum (United States)*
Vice Chair: *Przemyslaw Dykowski (Poland)*

Overview

General comment on the impact of COVID-19 in 2020 and early 2021
The severe impacts of COVID-19 on the activities of Sub-commission 2.1 and its members cannot be overstated. Each individual institution has almost surely been directly affected by the virus and the limitations it has generated, but COVID-19 has also impeded scientific progress in the field of gravimetry in general.

One of the most visible impacts relates to conferences and symposia. Scientific meetings are the most important activity in terms of scientific development and increasing the outreach of scientific progress. Unfortunately on-line meetings over the past year or so have been useful – but not ideal – conduits for communication.

The second major impact of COVID-19 is purely practical: Travel restrictions have imposed significant limitations on gravity surveys worldwide. Further, it has led to the cancellation or postponement of absolute instrument comparisons – activities crucial to the gravity reference distribution system.

All that said, we are still pleased to report on the activities that did go forward in 2019-2020 below, and we are looking forward to a safe and productive second half of the IAG term.

General activities of the Sub-commission
Cooperation with the CCM on Instrument Comparisons and Traceability

The results of the 2018 European regional comparison of absolute gravimeters at Wettzell (EURAMET.M.G-K3) were published in 2020 (Falk et al., 2020). Other regional comparisons had to be cancelled or postponed due to COVID-19. In conjunction with the Consultative Committee on Mass (CCM), the Sub-commission 2.1 is working to secure the Table Mountain Geophysical Observatory in Boulder, Colorado, USA as the site of the next International Comparison of Absolute Gravimeters in 2023.

Organization of Meetings and Conferences

While much “local” scientific work was able to continue during the pandemic, meetings, workshops, and conferences were greatly curtailed in 2020 and into 2021. However, virtual conferences like EGU and AGU did go forward, both with well attended sessions on terrestrial gravity and its applications: EGU Session G4 and AGU Session G016.

Looking forward, as things open up post COVID-19, the Sub-commission is actively supporting and promoting meetings and workshops devoted to

- Static Gravity field at the IAG Scientific Assembly in June 2021
- Metrology, and cooperation with the CCM (2022)
- Implementation of the International Gravity Reference System/Frame (2022)
- Gravity, Geoid, and Height Systems (GGHS, 2022)

Regional activities in gravimetry

Asia (reported by Wu Shuqing and Przemyslaw Dykowski)

- *China:* The past few years have seen a heavy emphasis on cold atom gravity meters in China. More than ten institutes or universities have developed such instruments (six Chines instruments participated in the ICAG-2017 in NIM China Beijing). Efforts are also focused on the deployment of absolute gravimeters on moving platforms such as marine gravimetry, and institutes are investigating the use of quantum AGs as a replacement for superconducting gravimeters.
- *Indonesia:* Advanced activities related to new geoid development. Gravity activities include A10-049 gravimeter surveys on multiple stations. Among those stations several are used as reference for airborne surveys for consistently improving coverage of gravity surveys in Indonesia.

North America (reported by John Crowley, Derek van Westrum, and Przemyslaw Dykowski)

- *Canada:* The present focus is to update the Canadian Gravity Standardization Net (CGSN) from IGSN71 to IGRS. The project consists of re-adjusting the entire network of historical relative gravity ties with all absolute gravity measurements in Canada. The adjustment also includes relative gravity ties to primary stations (and excenters) in USA and Greenland. These are included to improve robustness of the network. The adjustment does not include absolute gravity measurements outside Canada.

  Adjusted gravity will represent epoch 2020.0. The epoch transfer is done using absolute and relative time series and a gravity model determined from the GRACE monthly data. The data clean-up is overall completed and preliminary results are available. The adjustment solved the following parameters: gravity, gravity velocity, scale, and factor and drift for relative meters. Gravity values are in the zero tide system.

  In 2019, 14 sites of the CGSN were observed with the FG5. Field surveys were stopped due to COVID-19 in 2020. The focus is now to take monthly gravity measurements with the FG5 at the Canadian Absolute Gravity Site (CAGS, fundamental site for gravity) for a better understanding of the gravity variation (secular and seasonal). We plan to have the A10 back in operation soon in support of the national network. FG5 will be mostly limited to CAGS.
- *United States:* The National Geodetic Survey continues its Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project, collecting airborne gravity over the United States and its territories. The project is currently ~85% complete, projected to finish data collection in approximately 2023. A paper by van Westrum et al was published in January 2021, describing a ground truth validation experiment in the rugged terrain of Colorado (van Westrum et al., 2021).

  Though COVID-19 has slowed down most field activities, analyses of gravity instruments still continued. Relativistic effects in FG5 type instruments were investigated, as well as a side by side comparison of gPhoneX tidal gravimeters at the Table Mountain Geophysical Observatory (to be published).

  Gravity for geoid change monitoring is beginning near Anchorage, Alaska, with A10-025 and CG6 measurements slated for summer 2021.
- *Mexico:* A10 gravimeter (sn 056) has been delivered in 2021 to Instituto Nacional de

Estadística y Geografía (INEGI) for works related to gravity reference frames in the country. Prior to 2021 absolute gravity surveys were performed with assistance of US institutions.

Europe (reported by Mirjam Bilker-Koivula, Przemyslaw Dykowski)

- *Finland:* Repeated absolute gravity measurements are continuing in all Nordic countries. Two papers analysing long time series were published this year: Bilker-Koivula et al (2020) and another by Olsson et al. (2019).

  Marine gravity measurements in the Baltic Sea have been ongoing in order to calculate an improved geoid model for the Baltic Sea. Since the end of the FAMOS project, the work on finalizing the FAMOS geoid model is continued under the supervision of the Chart Datum Working Group of the Baltic Sea Hydrographic Commission. The FAMOS geoid will define the reference height surface for the Baltic Sea Chart Datum, the new common height reference for the Baltic Sea.

  In the winter of 2019-2020 absolute gravity measurements were performed on the Finnish Antarctic Station Aboa. The measurements are part of a long time series that together with continuous GNSS observations and modelling of the ice field around the station will help us to better understand the Glacial Isostatic Adjustment (GIA) mechanisms in Dronning Maud Land.

- *Greece:* A10 and relative surveys regarding gravity contribution required to become a International Height Reference System (IHRS) station (Natsiopoulos et al., 2021).

- *Italy:* Gravity monitoring at Etna volcano currently includes 3 iGrav superconducting gravimeters, an Absolute Quantum Gravimeter, number of Scintrex CG-6 instruments as well as the development of a “gravity imager” based on multiple MEMS type instruments (Carbone et al., 2020, Greco et al., 2020, Carbone et al., 2021). This set of instruments is a perfect showcase how precise modern gravimeters can be used in a very practical manner.

- *Ireland/Northern Ireland:* In 2019 works continued on the establishment of the AGN Ireland gravity network with cooperation between Ordnance Survey Ireland and the Institute of Geodesy and Cartography, Warsaw, Poland (IGiK). During 2019 in total 90% of the surveys have been done with the A10-020 absolute gravimeter (by IGiK Poland). In 2020 further activities have been postponed due to the COVID-19 pandemic, yet both parties express interest to finish the works. Related to the project continuous tidal gravity record has been completed in early 2021 in order to evaluate ocean tidal loading effect models for the island of Ireland (Dykowski et al., 2021).

- *Sweden:* final works concerning the gravity reference network in Sweden have been completed. The system is named the RG-2000 and is based on a combination of FG laboratory stations, A10 field stations and a densification network. Results have been published in Engfeldt et al. (2019).

- *Poland:* Activities in Poland include repeated surveys with A10-020 and FG5-230 absolute gravimeters at Borowa Góra and Jozefosław Observatories, respectively. Additionally, both instruments participate in 2 instrument AG comparisons at Borowa Góra Observatory in 2019, 2020 and early 2021. Joint surveys support the operation of the iGrav-027 superconducting gravimeter. The Borowa Góra Observatory is currently actively working in order to become and IGRS reference and comparison station.

Within the framework of EPOS-PL repeated absolute gravity surveys with the A10-020 gravimeter (IGiK) as well as relative densifications surveys with a Scintrex CG6 gravimeter are performed in the Silesian region on active mining areas (so called MUSE polygons - Mutke et al., 2019). In the years 2019-2021 4 additional campaigns have been performed (a total of 7 campaigns in 4 years). Also within the EPOS-PL project tidal gravity data is collected from multiple gPhoneX as well as other tidal gravimeters in Poland. The network of stations performing tidal gravity records has grown visibly in Poland in the last couple of years (Dykowski et al., 2021).

In 2020 first campaigns in the Polish shoreline were conducted with a MGS-6 seaborne gravimeter owned by Gdańsk Unversity of Technology (Pyrchla et al., 2020). Further surveys are expected to be done in the upcoming years.

Absolute quantum gravimetry

A visible growth in interest for the Absolute Quantum Gravimeter (manufactured by French company Muquans) is observed. Currently more than 10 units are either already delivered or in delivery to scientific/academic institutions around the world. Instruments are delivered in two variants: A – laboratory type, B – field capable type (temperature stabilized). Already multiple presentations (Champollion et al., 2020, Vermeulen et al., 2020, Güntner et al., 2021) and several publications (Cooke et. al., 2021) had been published on the operation and results coming from those instruments. This subject is surely of great current interest in the gravity community.

Additionally, Muquans is developing and absolute quantum gradiometer. In principal it is based on two AQG instruments in a single configuration (Janvier et al., 2020, Janvier et al., 2021).

A promising project is under way in Germany related to a very long baseline atom interferometer (VLBAI). A 10 meter atom interferometer is being built, which presents interesting potential in gravimetry and possible creation of a unique gravity reference site (Schilling et al., 2020).

References

Ashby N, van Westrum D., Comparison of Open and Solid Falling Retroreflector Gravimeters, Metrologia 57 035012 (2020).

Bilker-Koivula M., Makinen J., Ruotsalainen H., Naranen J., Saari, T.: Forty-three years of absolute gravity observations of the Fennoscandian postglacial rebound in Finland. J Geod 95, 24 (2021). https://doi.org/10.1007/s00190-020-01470-9

Bin Chen, et al, Portable atomic gravimeter operating in noisy urban environments, Chinese Optics Letters, 18 090201 (2020)

Bin Wu, et al, Dependence of the sensitivity on the orientation for a free-fall atom gravimeter, Optics Express, 27 (2019)

Carbone, D., Cannavò, F., Greco, F., Messina, A., Contrafatto, D., Siligato, G., Lautier-Gaud, J., Antoni-Micollier, L., Hammond, G., Middlemiss, R., Toland, K., de Zeeuw - van Dalfsen, E., Koymans, M., Rivalta, E., Nikkhoo, M., Bonadonna, C., and Frischknecht, C.: The NEWTON-g "gravity imager": a new window into processes involving subsurface fluids, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-16329, https://doi.org/10.5194/egusphere-egu2020-16329, 2020

Carbone, D., Antoni-Micollier, L., Greco, F., Lautier-Gaud, J., Contrafatto, D., Ménoret, V., and Messina, A.: Deploying and operating an Absolute Quantum Gravimeter on the summit of Mount Etna volcano, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-15186, https://doi.org/10.5194/egusphere-egu21-15186, 2021.

Cooke, A.-K., Champollion, C., Le Moigne, N.: First evaluation of an absolute quantum gravimeter (AQG#B01) for future field experiments, Geosci. Instrum. Method. Data Syst., 10, 65–79, 2021, https://doi.org/10.5194/gi-10-65-2021

Champollion, C., Cooke, A.-K., and Le Moigne, N.: Comparison and characterization of the field Atomic

Quantum Gravimeter (AQG#B01), EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-9076, https://doi.org/10.5194/egusphere-egu2020-9076, 2020

Cheinway Hwang et al, The Progress of Recent Indonesia Airborne Gravity Surveys, AGU Fall Meeting, 2020, Online, 1-17 December 2020, AGU2020-G016-05

Dykowski, P., Karkowska, K., Sękowski, M., and Kane, P.: Ocean tidal loading models assessment using 28 months of gravimetric tidal records in Dublin, Ireland, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-2422, https://doi.org/10.5194/egusphere-egu21-2422, 2021.

Dykowski P., Sękowski M., Wilde-Piórko M., Kryński J., Karkowska K., (2021): Rozwój grawimetrycznych rejestracji pływowych w Polsce, I konferencja naukowo-techniczna poświęcona projektowi EPOS-System Obserwacji Płyty Europejskiej (EPOS-PL+) współfinansowanemu przez Unię Europejską z Europejskiego Funduszu Rozwoju Regionalnego Konferencja online z użyciem platformy Microsoft Teams, Katowice, 25 marca 2021 r.

Engfeldt A., Lidberg M., Sekowski M., Dykowski P., Krynski J., Ågren J., Olsson P.-A., Bryskhe H., Steffen H., Nielsen J.E., (2019): RG 2000 – the new gravity reference frame of Sweden, FIG Congress 2018, 6–11 May 2018, Istanbul, Turkey; Geophysica, 54(1), pp. 69-92

Falk R., Pálinkáš V., Wziontek H., Rülke A., Val'ko M., Ullrich Ch., Butta H., Kostelecký J., Bilker-Koivula M., Näränen J., Prato A., Mazzoleni F., Kirbaş C., Coşkun ., Van Camp M., Casrelein S., Bernard J.D., Lothhammer A., Schilling M., Timmen L., Iacovone D., Nettis G., Greco F., Messina A.A., Reudink R., Petrini M., Dykowski P., Sękowski M., Janák J., Papčo J., Engfeldt A., Steffen H., (2020): Final report of EURAMET.M.G-K3 regional comparison of absolute gravimeters, Metrologia, Volume 57, Number 1A, DOI: 10.1088/0026-1394/57/1A/07019

Greco, F., Carbone, D., Cannavò, F., Messina, A., Contrafatto, D., Siligato, G., Reineman, R., and Warburton, R.: The benefits of performing continuous gravity measurements at active volcanoes using superconducting gravimeters, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18917, https://doi.org/10.5194/egusphere-egu2020-18917, 2020

Güntner, A., Reich, M., Reinhold, A., Glässel, J., and Wziontek, H.: First experiences with an absolute quantum gravimeter during field campaigns, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14072, https://doi.org/10.5194/egusphere-egu21-14072, 2021.

Hong-Tai Xie et al, Calibration of a compact absolute atomic gravimeter, Chinese Phys. B 29 093701 (2020)

Janvier, C., Ménoret, V., Lautier, J., Desruelle, B., Merlet, S., Pereira dos Santos, F., and Landragin, A.: Operating an industry-grade quantum differential gravimeter, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-9185, https://doi.org/10.5194/egusphere-egu2020-9185, 2020.

Janvier, C., Lautier, J., Merlet, S., Landragin, A., Pereira dos Santos, F., and Desruelle, B.: Pushing the stability of a Differential Quantum Gravimeter below 1Eötvös/1µGal , EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-9569, https://doi.org/10.5194/egusphere-egu21-9569, 2021.

Mutke G., Kotyrba A., Lurka A., Olszewska D., Dykowski P., Borkowski A., Araszkiewicz A., Barański A., (2019): Upper Silesian Geophysical Observation System A unit of the EPOS project, Journal of Sustainable Mining, Vol. 18, Issue 4, November 2019, pp. 198-207, https://doi.org/10.1016/j.jsm.2019.07.005

Natsiopoulos, D. A., Mamagiannou, E. G., Pitenis, E. A., Vergos, G. S., Tziavos, I. N., and Grigoriadis, V. N.: Gravity data collection with a CG5 gravitymeter for densification of the gravity data around the AUT1 IHRF station, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1677, https://doi.org/10.5194/egusphere-egu21-1677, 2021.

Olsson P., Breili K., Ophaug V., Steffen H., Bilker-Koivula M., Nielsen e., Oja T., Timmen L., Postglacial gravity change in Fennoscandia—three decades of repeated absolute gravity observations, Geophysical Journal International, Volume 217, Issue 2, May 2019, Pages 1141–1156, https://doi.org/10.1093/gji/ggz054

Pan-Wei Huang et al, Accuracy and stability evaluation of the 85Rb atom gravimeter WAG-H5-1 at the 2017 International Comparison of Absolute Gravimeters, Metrologia 56 045012 (2019)

Pyrchla, K, Pajak, M, Pyrchla, J, Idczak, J (2020). Analysis of free-air anomalies on the seaway of the Gulf of Gdańsk: A case study. Earth and Space Science 7, e2019EA000983. https://doi.org/10.1029/2019EA000983

Smith D. et al, The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum, NOAA White Paper: https://geodesy.noaa.gov/GRAV-D/pubs/GRAV-D_v2007_12_19.pdf

Schilling, M., Wodey, É., Timmen, L. et al. Gravity field modelling for the Hannover 10 m atom interferometer. J Geod 94, 122 (2020). https://doi.org/10.1007/s00190-020-01451-y

van Westrum D., Ahlgren K., Hirt C., Guillaume S., A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA, J Geod 95 9 (2021). https://doi.org/10.1007/s00190-020-01463-8

Vermeulen, P., Antoni-Micollier, L., Mazzoni, T., Condon, G., Ménoret, V., Janvier, C., Desruelle, B., Landragin, A., Lautier-Gaud, J., and Bouyer, P.: Operating the Absolute Quantum Gravimeter outside of the laboratory, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-8969,

https://doi.org/10.5194/egusphere-egu2020-8969, 2020
Zhijie Fu et al, A new type of compact gravimeter for long-term absolute gravity monitoring, Metrologia 56, 025001 (2019)
Zhijie Fu et al, Participation in the absolute gravity comparison with a compact cold atom gravimeter, Chinese Optics Letters 17, 011204 (2019)

Joint Working Groups of Sub-commission 2.1:

JWG 2.1.1: Establishment of the International Gravity Reference Frame

Chair: *Hartmut Wziontek (Germany)*
Vice Chair: *Sylvain Bonvalot (France)*

Members

- Mirjam Bilker Koivula (Finland)
- Przemyslaw Dykowski (Poland)
- Andreas Engfeldt (Sweden)
- Reinhard Falk (Germany)
- Jaakko Mäkinen (Finland)
- Urs Marti (Switzerland)
- Jack McCubbine (Australia)
- Ilya Oshchepkov (Russia)
- Vojtech Palinkas (Czech Republic)
- Victoria Smith (UK)
- Ludger Timmen (Germany)
- Claudia Tocho (Argentina)
- Christian Ullrich (Austria)
- Michel van Camp (Belgium)
- Derek van Westrum (USA)
- Marc Véronneau (Canada)
- Leonid Vitushkin (Russia)
- Shuqing Wu (China)
- Toshihiro Yahagi (Japan)

Activities and publications during the period 2019-2021

Status of the International gravity reference system and frame

The IAG Joint Working Group 2.1.1 "Establishment of a global absolute gravity reference system" has further developed the International Gravity Reference System and Frame to achieve an accurate, homogeneous, long-term global recording of Earth's gravity, while taking advantage of the potential of today's absolute gravity measurements. The concept is documented in Wziontek et al. (2021), see also Fig. 1.

The proposed definition of the International Gravity Reference System (IGRS) is based on the instantaneous acceleration of free-fall, expressed in the International System of Units (SI). This quantity is measured by absolute gravimeters and plays an important role in particular in metrology (e.g. for the realization of the kilogram). By the correction of time dependent effects due to tides, mass redistributions in atmosphere and polar motion, the conventional quantity „acceleration of gravity" is derived. To ensure the invariance of the system over time, the constant components of these time dependent corrections are part of the system definition: zero-tide system for the tidal correction, standard atmosphere ISO 2533:1975 and the reference pole of the International Earth Rotation and Reference Systems Service (IERS).

A set of conventional models (minimum requirements) for the correction of temporal gravity changes based on and compatible with International Absolute Gravimeter Base Network (IAGBN) Processing Standards is proposed with the IGRS Conventions 2020.

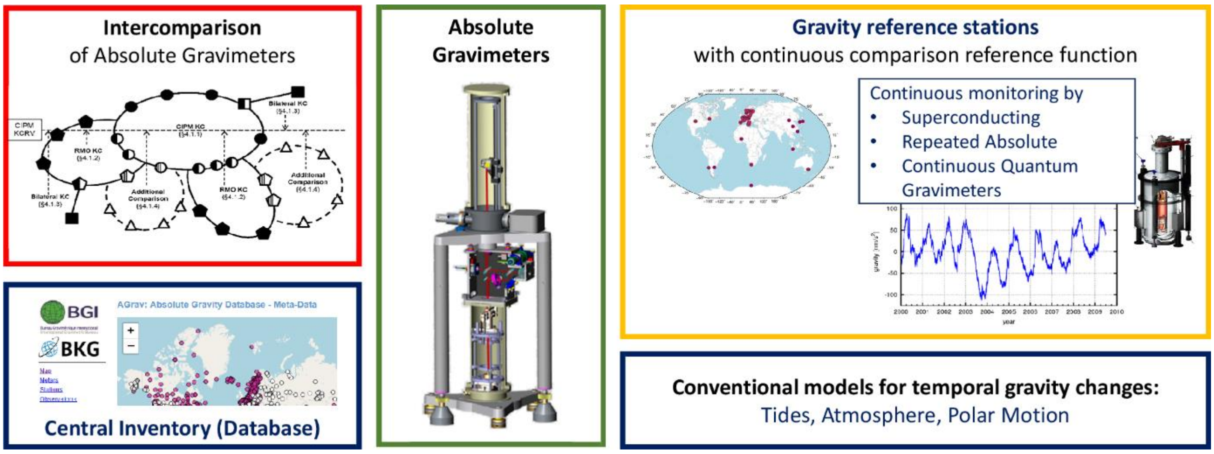


Fig. 1: Concept for the International Gravity Reference Frame.

The International Gravity Reference Frame (IGRF) is realized by measurements with absolute gravimeters (AGs) at the accuracy level of a few-µGal. A common reference level and the traceability to the SI of the AGs is ensured by key comparisons at the CIPM level and complemented by repeated regional comparisons. Comparison sites with extended facilities to compare AGs will therefore play an important role to ensure compatibility of AGs in long-term, needed for monitoring gravity variations at reference stations of the IGRF. Core stations with at least one available space geodetic technique will provide a link to the terrestrial reference frame. Continuous monitoring of temporal gravity variations and repeated absolute gravity observations are therefore recommended for GGOS core sites

In order to make the gravity system accessible to the stakeholders, efforts have been started to build up an infrastructure based of absolute gravity stations. This requires the support of and the cooperation with National agencies, which are encouraged by IAG resolution No. 4 of 2019 to establish compatible first order gravity networks and to provide information about existing absolute gravity observations. Such infrastructure should advantageously replace the previous IGSN71 network. The database AGrav at BGI and BKG will serve as a central archive for observations and all comparison results.

Reprocessing of comparisons of absolute gravimeters

Comparisons of absolute gravimeters (AGs) are essential for the IGRF. With a reprocessing and the analysis of recent comparisons (Pálinkáš et al. 2021), a concept for the evaluation of AG comparisons considering correlated observations and strictly applying the law of error propagation was published. All major AG comparisons from 2009 to 2018 were uniquely reprocessed, providing a frame for the elaboration of future comparisons. The significance of differences between FG5, FG5X and other types of gravimeters was assessed, concluding that both major groups of AGs can be described by the same normal distribution and that its

Meetings and further activities

Due to the pandemic the first meeting of the JWG 2.1.1 with 43 participants was held online on Mach 17th 2021, where the concept of IRS and IGRF was finally discussed and approved by the members prior to presentation at the IAG EC on March 26th by the president of Commission 2, Adrian Jäggi.

The IGRS was also presented at the Annual Meeting of the Indonesian Gravity Consortium (KGI) on March 31st 2021.

A collaboration with SIRGAS was initiated with the well-recognized online presentation "El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF)” on March 5th 2021 held by E. D. Antokoletz in Spanish with more than 100 participants and a considerable outreach. The cooperation will be continued with SIRGAS working group WGIII (Vertical Datum).

With the relaunch of the GGOS web site, the IGRF was included in the section of geodetic reference frames: https://ggos.org/item/gravity-reference-frame.

References

Pálinkáš, V., Wziontek, H., Vaľko, M., Křen, P., Falk, R.: Evaluation of comparisons of absolute gravimeters using correlated quantities: reprocessing and analyses of recent comparisons. J Geod 95, 21 (2021). https://doi.org/10.1007/s00190-020-01435-y

Wziontek, H., Bonvalot, S., Falk, R., Gabalda, G., Mäkinen, J, Pálinkáš, V., Rülke, A., Vitushkin, L.: Status of the International Gravity Reference System and Frame. J Geod 95, 7 (2021), https://doi.org/10.1007/s00190-020-01438-9

Sub-commission 2.2: Geoid, Physical Height Systems and vertical datum unification

Chair: *Georgios S. Vergos (Greece)*
Vice Chair: *Rossen S. Grebenitcharsky (Kingdom of Saudi Arabia)*

Overview

The IAG Sub-Commission 2.2 (SC2.2) promotes and supports scientific research related to methodological questions in geopotential, geoid and height determination, both from the theoretical and practical perspectives. The former refers in particular on methodological questions and practical numerical applications contributing to the realization of IHRS with the required sub-centimeter accuracy, the combination of local/regional vertical reference frames and their unification to the IHRF. This includes (among others):

- Realization of the International Height Reference System.
- Height system unification at regional scales and unification to the IHRF.
- Studies on W0 determination.
- Studies on data requirements, data quality, distribution and sampling rate to reduce the omission error to the sub-centimeter level in different parts of the world.
- Contributions of alternate data sources, such as altimetry sea surface heights and GNSS geometric heights to geopotential modeling and geoid determination at reference benchmarks.
- Investigation of the theoretical framework required to compute the sub-centimeter geoid.
- Investigation of the error budget of potential determination and vertical reference frames unification.
- Investigation and benchmarking of alternative regional geoid determination methods and software.
- Studies on theoretical and numerical problems related to the solution of the geodetic boundary value problems (GBVPs) in geoid determination.
- Studies on time variations of the gravity field and heights due to Glacial Isostatic Adjustment (GIA) and land subsidence.
- Development of relativistic methods for potential difference determination using precise atomic clocks.
- Investigating the role of traditional levelling in future regional/local height system realizations, combined with all available data linked to Earth's geopotential determination.

Its main program of activities refers to:

- Organizing meetings and conferences.
- Organization of local/regional workshops for the promotion of IHRF related studies.
- Inviting the establishment of Special Study Groups on relevant topics.
- Reporting activities of SC2.2 to the Commission 2.
- Communication/interfacing between different groups/fields relevant to the realization of IHRS.
- Conceptual and methodological support to working groups for national & regional vertical datums and reference frames definitions as realizations of IRHS

SC2.2 consists of a steering committee, through which participation to the various research activities are promoted. Within SC2.2 a JWG, namely JWG2.2.1 “Error Assessment of the 1cm geoid experiment” has been established. It focuses, after the successful completion during the previous term 2015-2019 of JWG 2.2.2 (The 1 cm geoid experiment), on the validation of the results, to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

During the reporting period, SC2.2 activities focused mainly on the publication of the results during the “1 cm geoid experiment”, the realization of the International Height Reference System (IHRS) through the Implementation of the International Height Reference Frame (IHRF), the organization of a dedicated session within the 2021 European Geosciences Union, the 2021 IAG Scientific Assembly and the organization of the next Gravity Geoid and Height Systems (GGHS) conference.

The successful completion of past period (2015-2019) JWG2.2.2 activities resulted in a number of publications of SC2.2 members in the dedicated Journal of Geodesy Special Issue (SI) “Reference Systems in Physical Geodesy” (ISSN: 0949-7714 (Print) 1432-1394 (Online)) which is currently in its finalization phase (https://bit.ly/3bVdU2a). The organization of the SI and the preparation of the publications has been a major goal of SC2.2 activities as it provides an analytic presentation of the various methodological schemes for geoid/quasi-geoid and potential determination, given a common set of input land and airborne gravity data and a common digital terrain model for the evaluation of the topographic effects. Finally, the validation and cross-validation between the various solutions has been performed using the same set of GNSS/Levelling data acquired during the GSVS campaign by the U.S. National Geodetic Survey. This SI encompasses the joint work and research efforts of 14 research groups worldwide, creating a valuable reference for related studies.

Peer-reviewed publications from the “1 cm geoid experiment”:

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3

Grigoriadis, V.N., Vergos, G.S., Barzaghi, R., Vassilios N., Carrion, D., Koç, Ö. Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. J Geod 95, 52 (2021). https://doi.org/10.1007/s00190-021-01507-7

Işık, M.S., Erol, B., Erol, S., Sakil, F.S. High-resolution geoid modeling using least squares modification of Stokes and Hotine formulas in Colorado. J Geod 95, 49 (2021). https://doi.org/10.1007/s00190-021-01501-z

Jiang, T., Dang, Y. & Zhang, C. Gravimetric geoid modeling from the combination of satellite gravity model, terrestrial and airborne gravity data: a case study in the mountainous area, Colorado. Earth Planets Space 72, 189 (2020). https://doi.org/10.1186/s40623-020-01287-y

Liu, Q., Schmidt, M., Sánchez, L., Willberg, M. Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado. J Geod 94, 99 (2020). https://doi.org/10.1007/s00190-020-01431-2

Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0

van Westrum, D., Ahlgren, K., Hirt, C, Guillaume, S. A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA. J Geod 95, 9 (2021). https://doi.org/10.1007/s00190-020-01463-8

Varga, M., Pitoňák, M., Novák, P., Bašić, T. Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. J Geod 95, 53 (2021). https://doi.org/10.1007/s00190-021-01494-9

Wang, Y.M., Li, X., Ahlgren, K., Krcmaric, J. Colorado geoid modeling at the US National Geodetic Survey. J Geod 94, 106 (2020). https://doi.org/10.1007/s00190-020-01429-w

Willberg, M., Zingerle, P. & Pail, R. Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment. J Geod 94, 75 (2020). https://doi.org/10.1007/s00190-020-01396-2

The next main activity of SC2.2 during the reporting period (2019-2021) refers to the involvement in the implementation of the IHRF. This is done through synergy with the Global Geodetic Observing System (GGOS) Focus Area (FA) Unified Height System (UAS) GGOS FA UHS and in particular GGOS-FA-UHS JWG0.1.3 "Implementation of the International Height Reference Frame (IHRF)" and the Inter-Commission Committee on Theory (ICCT) JSGT2.26 "Geoid/quasi-geoid modelling for realization of the geopotential height datum". Based on the strategy paper (Sánchez et al., 2021) already published in the aforementioned Journal of Geodesy SI, the main steps for the determination of IHRF geopotential values at IHRF sites have been determined. The activities are based on a geopotential determination based on a) global geopotential and topography potential models and b) local/regional geoid/quasi-geoid models either available at the SC2.2 and GGOS-FA-UHS participating members and the International Service for the Geoid repository. Already, a number of presentations and a peer-reviewed journal paper have been prepared.

Presentations and publications:

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3

Barzaghi, R., De Gaetani, C.I. & Betti, B. The worldwide physical height datum project. Rend. Fis. Acc. Lincei 31, 27–34 (2020). https://doi.org/10.1007/s12210-020-00948-0.

Barzaghi R., Sánchez L., Vergos G.: Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. European Geosciences Union (EGU) General Assembly 2020, Vienna, Austria, 10.5194/egusphere-egu2020-7961, 2020.

Sánchez, L.: Activities and plans of theGGOS Focus Area Unified Height System. GGOS Days 2020, Virtual Meeting, October 5-7, 2020.

Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0.

Sánchez L., Barzaghi R.: Activities and plans of the GGOS Focus Area Unified Height System. European Geosciences Union (EGU) General Assembly 2020, 10.5194/egusphere-egu2020-8625, 2020.

Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: Towards a Global Unified Physical Height System, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1500, https://doi.org/10.5194/egusphere-egu21-1500, 2021.

Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: GGOS Focus Area Unified Height System: achievements and open challenges, IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.

Sanchez, L., and IHRF Computation Team: Status of the International Height Reference Frame (IHRF), IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.

Dedicated Sessions during Conferences

During the reporting period, SC2.2 has participated in the organization of two related sessions in the 2021 EGU General Assembly and the 2021 IAG Scientific Assembly. During EGU2021 session G1.5 "Local/Regional Geoid Determination: Methods and Models" within the Geodesy Programme group has been organized, jointly with SC2.4 and the IGFS. 14 presentations have been given with virtual participation, referring to geoid/quasi-geoid determination, satellite data processing for geoid determination and theoretic aspects of geoid modeling. After the completion of the conference, it was decided that the session will be resubmitted for inclusion in the upcoming EGU2022, which will be help hopefully in person.

During the coming IAG2021 Scientific Assembly, to be organized virtually in June 28 -July

2, 2021, a joint session (Session 2a.2 “Vertical Reference Systems: methodologies, realization, and new technologies”) with Commission 1, ICCT, GGOS-FA-UHS and Project QuGe is organized. This session focuses on the unification of the existing height systems and vertical datums around the world, which can be achieved through the realization of an international vertical reference system that supports geometrical (ellipsoidal) and physical (normal, orthometric) heights with centimeter precision in a global frame.

Conference Organization and Planning

SC2.2 participates actively in the organization of the 3rd Joint IGFS and Commission 2 Meeting, Gravity Geoid and Height Systems, which was planned for Fall 2020, but due to the Covid-19 pandemic it was decided to be re-arranged. Currently, the plan is to organize the conference in person in the second week of September 2022 in Austin, Texas. The forthcoming GGHS2022 meeting is planned to encompass seven sessions focusing on:

- Current and future satellite gravity missions
- Global Gravity Field Modelling
- Local/regional gravity field modelling
- Absolute, Relative and Airborne Gravity - Instrumentation, Analysis, and Applications
- Height systems and vertical datum unification
- Satellite altimetry and applications
- Gravity for Climate & Natural Hazards: Inversion, Modeling, and Processes

The first announcement and the call for abstracts is foreseen for September 2021.

Joint Working Groups of Sub-commission 2.2:

JWG 2.2.1: Error assessment of the 1 cm geoid experiment

Chair: *Martin Willberg (Germany) (2019-2021.03)*
Tao Jiang (China) (2021.03-2023)
Vice Chairs: *Vassilios Grigoriadis (Greece) Matej Varga (Switzerland)*

Members
- Tao Jiang (China), Chair
- Vassilios Grigoriadis (Greece), Vice-chair
- Matej Varga (Switzerland), Vice-chair
- Laura Sánchez (Germany)
- Yan Ming Wang (USA)
- Marc Véronneau (Canada)
- Sten Claessens (Australia)
- Qing Liu (Germany)
- Rene Forsberg (Denmark)
- Hussein Abd-Emotaal (Egypt)
- Koji Matsuo (Japan)
- Bihter Erol (Turkey)
- Jonas Ågren (Sweden)
- Kevin Ahlgren (USA)
- Riccardo Barzaghi (Italy)
- Representative person USP (Brazil)

Activities and publications during the period 2019-2021

JWG 2.2.1 (Error assessment of the 1 cm geoid experiment) is the continuation of JWG 2.2.2 (The 1 cm geoid experiment) in the previous IAG period 2015-2019.

The objectives of this JWG are to validate the results, to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

14 groups from 13 countries participated in the Colorado 1 cm geoid experiment. The groups have computed 14 gravimetric geoid models and 13 gravimetric quasigeoid models in the area of Colorado using terrestrial gravity, airborne gravity, digital elevation models and global gravity field models. The accuracy of each gravimetric quasigeoid model was independently evaluated by the National Geodetic Survey (NGS) of USA using the GSVS17 height anomalies. The quasigeoid models agree with the GSVS17 height anomalies from 2.1 cm to 3.6 cm in terms of the standard deviation (STD) of the differences. The median of the STD is 3.1 cm. The 14 groups are as follows:

- AUTh: Aristotle University of Thessaloniki, Greece
- CASM: Chinese Academy of Surveying and Mapping, China
- CGS: Canadian Geodetic Survey, Canada
- Curtin: Curtin University, Australia
- DGFI: Deutsches Geodätisches Forschungsinstitut, Technical University of Munich, Germany

- DTU: Technical University of Denmark, Denmark
- Minia: Minia University, Egypt
- NGS: US National Geodetic Survey, NOAA, USA
- GSI: Geospatial Information Authority of Japan, Japan
- IAPG: Institute for Astronomical and Physical Geodesy, Technical University of Munich, Germany
- ITU: Istanbul Technical University, Turkey
- KTH: University of Gävle, Lantmäteriet, Royal Institute of Technology, Sweden
- NTIS-GEOF: University of West Bohemia, Czech Republic & University of Zagreb, Croatia
- Polimi: Politecnico di Milano, Italy

The geoid computation methods, analysis and results of most groups have been published in Journal of Geodesy.
The NGS has released all the GSVS17 field data including spirit leveling, GPS, gravity, and deflection of vertical on its web page:
https://www.ngs.noaa.gov/GEOID/GSVS17/DataFiles.shtml.

An online meeting was organized on March 11, 2021, to discuss the aspects corresponding to the written terms of reference of this JWG. The main conclusions of the meeting were:

- The following aspects are the current main focus of this JWG:
  a) validate the geoid models by comparisons to the GSVS17 data
  b) identify and quantify potential error sources for geoid modeling
  c) analyze the differences of individual geoid results and find the most possible reasons
- Kevin Ahlgren from the NGS agreed to make an extended GSVS17 data file for this working group, which will be used by each group in this JGW for further and comprehensive geoid model validation and error analysis. Kevin Ahlgren has been working on preparing this GSVS17 data file.
- All groups should check their own solution for differences and similarities with the GSVS17 validation data from GPS/leveling and DoV
- The individual groups will try to find the discrepancies of various computation methods based on a unified and simplified data scenario.
- Due to personal reasons, Martin Willberg was not able to continue as a chair of the JWG. The JWG decided to select a new chair and two vice-chairs, and this was reported to Adrian Jäggi, the President of Commission 2:
  Chair: Tao Jiang
  Co-chairs: Vassilios Grigoriadis, Matej Varga

Peer-reviewed publications

Bjelotomić Oršulić, O., Markovinović, D., Varga, M., Bašić, T. The impact of terrestrial gravity data density on geoid accuracy: case study Bilogora in Croatia. Survey Review 52.373 (2020): 299-308. https://doi.org/10.1080/00396265.2018.1562747

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3

Grigoriadis, V.N., Vergos, G.S., Barzaghi, R., Vassilios N., Carrion, D., Koç, Ö. Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. J Geod 95, 52 (2021). https://doi.org/10.1007/s00190-021-01507-7

Işık, M.S., Erol, B., Erol, S., Sakil, F.S. High-resolution geoid modeling using least squares modification of

Stokes and Hotine formulas in Colorado. J Geod 95, 49 (2021). https://doi.org/10.1007/s00190-021-01501-z

Jiang, T., Dang, Y. & Zhang, C. Gravimetric geoid modeling from the combination of satellite gravity model, terrestrial and airborne gravity data: a case study in the mountainous area, Colorado. Earth Planets Space 72, 189 (2020). https://doi.org/10.1186/s40623-020-01287-y

Liu, Q., Schmidt, M., Sánchez, L., Willberg, M. Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado. J Geod 94, 99 (2020). https://doi.org/10.1007/s00190-020-01431-2

Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0

van Westrum, D., Ahlgren, K., Hirt, C, Guillaume, S. A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA. J Geod 95, 9 (2021). https://doi.org/10.1007/s00190-020-01463-8

Varga, M., Pitoňák, M., Novák, P., Bašić, T. Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. J Geod 95, 53 (2021). https://doi.org/10.1007/s00190-021-01494-9

Wang, Y.M., Li, X., Ahlgren, K., Krcmaric, J. Colorado geoid modeling at the US National Geodetic Survey. J Geod 94, 106 (2020). https://doi.org/10.1007/s00190-020-01429-w

Willberg, M., Zingerle, P. & Pail, R. Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment. J Geod 94, 75 (2020). https://doi.org/10.1007/s00190-020-01396-2

Sub-commission 2.3: Satellite Gravity Missions

Chair: *Frank Flechtner (Germany)*
Vice Chair: *Matthias Weigelt (Germany)*

Overview

SC2.3 shall promote and stimulate activities providing the scientific environment for the development of the next generation of static and temporal gravity field solutions based on observations from the satellite gravity missions CHAMP, GRACE, GOCE, and GRACE-FO, as well as optimum combination with complementary data types (SLR, terrestrial and air-borne data, satellite altimetry, etc.), developing alternative methods and new approaches for global gravity field processing with special emphasis on functional and stochastic models and optimum data combination, fostering the exchange of knowledge and data among processing entities, the communication and interfacing with gravity field model user communities (climatology, oceanography/altimetry, glaciology, solid Earth physics, geodesy, ...) as well as relevant IAG organizations such as the GGOS Committee on Satellite and Space Missions and the GGOS Bureau of Products and Standards, the identification, investigation and definition of enabling technologies for future gravity field missions such as observation types, technologies or mission architectures, and triggering new gravity field mission proposals and supporting their implementation.

Highlights throughout 2019-2021 (examples) were

COST-G: A new service to provide combined time-variable gravity field solutions

The International Combination Service for Time-variable Gravity Fields (COST-G) is the Product Center of the International Gravity Field Service (IGFS) for time-variable gravity fields. COST-G (https://cost-g.org) provides consolidated monthly global gravity models in terms of spherical harmonic (SH) coefficients and thereof derived grids by combining existing solutions or normal equations (NEQs) from COST-G analysis centers (ACs) and partner analysis centers (PCs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from GRACE/GRACE-FO low-low satellite-to-satellite tracking (ll-SST), high-low satellite-to-satellite tracking (hl-SST), Satellite Laser Ranging (SLR).
COST-G continues the activities of the Horizon2020 project European Gravity Service for Improved Emergency Management (EGSIEM) to realize a long-awaited standardization of gravity-derived mass transport products and to improve the quality, robustness, and reliability of individual solutions and to enable hydrologists, glaciologists, oceanographers, geodesists and geophysicists to take full advantage of one well-defined, consolidated monthly gravity product.
A draft version of the COST-G terms of references (ToR) has been initially discussed at the IAG Executive Board meeting during the EGU General Assembly 2017 in Vienna, Austria. Finally, the International Union of Geodesy and Geophysics (IUGG) established COST-G as a new Product Center of IAG’s International Gravity Field Service (IGFS) for time-variable gravity fields at its 2019 General Assembly.

COST-G performs a quality control of the individual contributions before combination and provides (see Fig 2),

- Combined gravity field solutions in SH coefficients (Level-2 products) derived from a weighted combination of individual normal equations (NEQs) generate by the different ACs,

- Spatial grids and other high-level products (Level-3 products) of the Combined Solutions for hydrological, oceanic and polar ice sheets applications.

The Level-2 products are made available through the International Center for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de), the Level-3 products by the Information System and Data Center (ISDC, https://isdc.gfz-potsdam.de). The Level-3 products can be visualized at the COST-G Plotter (https://cost-g.org) and the Gravity Information Service (GravIS, http://gravis.gfz-potsdam.de) at GFZ Potsdam (see Fig X2).

The initial Analysis Centers (AC), in charge of computing time-variable gravity field solutions from GRACE and GRACE-FO, are (in alphabetical order) the

- Astronomical Institute, University of Bern (AIUB),
- Centre National d'Etudes Spatiales (CNES),
- German Research Centre for Geosciences (GFZ), and
- Institute of Geodesy, Graz University of Technology (IFG)

Current Partner Analysis Centers (PAC) are the

- Center for Space Research (CSR), and
- NASA's Jet Propulsion Laboratory (JPL)

Just recently the Institut für Erdmessung of the Leibniz University of Hannover was selected to become also an AC (passing all tests as described in Lasser et al. (2020)). Discussions with various Chinese processing centers such as IGG, SUSTech, Tongji, HUST or Whuhan to be become COST-G ACs are ongoing.

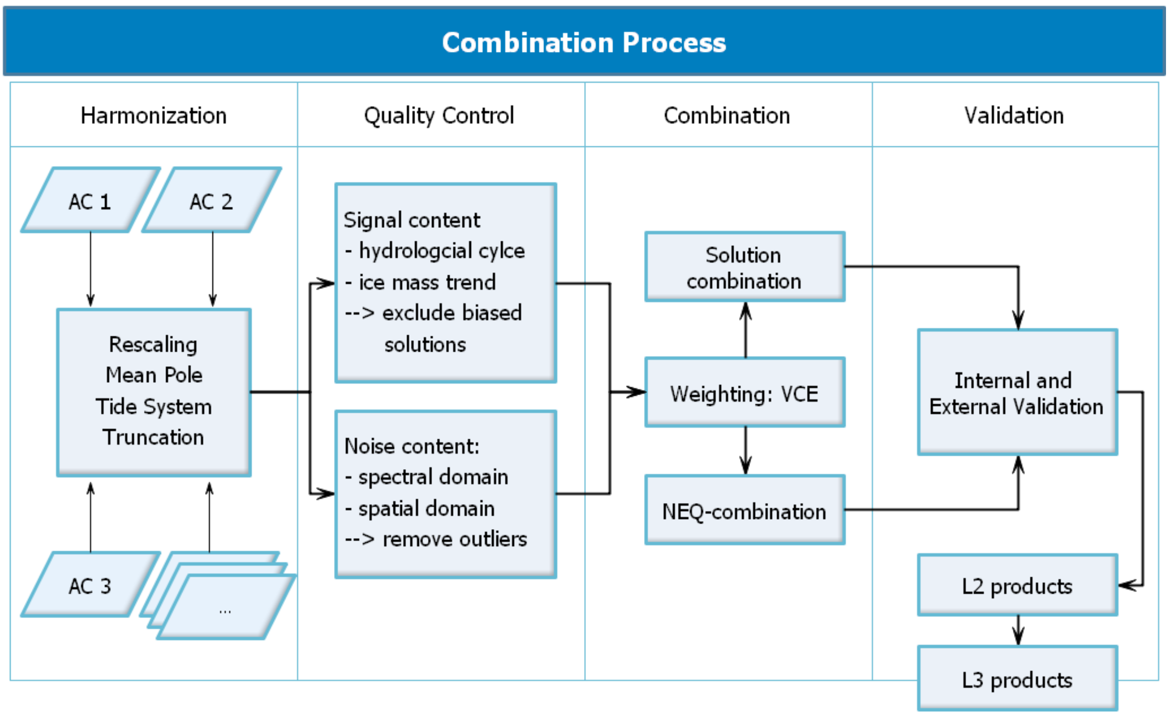


Figure 2: COST-G combination process.

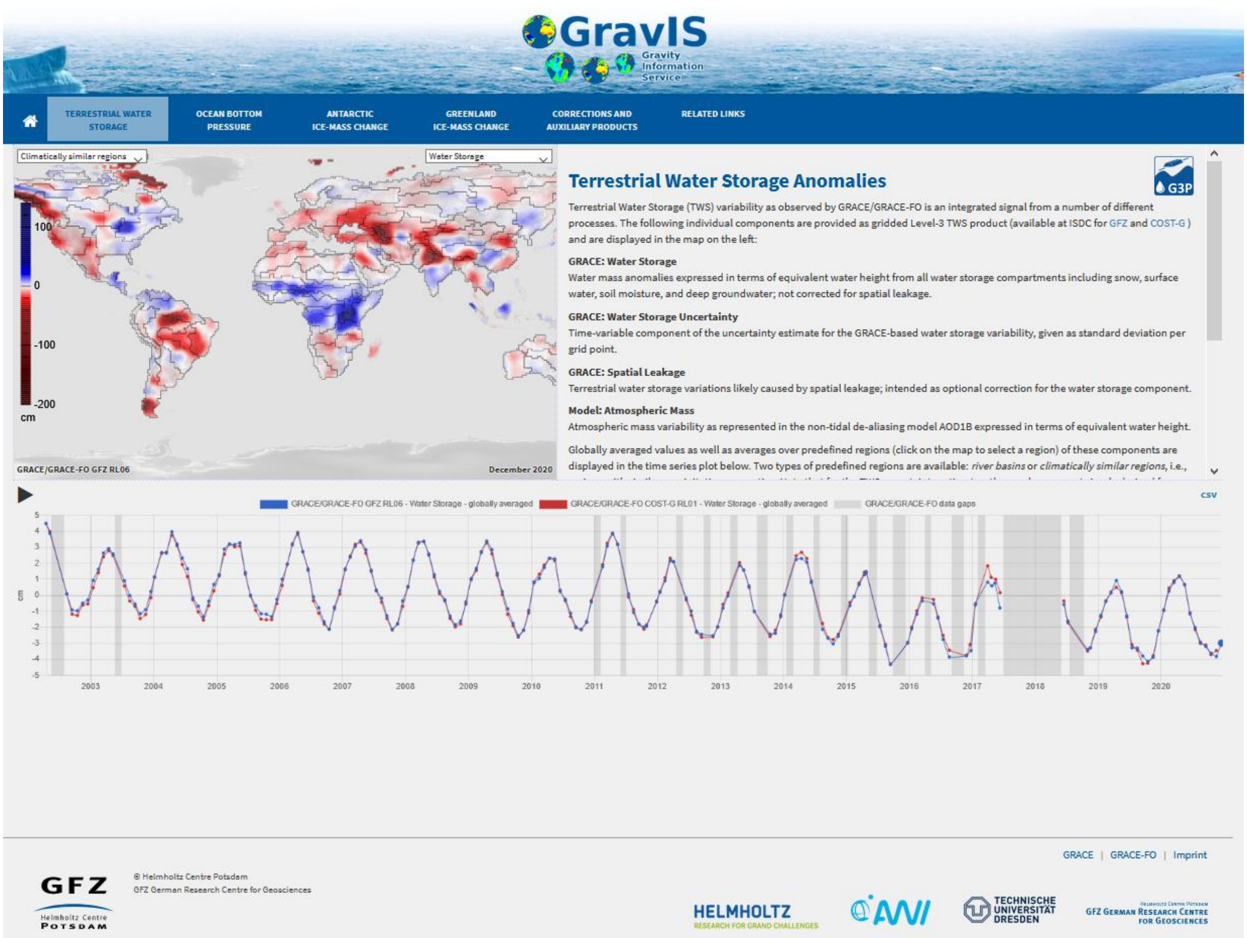


Figure 3: Screenshot of the GFZ Potsdam GravIS portal showing GFZ RL06 and COST-G based Level-3 global Terrestrial Water Storage Anomalies for climatically similar regions (more details on the webpage)

Total Water Storage became Essential Climate Variable

The Global Climate Observing System (GCOS) defines Essential Climate Variables (ECVs) as variables that are critical for characterizing the climate system and its changes. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, to underpin climate services, among others. A list of ECVs is available at https://gcos.wmo.int/en/essential-climate-variables.

In the hydrological branch, one of the already established ECVs is groundwater. The Steering Committee of GCOS recommended in December 2020 to establish also Total Water Storage (TWS), the prime output of GRACE and GRACE-FO, as an additional ECV. This process was strongly supported by SC members. The official inclusion in the GCOS Implementation Plan is expected for 2022. While the European Union's Earth Observation Programme Copernicus does not yet provide data products for these ECVs, this gap is about to be filled by the EU research project G3P (Global Gravity-based Groundwater Product; www.g3p.eu) which started in 2020 under leadership of GFZ Potsdam.

The G3P consortium combines key expertise from science and industry across Europe that optimally allows to (1) capitalize from the unique capability of GRACE and GRACE-FO satellite gravimetry as the only remote sensing technology to monitor subsurface mass variations and thus groundwater storage change for large areas, (2) incorporate and advance a wealth of products on storage compartments of the water cycle that are part of the

Copernicus portfolio, and (3) disseminate unprecedented information on changing groundwater storage to the global and European user communities, including a European use case as a demonstrator for industry potential in the water sector. In combination, the G3P development is a novel and cross-cutting extension of the Copernicus portfolio towards essential information on the changing state of water resources at European and global scales.

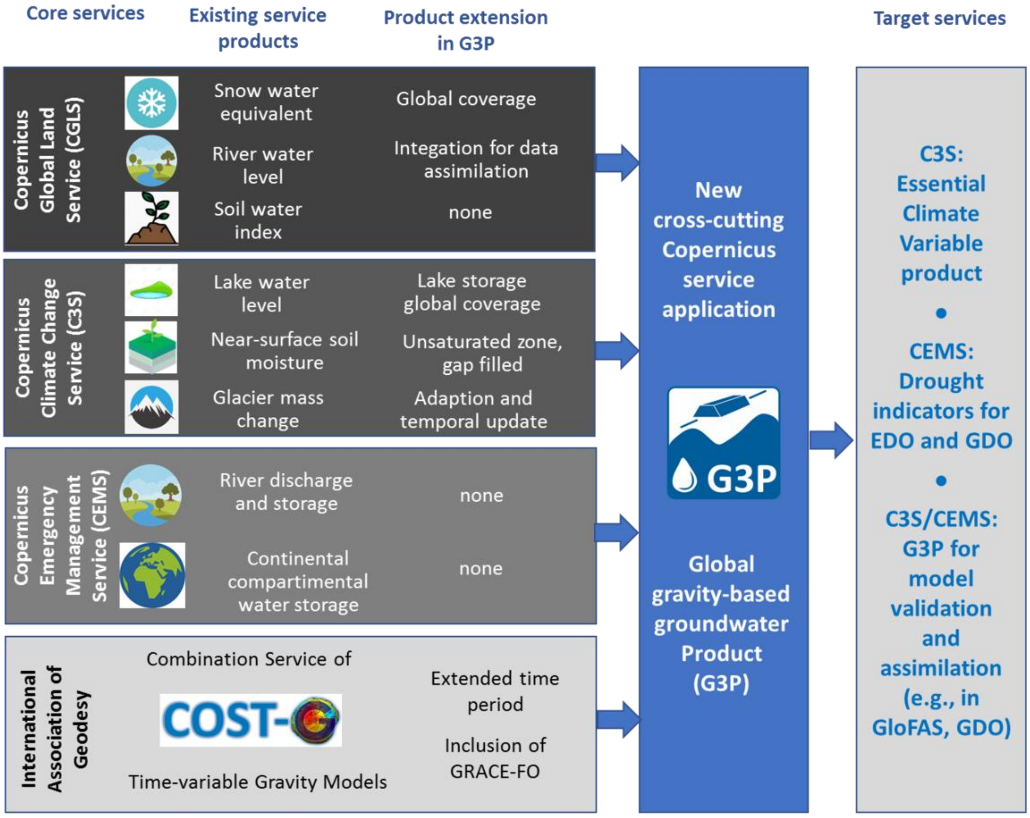


Figure 4: G3P overview (from https://www.gfz-potsdam.de/en/section/hydrology/projects/g3p-global-gravity-based-groundwater-product/). Note that the G3P time-variable gravity field models will be provided by the IAG COST-G Service (see above) via the Gravity Information Service GravIS at GFZ (see Figure X2)

Towards realization of future gravity missions

Mass change (MC) has been identified in the U.S. National Academies of Sciences, Engineering and Medicine (NASEM) 2017 Decadal Survey, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space" as a Designated Observable, and the NASA decadal survey (DS) recommends a mass change mission (MCM) to continue, and potentially improve upon, the observational record established by the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions. In response to guidance for multi-center study plans issued by NASA in June 2018, the Jet Propulsion Laboratory (lead), along with NASA's Ames Research Center, Goddard Space Flight Center, and Langley Research Center submitted a joint study plan to the NASA Earth Science Division to study implementation options for a Mass Change Observing System.

The MC study has three main objectives (https://science.nasa.gov/earth-science/decadal-mc):

1. Identify and characterize a diverse set of high-value mass change observing architectures responsive to the decadal strategy report's scientific and application

objectives for mass change.
2. Assess the cost effectiveness of each of the studied architectures.
3. Perform sufficient in-depth design of one or two select architectures to enable rapid initiation of a phase-A study.

Consequently, NASA approved and initiated a 3-year study for MC, along with concurrent multi-center studies for four other Designated Observables identified in the DS. The charter given to all studies was to investigate observing system architectures while considering synergies with other observation systems, accelerating research and applications, and (international) partnerships. The status of the MC study has been presented at various meetings, e.g. at the AGU Town Hall 2020 or EGU 2021. Major outcomes of the derived architecture and technology trade space matrix are:

1. Precise orbit determination based on GNSS observations has a low science value and does not fulfill the science objectives for MC
2. Gravity gradiometry has a high science value but low Technical Readiness Level (TRL) and a long/uncertain development schedule
3. A LEO/MEO Satellite-Satellite Tracking (SST) concept has technical challenges and a science value that does not offer significant improvements relative to the GRACE and GRACE-FO single in-line pair architectures
4. A small-satellite SST constellation is not cost effective and lacks interest of an international partner
5. A SST architecture is identified as having the highest value, and the following promising variants have been identified:
    a. A single in-line polar pair (such as “GRACE-I” as suggested by DLR/GFZ (Germany))
    b. A pendulum pair or an in-line polar pair combined with a pendulum satellite (such as “MARVEL” as suggested by CNES (France))
    c. Two in-line pairs in a Bender (i.e. one polar pair, one inclined pair) constellation (such as “NGGM/MAGIC” as suggested by ESA/NASA)

GRACE-I

To realize a MCM NASA is seeking for international partnership. A future continuation of the very successful technological and scientific GRACE/GRACE-FO partnership between the U.S. and Germany is in the involved partners’ highest interest and would be based on a strong heritage in the fields of satellite manufacturing, laser ranging interferometry (LRI) or science data utilization. The goal of a study, jointly performed in summer 2020 between German Aerospace Center (DLR), industry and Helmholtz Foundation (HGF) and Max-Plank-Foundation (MPG) scientists, was to bundle up an attractive scientific and technological German package for further discussions with NASA which 1) compares the cost and benefit of technical modifications with respect to GRACE-FO, 2) is not only attractive for a future MCM but also for the Laser Interferometer Space Antenna (LISA) and 3) strengthens at the same time Germany´s role towards ESA´s Next Generation Gravity Mission (NGGM) implementation. An ICARUS (International Cooperation for Animal Research Using Space) payload, currently successfully operated as a technology demonstrator onboard the International Space Station, on a future polar-orbiting GRACE-like “GRACE-ICARUS” (or short “GRACE-I”) mission could provide a much-desired scientific extension of biodiversity monitoring, which is synergistic with the Surface Biology and Geology Designated Observable in NASA´s Decadal Survey.

In March 2021 a Phase-0 study has started at Airbus (Friedrichshafen) which shall investigate till September 2021 the following realization options in close collaboration with NASA/JPL:

1. A GRACE-type single polar pair with Laser (LRI) redundancy @ 420 km (with drag compensation) or 490 km with a launch not later than 2027 to enable gap-free continuity to GRACE-FO (plus optional payloads such as ICARUS, spacecraft and LRI related enhancements or inclusion of technology demonstrators based on quantum technologies). "Bender constellation" demonstration via GRACE-FO / GRACE-I combination is an option, depending on health status of GRACE-FO.
2. Adding a 3rd pendulum satellite such as MARVEL (see below) could be an attractive companion to GRACE-I (if not a schedule driver).
3. GRACE-I combination with one or two advanced GRACE-type satellite pairs @ ca. 350 km developed in NASA/ESA collaboration such as NGGM/MAGIC (see below) due for launch ~2030/2037. The first pair could operate in a Bender constellation with GRACE-I, while the second pair could later replace GRACE-I and create a Bender constellation of two pairs both at lower altitudes."

Marvel

The MARVEL (Mass And Reference Variations for Earth Lookout) concept was proposed to the 2019 CNES Seminar of Scientific Prospective and was ranked with the highest priority in the class of "large missions". This seminar takes place every four or five years and its recommendations serve CNES as a "roadmap" for the development of medium-term space science programming and associated programmatic decisions. One of the main driver and a key recommendation is international cooperation.

The initial concept of MARVEL aimed to achieve in a single mission two different and complementary scientific objectives:

i) Monitor mass transfers in the Earth system with improved accuracy w.r.t. current observing systems (GRACE/GRACE-FO), and
ii) Realization, at the millimeter level, of the International Terrestrial Reference Frame (ITRF).

This concept could be implemented by launching two constellations in a polar orbit: a low-flying one at 470 km and a higher one at 7000 km with a laser SST link between the two constellations. The reference frame objective would be reached by equipping the higher constellation with precisely collocated beacons of the four space geodetic techniques (GNSS, SLR, Doris, VLBI) on-board one of the satellites of the upper constellation.

A Phase-0 study started at CNES in January 2020. However, it soon became obvious that

1) The LEO/MEO concept had a low science value with the envisaged ranging accuracy between the lower and upper constellations
2) The cost associated with such a mission was unrealistic, particularly given the first point.

On the contrary, the "Pendulum" concept, also studied during the first stages of Phase-0, presented a high scientific benefit, on the same level as a Bender configuration (Fig. X4, right), with a very favorable cost/benefit ratio. The advantage of the Pendulum (or also Bender) concept is that it solves the problem of the strong anisotropy of the measurements which is one of the most handicapping points in the "polar in-line pair" concept of GRACE and GRACE-FO. A Pendulum pair is composed of two satellites in a polar orbit with a small offset of their ascending node and mean anomaly. In that way, the ranging measurement between the satellites oscillates alternatively from left to right between the ascending and descending tracks (Fig. X4, left). This concept was initially suggested in the "e.motion" proposal to ESA in the framework of the EE8 call. The Pendulum concept can also be associated with a classical in-line pair, in a 3-satellite configuration (Fig. X4, middle).

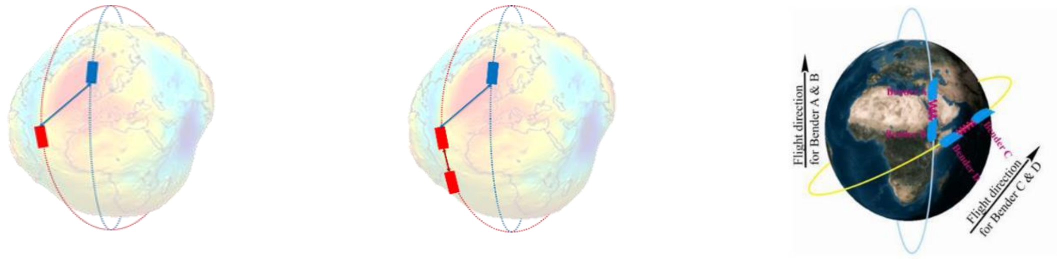


Figure 5: 2-satellite (left) and 3-satellite (middle) Pendulum and 2-pair Bender (right) configuration

The inter-satellite telemetry instrument being designed in Phase-0 is a chronometric laser link (i.e. a measurement of the time of flight of an optical signal, and not a laser interferometer). The target accuracy of this instrument in range and range-rate is 1 µm and 0.1 µm/s, respectively. This is about three orders of magnitude better than what is reached from the ground by SLR. It is based on existing telecom technologies, with a TRL of 9 on ground. The pointing mechanism enables a +/- 45° amplitude of pointing and is designed to generate extremely low levels of dynamical perturbations. The reflector part of the instrument can be totally static.

The second stage of Phase-0 started in September 2020, focusing on the Pendulum concept, and is expected to last until September 2021. Discussions are underway between CNES on the one hand and NASA, ESA and DLR/GFZ on the other hand to harmonize numerical simulation standards and to see whether MARVEL could fit into NGGM/MAGIC or GRACE-I projects.

NGGM/MAGIC

In the frame of the Missions of Opportunity enabled by international cooperation, ESA and NASA have coordinated studies of gravity monitoring constellations optimised to observe mass changes and transport in the Earth system. Already in 2016 the report from the ESA-NASA Interagency Gravity Science Working Group defined the benefits of such a unique cooperative effort. The objective of the NGGM (Next Generation Gravity Mission) also known as MAGIC (Mass-change and Geosciences International Constellation) is the long-term monitoring of the temporal variations of Earth's gravity field at high resolution in time (down to 3 days) and space (100 km). NGGM/MAGIC will observe Earth mass change and reinforce services by monitoring hydrology, cryosphere, oceanography, solid Earth and climate change. This gravity mission evolution will provide continuity of science and services with respect to predecessor missions like GRACE, GOCE and GRACE Follow-On and will complement other ESA Earth Explorer programme and Copernicus missions.

The constellation concepts identified meet the goal of synergetic international collaboration fulfilling the needs of many user communities, including operational communities, in a way not achievable by a single Agency. Given that a single pair of satellites will not meet (pre-) operational needs since it cannot support key applications, e.g. ground-water and aquifer monitoring and management, at the required spatio-temporal resolution, a cooperation programme between ESA and NASA is necessary and timely. From a (pre-) operational standpoint, among current EO-enabled services, those for land, climate, ocean, and emergency management would especially benefit from improved mass change data as available only from a constellation, such as a double-pair Bender constellation (see Fig. X4, right) at very low altitude (e.g. 350 km) and with improved instrumentation (e.g. for accelerometry observing non-gravitational forces, drag compensation system, etc.). One option for such a Bender constellation could be a combination of GRACE-I with a second NGGM/MAGIC-type pair.

In May 2021 ESA enabled two Phase A system studies, whose main objective will be the determination of the programmatic, technical and technological feasibility of the mission within its boundary conditions. In parallel a Science Support Study was initiated (TU Munich, GFZ, CNES, TU Delft) to simulate the gain in performance of different constellation scenarios and processing methods. The final results are expected for September 2022. A decision on implementation of NGGM/MAGIC will not be made before the ESA Ministerial Conference end of 2022.

Sub-commission 2.4: Regional Geoid Determination

Chair: Hussein Abd-Elmotaal (Egypt)
Vice Chair: Xiaopeng Li (USA)

Overview

The main purpose of Sub-Commission 2.4 is to initiate and coordinate the activities of the regional gravity and geoid sub-commissions.
Currently there are 6 of them:

- SC 2.4a: Gravity and Geoid in Europe (chair H. Denker, Germany)
- SC 2.4b: Gravity and Geoid in South America (chair G. Guimarães, Brazil)
- SC 2.4c: Gravity and Geoid in North and Central America (chair X. Li, USA)
- SC 2.4d: Gravity and Geoid in Africa (chair H. Abd-Elmotaal, Egypt)
- SC 2.4e: Gravity and Geoid in the Asia-Pacific (chair C. Hwang, China-Taipei)
- SC 2.4f: Gravity and Geoid in Antarctica (chair M. Scheinert, Germany)

These regional SC nominally cover the whole world with the exception of a larger region in the Middle East. But it is clear that not all countries which are listed as a member of a regional SC, are actively participating in international projects or data exchange agreements. This is especially true for some countries in Central America, the Caribbean, Africa and Asia.

Short summary of the activities of the regional SCs

SC 2.4a: European Gravity and Geoid

The main focus was on the update and of the digital elevation models. About 10 new global and regional elevation models were collected, validated and included in the European database. New global gravity field models and selected terrestrial gravity data sets were also added to the database. Furthermore, contributions were made to several projects related to optical clocks and chronometric levelling as well as to EUREF and the International Height Reference System (IHRS).

SC 2.4b: Gravity and Geoid in South America

In the last years, a big effort has been carried out by many different organizations to improve the absolute gravity measures over South America. As a result, more than 40 stations have been measured. At the same time, special attention has been given in terms of gravity densification, around IHRF stations. In South America, 17 stations were selected for the IHRF network. Some gravity measurements have been carried out around those stations.

SC 2.4c: Gravity and Geoid in North and Central America

The activities of the sub-commission 2.4c (Gravity and Geoid in North and Central America) is principally focused around the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA’s National Geodetic Survey (NGS). A geoid model, xGeoid20, was computed by NGS, NRCan, and INEGI. This is the first time that the three agencies generate a common geoid model for the entire North American area.

SC 2.4d: Gravity and Geoid in Africa

In Africa, a recent precise geoid model has been determined. Another geoid model using the shell layer method has been computed. Studies for the effect of the great lakes and depressions on the gravity and geoid have been carried out.

SC 2.4e: Gravity and Geoid in the Asia-Pacific

A first workshop was held to promote geoid modeling in the Asia-Pacific region and a special issue in the journal Terrestrial, Atmospheric and Ocean Sciences (TAO) was initiated to show recent gravity data processing and geoid modeling.

SC 2.4f: Gravity and Geoid in Antarctica (AntGG)

Due to the pandemic crisis the vast majority of re-search activities in Antarctica had to be cancelled especially for the season 2020/2021. But several aspects of the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic model were successfully investigated and published.

Sub-commission 2.4a: Gravity and Geoid in Europe

Chair: Heiner Denker (Germany)

Overview

The primary objective of SC 2.4a is the development of improved regional gravity field models (especially geoid/quasigeoid) for Europe, which can be used for applications in geodesy, oceanography, physics, geophysics and engineering.

So far, the work concentrated mainly on the update and of the digital elevation models. About 10 new global and regional elevation models were collected. The data were converted into common formats and then compared with the previous global and national data sets available. Furthermore, new global gravity field models were collected and selected new gravity data sets were included in the European database, all this in cooperation with the national contacts, either new or existing from previous SC 2.4a cooperation.

In addition to this, SC 2.4a contributed to several projects in Germany and Europe related to optical clock comparisons for chronometric levelling at the cm level, where the quasigeoid models together with GNSS measurements served for providing ground truth data by the so-called GNSS/geoid approach. Further contributions and cooperations of the sub-commission were related to the IAG enterprises EUREF and the International Height Reference System (IHRS), and also the IAG Colorado test data set was analysed for checking the software and methodology used for Europe.

Sub-commission 2.4b: Gravity and Geoid in South America

Chair: *G. Guimarães (Brazil)*
Vice Chair: *Ayelen Pereira (Argentina)*

Overview

This report intends to cover most of the activities in South America related to gravity field determination. It is certainly not complete due to the many activities going on in different organizations, universities and research institutes. Sub-commission 2.4b acknowledged Ezequiel Antokoletz (UNLP and CONICET - Argentina), Denizar Blitzkow (EPUSP and CENEGEO - Brazil), Ana Cristina Oliveira Cancoro de Matos (CENEGEO - Brazil), Giuliano Sant'Anna Marotta (UnB - Brazil), José Luis Carrión Sánchez (IGM - Ecuador) and Leidy Johanna Moisés Sepúlveda (IGAC - Colombia) for the contributions.

Improvements of gravity databases

A big effort was carried out by many different organizations in the last few years to improve the gravity data coverage all over South America. As a result, approximately 920,043 points of gravity data are now available for geoid determination. Figure 6 shows the new (blue points) and old (red points) gravity data. The 10,170 new gravity observations have been carried out with LaCoste&Romberg and/or CG5 gravity meters. GNSS double frequency receivers have been used to derive the geodetic coordinates of the stations.

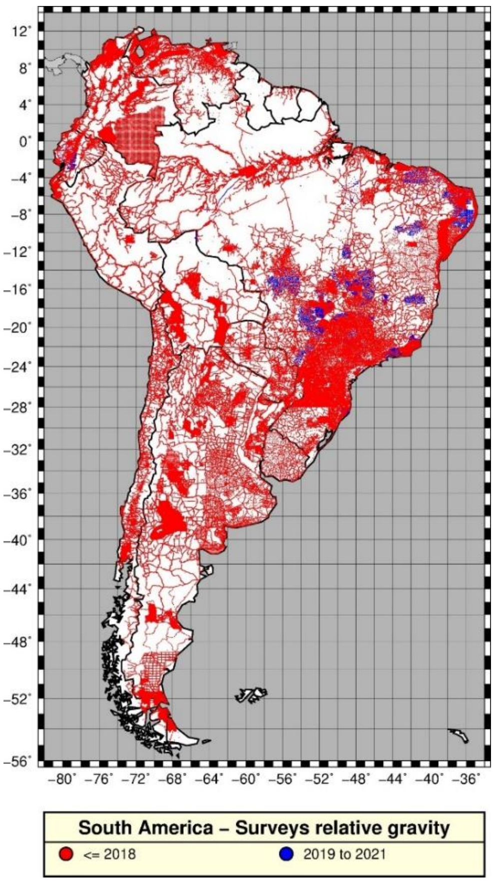


Figure 6 South America gravity data points.

Brazil

In the last two years, a total of 8,902 new gravity stations have been measured (blue points in Figures 7a, 7b and 7c) by IBGE (CGED), Laboratory of Surveying and Geodesy (EPUSP-LTG), Centro de Estudos de Geodesia (CENEGEO).

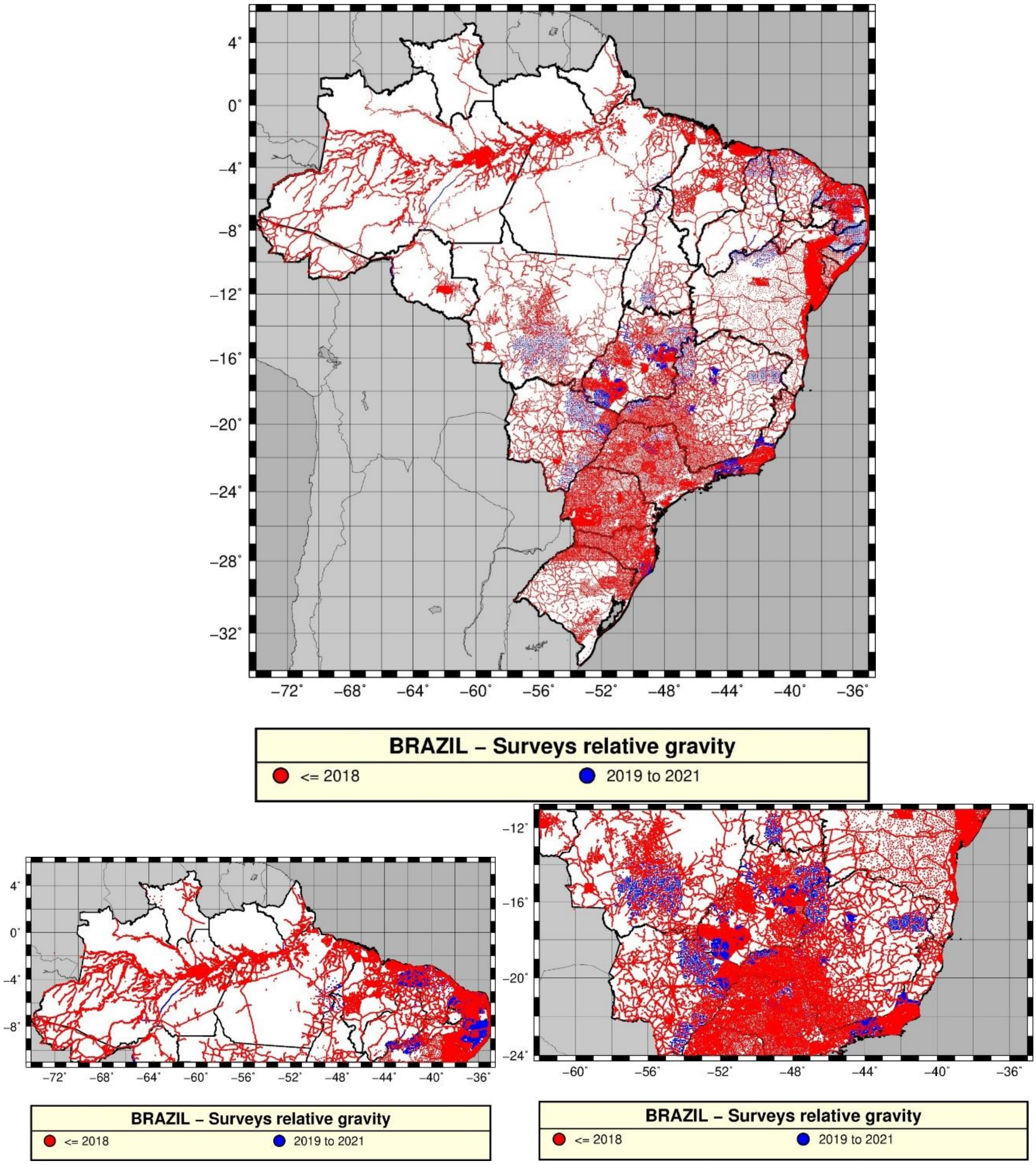


Figure 7 a) Brazil new gravity data (up); b) New gravity data in North and Northeast of Brazil (left); c) New gravity data in Midwest and Southeast of Brazil.

Colombia

Some improvements have been carrying out in the Colombian gravity network. In 2019, 329 gravity stations (Figure 8, red points) were collected by the Geographic Institute Agustín Codazzi (IGAC). In 2021, around 200 stations are planned to be measured.

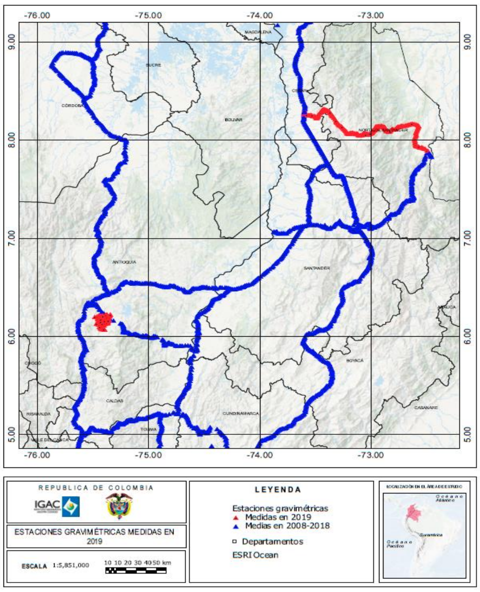


Figure 8 New gravity data in Colombia.

Ecuador

From 2019 up to 2021, gravimetric surveys in Ecuador obtained 1,268 new points. The gravity data were surveyed by the Ecuadorian Military Geographic Institute (IGM). The gravity values of the densification surveys were connected to the Ecuador Gravity Reference Frame (EGRF) established in 2017 in a total of 26 stations. The efforts were supported by IGM, CENEGEO. An A-10 gravity meter, number 32, from the Institute of Geography and Cartography (IGC), was used. Figure 9 shows the surveys until January 2019 (red points), and from February 2019 through May 2021 (blue points), respectively.

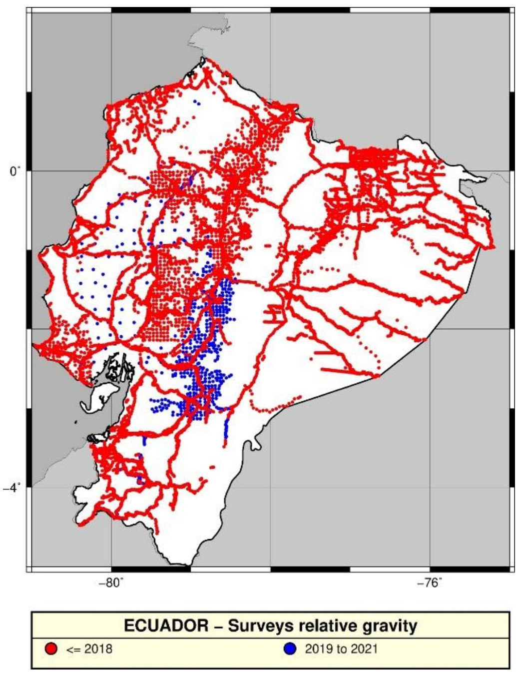


Figure 9 Gravity data in Ecuador.

Absolute gravity measurements

Argentina - Establishment of the International Gravity Reference Frame (IGRF)

The Argentinean-German Geodetic Observatory (AGGO) is a fundamental geodetic observatory located close to the city of La Plata, Argentina. The observatory is operated jointly by the German Federal Agency for Cartography and Geodesy (BKG) and the National Scientific and Technical Research Council of Argentina (CONICET). All main space geodetic techniques are co-located: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS). Moreover, a gravity laboratory is established at AGGO where the superconducting gravimeter SG038 has been continuously recording gravity changes since December 16th, 2015; and a FG5 absolute gravity meter was installed in January 2018. Figure 10 shows the floor plan of the gravity laboratory and both instruments that are installed.

The gravity laboratory is also equipped with two auxiliary pillars, which will serve for comparisons of absolute gravimeters, in the frame of the International Gravity Reference System (IGRS). Antokoletz et al. (2020a) presented the gravity reference function for the observatory. This is based on the combination of the observations of the SG038 with the observations of the FG5. By this, a continuous and stable absolute gravity reference function was determined, which will serve for absolute gravimeter comparisons. With these results, AGGO has been established as the only station providing a continuous gravity reference function in South America and the Caribbean, suitable for AG comparisons. The station is now well qualified to become one of the core stations of the International Gravity Reference Frame (IGRF), linked to the International Terrestrial Reference Frame (ITRF) and the International Height Reference Frame (IHRF).

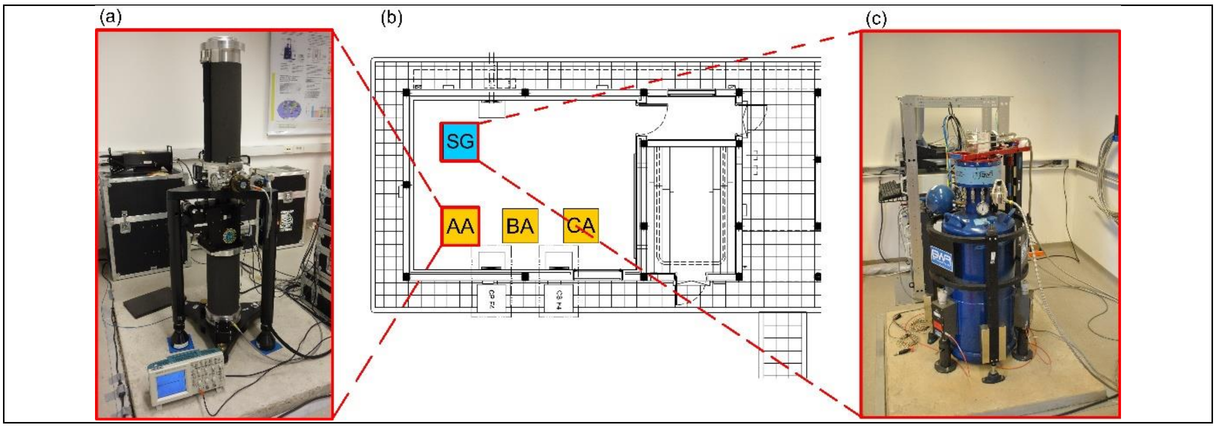


Figure 10 (a) FG5 absolute gravimeter. (b) Floor plan of the gravity laboratory. (c) SG038.

Brazil

In Brazil, the Institute of Geography and Cartography of the State of São Paulo owns a gravity meter A-10 under the responsibility of the University of São Paulo. Figure 11 shows the establishment of absolute stations in Brazil by year.

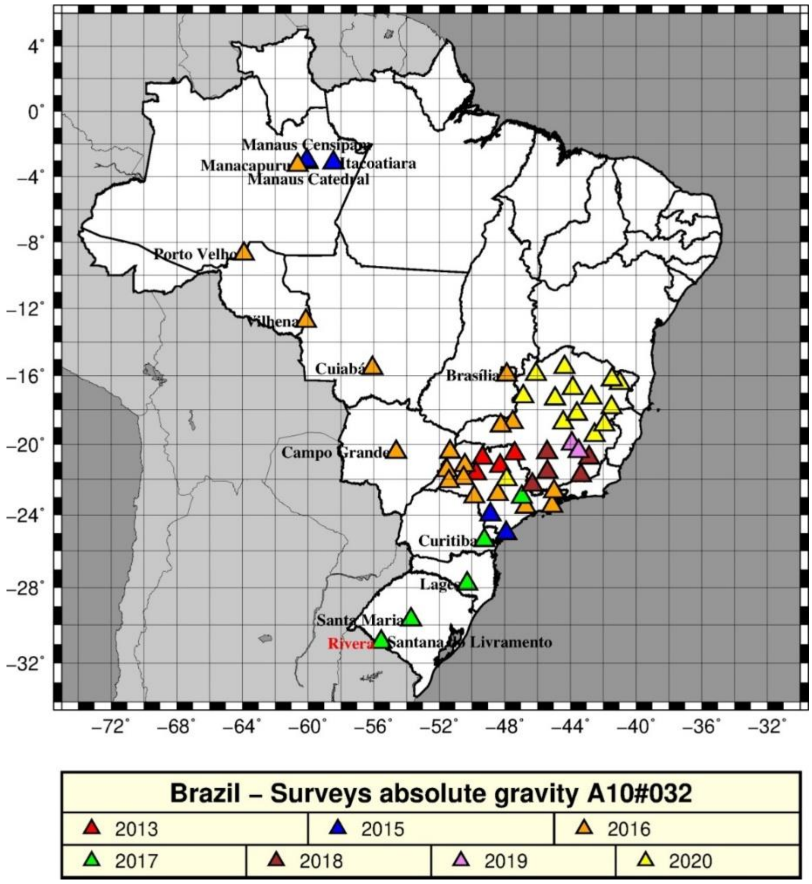


Figure 11 Absolute gravity stations in Brazil.

Figure 12 shows the establishment of absolute stations in Minas Gerais State and twelve new stations that were established between 2019 and 2020. The stations were measured by the Federal University of Uberlândia (UFU) and the University of São Paulo, Polytechnic School, Department of Engineering Transportation (EPUSP-PTR) supported by the Institute of Geography and Cartography (IGC) of São Paulo and Centro de Estudos de Geodesia (CENEGEO).

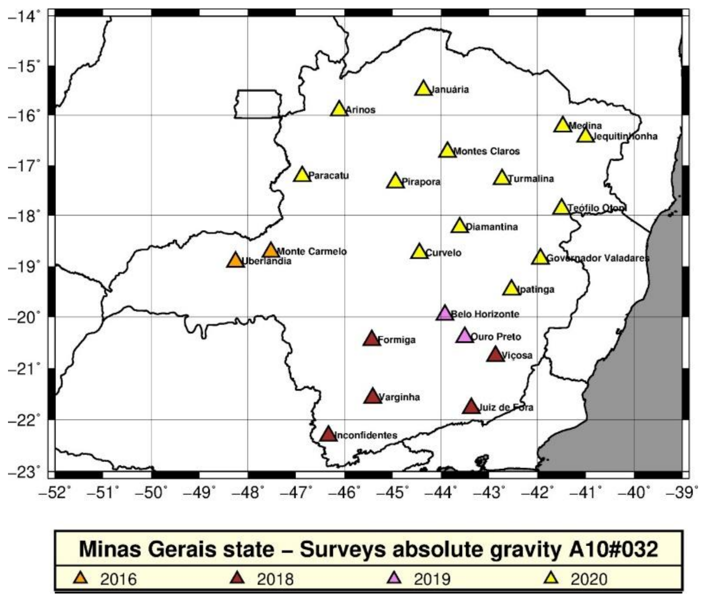


Figure 12 Absolute gravity stations in Minas Gerais State.

Colombia

An absolute gravity reference is planned to be established in Colombia in 2021. A set of 15 stations were materialized (Figure 8, red triangle), and the Colombian Geologic Service and the Bureau Gravimetrique International (BGI) are planning to start the measures at the end of 2021.

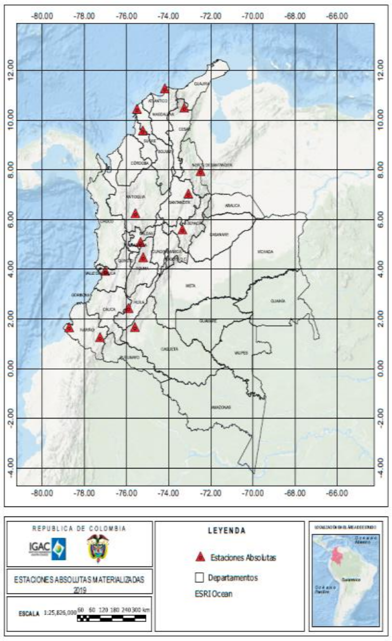


Figure 13 Expected absolute gravity reference in Colombia.

Geoid Models

Four regional/local geoid models (Figure 14) were computed in Brazil in the last two years. The models of the Federal District (Marotta; Almeida; Cherubim, 2019) and Goiás (Castro Junior; Guimarães; Ferreira, 2018) state werecomputed in terms of geoid undulation, while the models of São Paulo and Minas Gerais states, in terms of height anomaly (Silva et al., 2021). The reference field used at the São Paulo model was GOCO05s up to degree 250, while in the computation of Minas Gerais, quasi geoid XGM2019, up to degree 200 was selected..

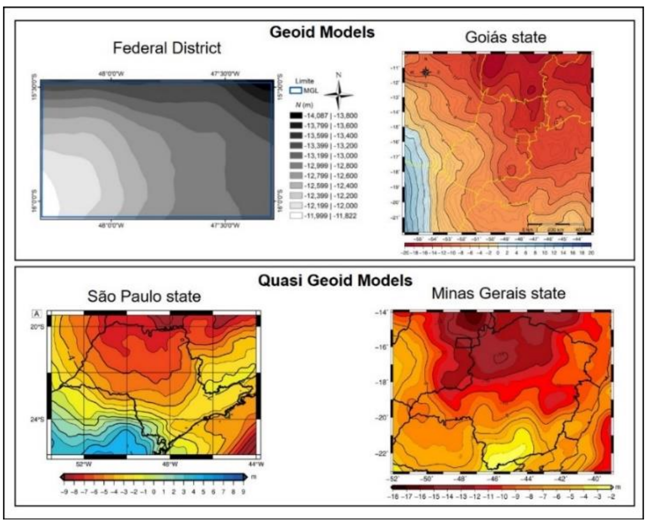


Figure 14 Geoid and quasi geoid models computed in Brazil.

International Height Reference System

In the context of the International Height Reference Frame, 19 stations were selected in Latin America and the Caribbean, of which 17 stations are located in South America (Figure 15). From this total, six stations are in Brazil, five in Argentina, and one station in Chile, Peru, Ecuador, Colombia, Uruguay and French Guiana.

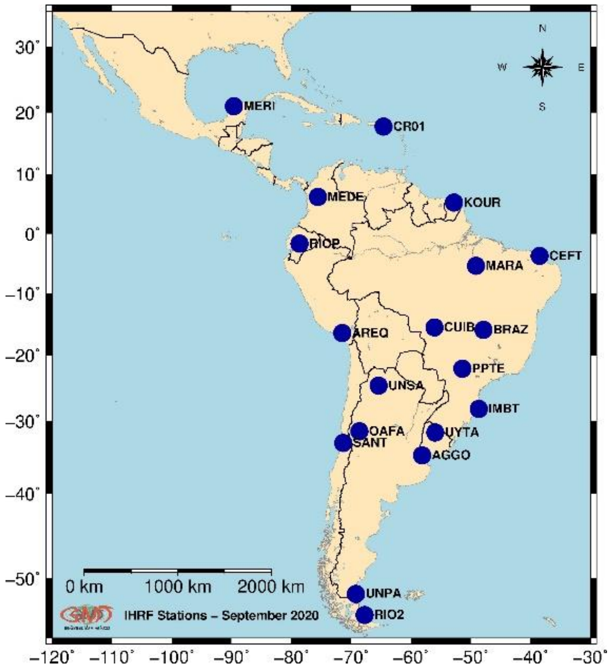


Figure 15 Distribution of IHRF in Latin America.

An analysis of the IHRF stations has been accomplished from the calculation of the potential values using the global gravity models (comparison with the XGM2019 model) (Figure 11). This diagnosis is important to consider in which station(s) the efforts should be concentrated in terms of studies and improvements of the gravimetric distribution.

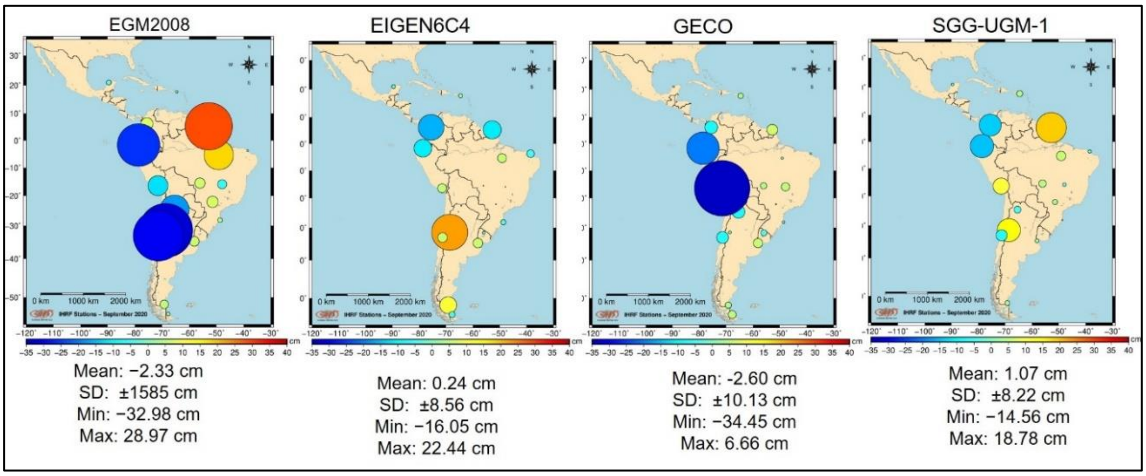


Figure 16 Geopotential values difference between XGM2019 and recent models.

Argentina

Argentina has proposed 5 stations to contribute to the realization of the International Height Reference Stations (IHRS). These stations are from north to south: UNSA, OAFA, AGGO, UNPA and RIO2. Figure 17 shows the location of the stations together with the topography. All of them are GNSS stations. OAFA is in the Observatorio Astronómico Felix Aguilar where a GNSS, a DORIS and a SLR station are co-located. AGGO is a fundamental geodetic observatory located close to the city of La Plata. All main geodetic techniques are co-located, together with a gravity laboratory where a superconducting gravimeter and a FG5 absolute gravity meter are operated. AGGO is also well prepared to belong to the International Gravity Reference Frame (IGRF). RIO2 is located in Rio Grande on the on the province of Tierra del Fuego, Antártida e Islas del Atlántico Sur, Argentina. A DORIS station is co-located.

All GNSS stations contribute to the continuously operating reference network of the Geodetic Reference System for the Americas (SIRGAS-CON) and are also included in the Argentine Continuous Satellite Monitoring Network (RAMSAC). Besides UNSA, AGGO and RIO2 belong to the global network of the International GNSS Service (IGS).

Tocho et al. (2020) presented a preliminary computation of geopotential values based on the current official geoid model from Argentina, GEOIDE-Ar16. Currently, the first realization of the IHRS is in preparation by the IHRF working group, where these stations are included.

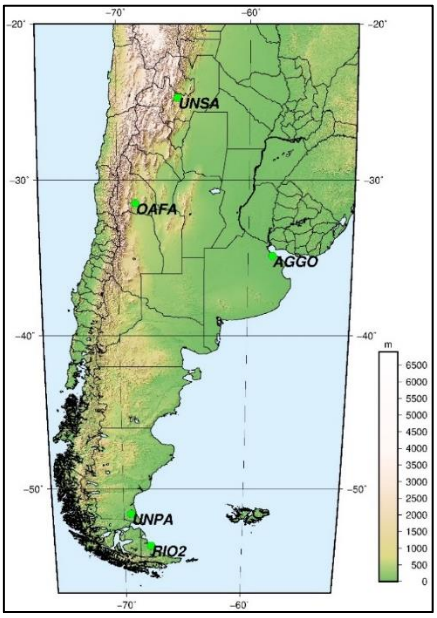


Figure 17 Distribution of selected IHRF stations in Argentina.

Brazil

In order to implement the International Height Reference Frame in Brazil, the Instituto Brasileiro de Geografia e Estatística (IBGE) selected 6 stations from the Rede Brasileira de Monitoramento Contínuo do Sistema GNSS (RBMC), distributed in the national territory, in the cities of Brasilia (BRAZ); Fortaleza (CEFT); Cuiabá (CUIB); Imbituba (IMBT); Marabá (MABA) and Presidente Prudente (PPTE). Station IMBI is the local vertical reference in Brazil, while a VLBI is co-located in station CEFT. BRAZ is in Brasília city and is co-located with SLR and an absolute gravity station. MARA and CUIB stations are in the entering of the Amazon region. Recently in CUIB, BRAZ and PPTE absolute gravity observations have been undertaken with an A-10/032 gravity meter; similar measurements should be obtained soon in the remaining stations. The actual gravity data distribution around a 210 km (~2°) radius is shown in Figure 18. To reach IHRF requirements, terrestrial gravity densification around IHRF stations has been carried out since 2017 by IBGE. Another future issue is to connect IHRF stations to the leveling network.

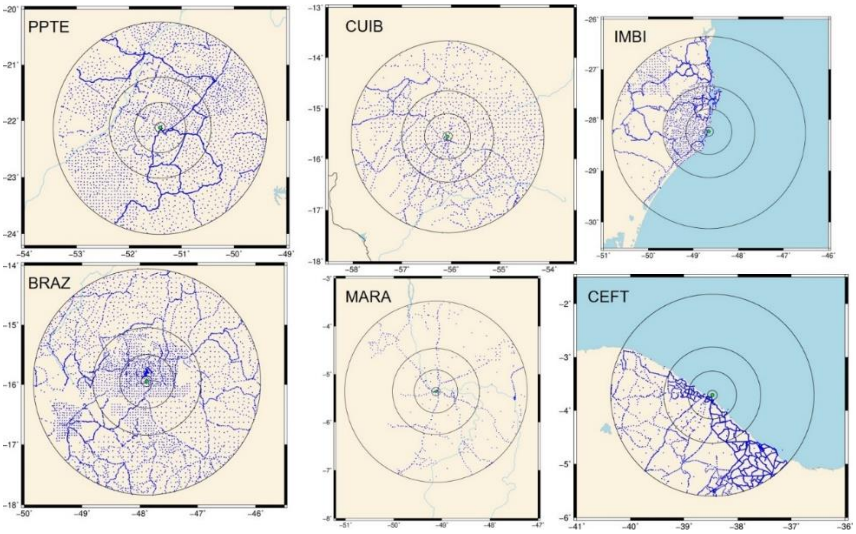


Figure 18 Gravity distribution available at IBGE and BNDG dataset at IHRF station in Brazil.

Guimarães et al. (2019) presented a preliminary potential values computation using Least Squares Collocation and Numerical Integration. The geopotential model GOCO05s (n=m=200 and 100) was adopted as a reference gravitational field.

In the state of São Paulo, besides the station in Presidente Prudente (PPTE), three other IHRF stations are being established by EPUSP and CENEGEO: São José do Rio Preto (SJRP), São Carlos (EESC) and Botucatu (SPBO). Absolute gravimetric measurements and relative gravimetric densification were finalized.

Ecuador

Ecuador has proposed the RIOP station to belong to the realization of the IHRS. In the last two years, IGM has collected around 500 gravity points, which were added to the 2,889 points collected earlier (Figure 19). Besides that, Ecuador has worked at the restructuring of the fundamental leveling network. In 2019, around 400 km of precise leveling was carried out, and in 2020 more than 1,000 km.

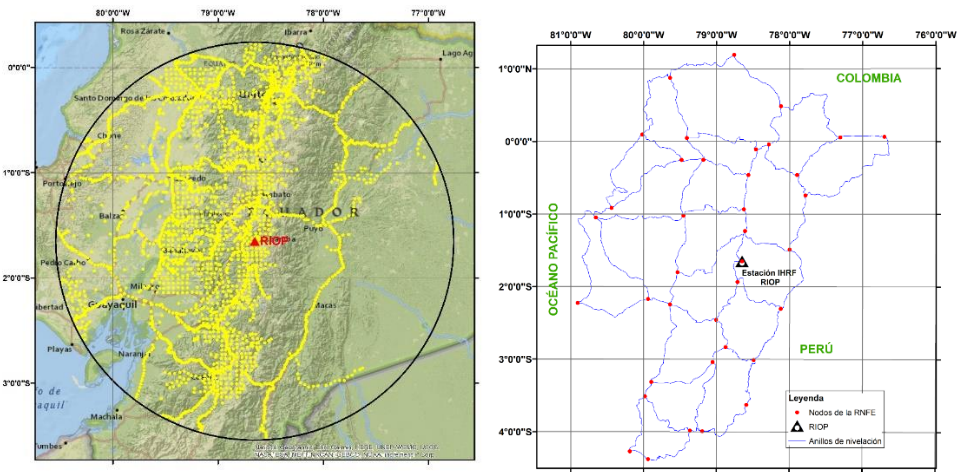


Figure 19 Gravity distribution around RIOP station (at left) and Ecuadorian leveling network (at right).

Earth tide model

In A new Earth tides model was developed based on three years of continuous observations of the superconducting gravimeter SG038 located at the Argentinean-German Geodetic Observatory (AGGO). This model includes 55 tidal parameters determined from a tidal analysis made with the last version of the ETERNA ETA34-X software (http://ggp.bkg.bund.de/eterna/). Moreover, the impact of different ocean tide models on the parameters has been analyzed in order to separate the effects of Earth tides and ocean tide loading. Results are published in Antokoletz et al. (2020b).

Brazil

The University of São Paulo, supported by a few organizations, is involved in a project for the Earth Tides model for Brazil. The idea is to occupy a sequence of 13 stations around the country for one year in each station (Figure 20). The cities planned for occupation are: Cananeia, Valinhos, São Paulo, Presidente Prudente, Porto Velho, Manaus, Brasilia, already observed; the cities in regions northeast (Fortaleza and Salvador), midwest (Cuiabá and Campo Grande) and south (Curitiba and Santa Maria) to be observed in the future. For this purpose, two g-Phone gravity meters are available.

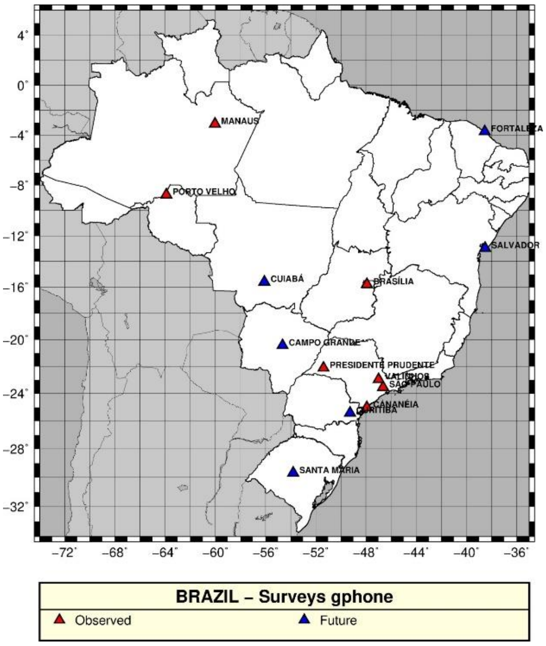


Figure 20 Distribution of g-phone stations.

SIRGAS Webinar "The new International Gravity Reference System (IGRS) and its realization (IGRF)"

On March 5th, 2021, the SIRGAS Webinar "The new International Gravity Reference System (IGRS) and its realization (IGRF)" was organized by the Working Group III of SIRGAS, together with the support of the Federal Agency for Cartography and Geodesy (BKG), Germany. The Webinar took place online and about 150 people assisted from different countries belonging to SIRGAS.

Regional School "New geodetic techniques for Latin America and the Caribbean"

From 5th to 10th of April, 2021, the Regional School "New geodetic techniques for Latin America and the Caribbean" took place at the National University of La Plata, Argentina, and gathered online. The School was focused on the different geodetic techniques operated at the Argentinean-German Geodetic Observatory (AGGO). In particular, two days were dedicated to introducing the concepts of the International Height Reference System (IHRS) and Frame (IHRF), the International Gravity Reference System (IGRS) and Frame (IGRF), and to the gravity techniques operated at AGGO. The School had 126 participants from 17 countries from Latin America and the Caribbean.

References

Antokoletz, E.D., Wziontek, H., Tocho, C.N. & Falk, R. (2020a). Gravity reference at the Argentinean–German Geodetic Observatory (AGGO) by co-location of superconducting and absolute gravity measurements. Journal of Geodesy 94, 81. https://doi.org/10.1007/s00190-020-01402-7

Antokoletz E.D., Tocho C., & Wziontek H. (2020b). Un modelo de mareas para el Observatorio Argentino-Alemán de Geodesia (AGGO) utilizando observaciones del gravímetro superconductor SG038. Revista Cartográfica, (101), 71-97. https://doi.org/10.35424/rcarto.i101.689

Júnior, C. A. C. C.; Guimarães, G. N.; Ferreira, N. C. (2018) The Geoid Model of Goiás - MODGEO-GO. ANUÁRIO DO INSTITUTO DE GEOCIÊNCIAS (UFRJ. IMPRESSO), v. 41, p. 460-469.

Marotta, G.; Almeida, Y.; Chuerubim, M. L. (2019) Análise da Influência do Valor de Densidade na Estimativa do Modelo Geoidal Local para o Distrito Federal, Brasil. Revista Brasileira de Cartografia, v. 71, n. 4, p. 1089-1113, 13 dez.

Silva, V., Guimarães, G., Blitkow, D., and Matos, A. C. (2021). New geoid models computation in the Southeast part of Brazil, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-3284, https://doi.org/10.5194/egusphere-egu21-3284.

Tocho, C. N., Antokoletz, E. D., Piñón, D. A. (2020) Towards the Realization of the International Height Reference Frame (IHRF) in Argentina. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2020_93

Sub-commission 2.4c: Gravity and Geoid in North and Central America

Chair: *Xiaopeng Li (U.S.A.)*
Vice Chair: *David Avalos (Mexico)*

Overview

During the period 2019 – 2020, the activities in North and Central America are mostly driven by the national geodetic agencies, with relevant contributions from the academia. The scientists in this region continue to develop some interesting advancements in the gravity field and geoid modeling at national and regional scale with promising results. Remarkably, the international collaboration has been promoted with a clear goal to construct a regional geoid model that can be used by a number of countries in the near future.

The sections below show some of the major activities that the sub-commission is working on from 2019 to 2021. The list is not necessarily exhaustive.

International collaboration.

The geodetic agencies from Canada, USA and Mexico maintain a close communication by meeting on a regular basis, where geoid specialists share and discuss the scope of geoid modeling processes. By the end of 2020, this collaboration yields the consolidation of data exchange, unification of fundamental computation parameters and the release of experimental models for geoid and gravity field, which have been compared to learn their characteristics in depth. Great achievements in synchronization have been reached, specially between Canada and the USA.

Particularly the geoid team at US National Geodetic Survey (NGS) promotes the integration of all new results into a combined product. They have produced an experimental combination of Canada and US geoid models with promising results. This effort leads the way forward in the region.

Another collaborative effort is carried out between the geodetic agencies of Jamaica and Mexico. In order to support the future development of geodetic vertical control in Jamaica, the National Land Administration is receiving support from Mexico’s INEGI to learn about the modern and practical aspects of geodetic control in general.

North American-Pacific Geopotential Datum

The largest project for modernization of the vertical datum in the region is the US National Spatial Reference System (NSRS) under the leadership of NGS. This modernisation includes not only the update of the NAVD 88 height reference system to a geoid-based height reference system (to be called NAPGD2022), but also the replacement of the NAD 83 (NSRS) geometric reference frame by a North American plate-fixed geocentric frame aligned with an IGS solution (to be called NATRF2022). Naturally, this project contributes to the vertical component of the modernisation. (https://www.ngs.noaa.gov/datums/newdatums/)

Under this project, the NGS continues to release an experimental geoid (xGEOID) model every year. On 2020 the models produced contain the gravity data from the latest satellite gravity models, the terrestrial gravity and most importantly, the airborne gravity from the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project.

The main product released on 2020 was the development of the experimental geoid model

XGEOID20 for NAPGD2022. It is the first North American geoid model built with the external collaboration from INEGI and CGS. The consolidated models from independent geoid solutions were based on a common dataset organized by the three agencies (terrestrial gravity data, GRAV-D airborne gravity data, satellite altimetry-derived gravity data (DTU15), and a merged/corrected DEM from different models available). The independent models used the same underlay global Earth Gravity Models (EGMs) developed at NGS. The independent solutions from NGS and CGS show good agreement, in fact it is the best agreement ever between models developed at NGS and CGS. However, the discrepancies in some regions are still larger than expected for a unified geoid model. The three agencies are in the process of writing the technical report on the experimental model XGEOID20. More work is in progress to improve the national and continental solutions. In the meantime, CGS started a study of data requirement for determining temporal change of CGVD2013, and presented a poster at the AGU100 meeting in San Francisco.

During the course of the development of XGEOID20, NGS and CGS worked on different methods and procedures for downward continuation. A paper is in preparation. The gravity disturbance grids have been produced from 63 GRAV-D blocks at the mean flight level and on the reference ellipsoid. In addition, the two agencies worked on the transformation between geoid and quasi-geoid models by enhancing the topographical correction, i.e., taking care of the terrain roughness. The study also looked into the impact of the topographical density and downward continuation. This same procedure was also used to improve the calculation of the orthometric heights at benchmark (levelling) by estimating more precisely the mean gravity along the plumbline.

Then the models from different methods are weighted averaged to a common vertical datum, called xGeoid20. It is the first model of the joint effort of three agencies. For more information, please visit the xGeoid20 website at:

https://beta.ngs.noaa.gov/GEOID/xGEOID20/

The Colorado 1-cm geoid experiment

The Colorado experiment is an effort by the international geodetic community coordinated by IAG to examine (quasi)geoid disagreements caused by computation methods and software used by different groups. This study was coordinated within IAG, in particular, the IAG Sub-commission 2.2: Methodology for geoid and physical height systems (Ågren and Ellmann, 2019); the joint working group 2.2.2: The 1-cm geoid experiment in Colorado (Wang and Forsberg, 2019); the study group 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimeter accuracy of the IAG Inter-Commission Committee on Theory – ICCT (Huang and Wang, 2019), and the working group 0.1.2: Strategy for the realization of the IHRS of the Focus Area Unified Height System of the Global Geodetic Observing System - GGOS (Sánchez, 2019; Sánchez and Barzaghi, 2020). The data sets used in this experiment were provided by the U. S. National Geodetic Survey.
More than a dozen geoid modeling groups in the world participated this study where a variety of modeling approaches have been tested. The technical details and results of each successful methods can be found in a special issue, named reference systems in physical geodesy, in the Journal of Geodesy.

New INEGI geoid model for Mexico

By the end of 2020 INEGI produced an experimental geoid model for Mexico, based on an improved algorithm to calculate the contribution to geoidal height from satellite-only geopotential models. This result was compared to the combined geoid model of NGS/CGS 2020 and it presents a good general agreement in the US territory, with some large differences over specific areas. This exercise has lead to new ideas about the main error sources of the geoid in Mexico, which are being explored currently to produce a new model in 2021 where the main goal is to diminish the differences with the solutions from Canada and the US while using an independent methodology.

CGS produces a new terrain correction for North America

CGS calculated a 30” x 30” grid of mean terrain corrections for North America using a 3” x 3” DEM. It makes use of the same DEM imbedded in the development of XGEOID20. This grids can contribute in the development of and the transformation between free-air, Bouguer, and refined Bouguer gravity grids. A new CGS experimental geoid model is also computed based on this new TC model.

CGS evaluated recent EGMs

CGS analysed recent EGMs that are augmented global topographic potential models such as GFZ’s ROLI and Earth2014 against independent validation datasets (e.g., GPS on BMs). These EGMs were also used to develop experimental regional models for North America.

CGS analyzed new gravity data

CGS completed the validation of some 200,000 gravity points in Canada that we received from the U.S. National Geospatial-intelligence agency. This represents the largest increase in terrestrial gravity data in Canada in many years.

International Great Lakes Datum

CGS and NGS are working together with the U.S. and Canadian hydrographic services on the update of the International Great Lakes Datum (IGLD). This datum will rest on NAPGD2022, but the type of heights will be dynamic (opposed to orthometric) for proper management of water resources. Current activities include evaluation of geoid models at water gauges to demonstrate that each lake surface represents or is close to an equipotential surface.

vEGU21 session G1.5

The subcommittee SC2.4c is working together with SC2.4d and SC2.2 as well as IGFS for organizing and convening a local geoid session in vEGU21. Researchers from all over the world gathered together virtually in the G1.5 session, Local/Regional Geoid determination: Methods and Models on April 29th 2021. A total of 14 presentations were given in variety of issues related to local geoid quasi geoid computation. An extended break room discussions were kindly provided by vEGU to this session for some in-depth discussions.

Downward Continuation of Airborne Gravity Data

The working group SG2.4.1 is holding semi-yearly virtual meetings after its establishments. Extended discussions and computational tests have been carried to demonstrate the ill-posedness of the downward continuation problem and its stabilization. A paper is in its final step to submit to the journal as a recommendation of downward continuation airborne gravity data.

References

Ågren J and Ellmann A (2019) Report of the Sub-commission 2.2: Methodology for Geoid and Physical Height Systems, Reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG Vol. 41, Commission 2, pages 33-38.

Huang J and Wang YM (2019) Report of Joint Study Group 0.15: Regional geoid/quasigeoid modelling – theoretical framework for the sub-centimetre, Reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG Vol. 41, Inter-Commission Committee in Theory, pages 40-45.

Sánchez L, Barzaghi R (2020) Activities and plans of the GGOS Focus Area Unified Height System, EGU General Assembly 2020, EGU2020-8625, https://doi.org/10.5194/egusphere-egu2020-8625.

Sánchez L (2019) Report of the GGOS Focus Area "Unified Height System" and the Joint Working Group 0.1.2: Strategy for the Realization of the International Height Reference System (IHRS), Reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG Vol. 41, Global Geodetic Observing System (GGOS), pages 42-51.

Wang YM and Forsberg R (2019) Report of the Joint Working Group 2.2.2: The 1 cm geoid experiment, Reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG Vol. 41, Commission 2, pages 56-58.

Wang, Y.M., Li, X., Ahlgren, K. et al. Colorado geoid modeling at the US National Geodetic Survey. J Geod 94, 106 (2020). https://doi.org/10.1007/s00190-020-01429-w

Sub-commission 2.4d: Gravity and Geoid in Africa

Chair: Hussein Abd-Elmotaal (Egypt)
Vice-Chair: S.A. Benahmed Daho (Algeria)

Main activities (2019–2021)

Effect of Land Depression on Gravity and Geoid

Abd-Elmotaal and Kühtreiber (2020) have studied the effect of Qatara depression, Egypt, on the gravity anomalies and geoid. This effect is significant and extends over a large rejoin. The effect of Qattara Depression on the gravity anomalies reaches 20 mGal and is located only at the area of the depression. The effect of Qattara depression on the geoid exceeds 1 m and is not only limited to the area of the depression but rather spreads out all over the whole country (in a radius of about 1000 km). This shows its significance and importance to be taken into account for a precise geoid determination.

Effect of Great Lakes on Gravity and Geoid

Abd-Elmotaal et al. (2020a) have studied the effect of Victoria Lake on the gravity anomalies and the geoid. The study utilized two different techniques to determine the effect of the lake. The results proved that both developed approaches are capable to determine the effect of Lake Victoria on gravity anomaly and geoid undulation. Both approaches give practically the same results in all cases. The total topographic-isostatic effect of Lake Victoria on the gravity anomaly reaches about 4 mGal and is confined mainly to the area of the lake. The total effect of Lake Victoria on the geoid undulation has an isotropic behaviour attaining its maximum value at the lake, with a value of about 28 cm, and decreases with radial distance outwards. It practically vanishes outside a radial distance from the lake of more than 3o. Accordingly, the effect of Lake Victoria on the geoid is rather significant and should then be considered for precise geoid determination.

New AFRGDB_V2.2 Gravity Database for Africa

Abd-Elmotaal et al. (2020b) have established a new gravity database for Africa (AFRGDB_V2.2). The AFRGDB_V2.2 African gravity database has been established using a combination of real data on land and sea and an underlying grid filling the large data gaps. This underlying grid, used to fill-in the data gaps before the interpolation process, has been created using the GOCE Dir_R5 model up to degree and order 280. A 3′ grid filtering has been applied to the sea data to decrease their dominance on the solution. A 1′ grid filtering has been applied to the land data to improve the behaviour of the empirically determined covariance function, especially near the origin. The RTM remove-restore technique has been used with the GOCE Dir_R5 model, up to degree and order 280, representing the global model. An unequal weight least-squares prediction technique has been carried out to interpolate the reduced anomalies on a 5′ grid. The established AFRGDB_V2.2 gravity database for Africa has an internal precision of about 5.5 mGal.

The validation of the AFRGDB_V2.2 gravity database shows a similar quality as the previous AFRGDB_V2.0gravity database, measured with an external accuracy of about 7 mGal. This already indicates that establishing the gravity database for Africa has become robust to some extent.

The computation efforts and CPU-time needed for the AFRGDB_V2.2 gravity database are much less compared to those of the previous database (AFRGDB_V2.0).

Regional Geoid Determination for Africa

Abd-Elmotaal et al. (2020c) have computed a precise model for the regional geoid for the whole continent of Africa (cf. Fig. 1). This geoid model has utilized the AFRGDB_V2.1 gravity database of Africa.

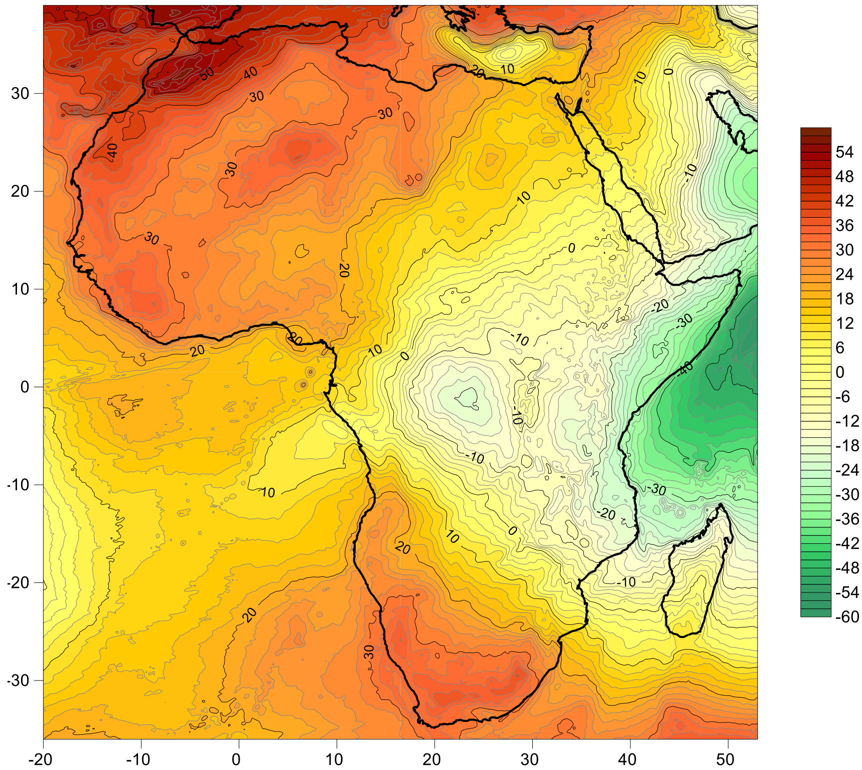


Figure 21 The African geoid model AFRgeo2019 (after Abd-Elmotaal et al., 2020c).

Important Complementary Studies in Africa

Odera (2019) has accomplished an assessment study of the latest GOCE-based global gravity field models using height and free-air gravity anomalies over South Africa. Odera (2020) has evaluated the recent high-degree combined global gravity-field models for geoid modelling over Kenya, Africa. Ashry et al. (2021) have computed a geoid model for Africa employing the shallow layer method. This geoid model has been compared with the recent AFRgeo2019 geoid model. Compatabilities benween the two geoid models were concluded. Abd-Elmotaal and Kühtreiber (2021) have done a remarkable development within the used expressions for the window remove-restore technique, which will definitely contribute in a better geoid modeling for Africa.

Future Activities

A study of the optimum DTM resolution to be used within the window remove-restore technique for geoid determination in African is undertaken meanwhile and is going to be presented in the IAG Scientific Assebmly, Beijing, June 28 – July 4, 2021, by Abd-Elmotaal and Kühtreiber. Odera is currently supervising 4 PhD students carrying out research related to geoid modelling and height systems in various countries in Africa (South Africa, Kenya, Zimbabwe, and Nigeria).

Problems and Request

The IAG sub-commission on the gravity and geoid in Africa suffers from the lack of data (gravity, GNSS/levelling …). The great support of IAG is needed in collecting the required data sets. It can hardly be all done on a private basis. Physical meetings of the members of the sub-commission would help in solving the problems and would definitely contribute to the quality of its outputs. IAG is thus kindly invited to support that action.

Publications

Abd-Elmotaal, H. and Kühtreiber, N. (2020) Effect of Qattara Depression on Gravity and Geoid Employing Unclassified Digital Terrain Models. Studia Geophysica et Geodaetica, Vol. 64, 186–201, DOI: 10.1007/s11200-018-1240-x.

Abd-Elmotaal, H., Seitz, K., Ashry, M. and Heck, B. (2020a) Effect of Great Lakes on Gravity Reduction and Geoid Determination Caused by Unclassified DTMs: Case Study for Lake Victoria, Africa. Journal of Geodesy, Vol. 94, DOI: 10.1007/s00190-020-01410-7.

Abd-Elmotaal, H., Kühtreiber, N., Seitz, K. and Heck, B. (2020b) The New AFRGDB_V2.2 Gravity Database for Africa. Pure and Applied Geophysics, Vol. 177(9), 4365–4375, DOI: 10.1007/s00024-020-02481-5.

Abd-Elmotaal, H., Kühtreiber, N., Seitz, K. and Heck, B. (2020c) A Precise Geoid Model for Africa: AFRgeo2019. International Association of Geodesy Symposia, DOI: 10.1007/1345_2020_122.

Abd-Elmotaal, H. and Kühtreiber, N. (2021) Direct Harmonic Analysis for the Ellipsoidal Topographic Potential with Global and Local Validation. Surveys in Geophysics, Vol. 42, 159–176, DOI: 10.1007/s10712-020-09614-4.

Ashry, M., Shen, W. and Abd-Elmotaal, H. (2021) An alternative geoid model for Africa using the shallow-layer method. Studia Geophysica et Geodaetica, Vol. 65, 148–167, DOI: 10.1007/s11200-020-0301-0.

Odera, P.A. (2019) Assessment of the latest GOCE-based global gravity field models using height and free-air gravity anomalies over South Africa. Arabian Journal of Geosciences, Vol. 12 (5), No. 145, 1–7. https://doi.org/10.1007/s12517-019-4337-9.

Odera, P.A. (2020) Evaluation of the recent high-degree combined global gravity-field models for geoid modelling over Kenya. Geodesy and Cartography, Vol. 46, No. 2, 48–54. https://doi.org/10.3846/gac.2020.10453.

Sub-commission 2.4e: Gravity and Geoid in Asia-Pacific

Chair: Cheinway Hwang (China-Taipei)
Vice Chair: Wenbin Shen (China)

Activities from 2019 to 2021

The First Asia Pacific geoid workshop for IAG-SC2.4e, October 29, 2020

This workshop was held on October 29, 2020 to promote geoid modeling in the Asia-Pacific region.

- This workshop was jointly organized by the IAG SC2.4e members: Cheinway Hwang, Wenbin Shen, Will Featherstone, Koji Matsuo, Ami Hassan Md Din, Chalermchon Satirapod, Kosashi Prijatna, Dinh Toan Vu, Ronaldo Gatchalian, Ropesh Goyal and Matt Amos.
- Workshop web page: http://space.cv.nctu.edu.tw/The-First-Asia-Pacific-geoid-workshop-4e
- The workshop organized 3 geoid lectures (40 to 60 minutes; 2 US speakers and one Australian speaker) and 11 oral presentations by geoid modelers from member countries/regions in the Asia Pacific region.

A special issue in the journal Terrestrial, Atmospheric and Ocean Sciences (TAO)

TAO is a SCI-indexed journal. The title of this special issue is: Gravity and geoid in the Asia Pacific. It invites submissions that show recent gravity data processing and geoid modeling works in the Asia Pacific region (http://tao.cgu.org.tw/index.php/call-for-papers/item/1737). In particular, we welcome papers presented in the first Asia Pacific geoid workshop (October 29, 20202; http://space.cv.nctu.edu.tw/The-First-Asia-Pacific-geoid-workshop-4e). This special issue welcomes papers that (1) show numerical methods for geoid modelin and the societal impact of a high-quality geoid model, (2) use latest global gravity models as reference fields in the remove-compute-restore procedure, (3) model the terrain effects on geoid, (4) use transnational gravity data for geoidal modeling and accuracy improvement, (5) report results of regional airborne and shipborne gravity surveys, (6) show the benefit of high-resolution, high-accuracy altimeter-derived gravity to geoid modeling, (7) use GNSS, deflection and leveling data to assess geoidal accuracy, and (8) reports potential use of new gravity data for geophysical studies, particularly in plate tectonics, volcanism, and seismology.

Guest editors: Cheinway Hwang, Wenbin Shen, Xiaopeng Li and Ami Hassan Md Din. We expect to have 10 accepted papers in this issue.

Sub-commission 2.4f: Gravity and Geoid in Antarctica

Chair: *Mirko Scheinert (Germany)*
Vice-Chair: *Fausto Ferraccioli (U.K.)*

Overview

The Sub-Commission is dedicated to the determination of the gravity field in Antarctica. In terms of observations, mainly airborne but also terrestrial campaigns have been and are being carried out to complement and to densify satellite data. Because of the region and its special conditions, the collaboration extends beyond the field of geodesy – the cooperation is truly multi-disciplinary, especially incorporating experts from the fields of geophysics and glaciology. This is also reflected in the group membership (cf. below).
During the last period (2019 – 2021) new ground-based or airborne gravity data could not be incorporated into the AntGG database. Due to the pandemic crisis the vast majority of research activities in Antarctica had to be cancelled especially for the season 2020/2021.
In terms of the re-processing of all available terrestrial gravity data incorporating new data available since the publication of the first gravity anomaly grid (Scheinert et al. 2016) considerable progress could be made. Within a project funded by the German Research Foundation (DFG), led by Roland Pail (Munich, Germany) and Mirko Scheinert (Dresden, Germany), several aspects of the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic model were successfully investigated and published (Zingerle et al. 2019, 2021). Preliminary results were presented at the EGU 2021 virtual conference (Scheinert et al. 2021). It is intended to refine the grid spacing from 10 to 5 km as well as to enlarge the number of products to be provided with this updated AntGG solution w.r.t. the data published by Scheinert et al. (2016). Fig. 22 exemplarily shows the preliminary results in terms of gravity disturbances and height anomalies.

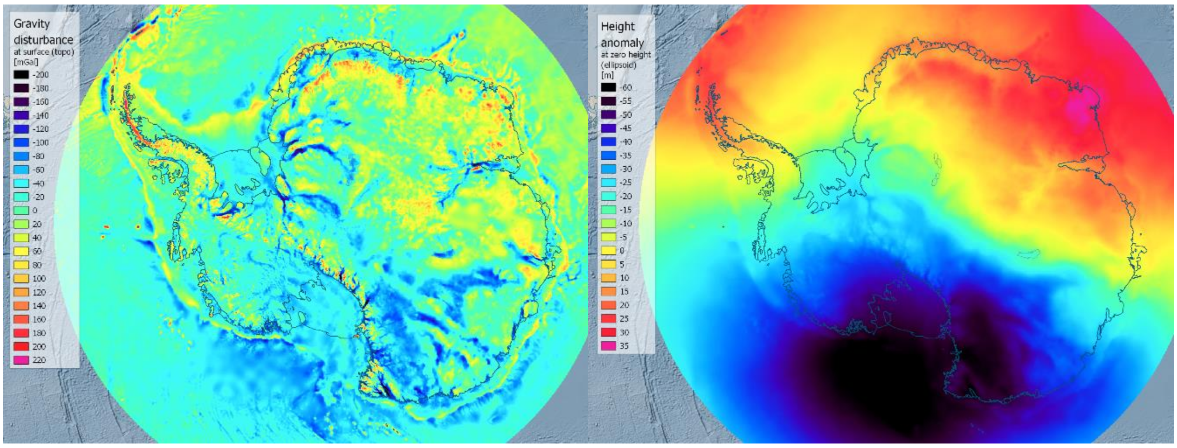


Figure 22 Preliminary results of the new processing of the regional gravity field in Antarctica. Left: Gravity disturbance; right: height anomaly, as presented at vEGU 2021 (Scheinert et al. 2021).

Linkage

A close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR) and its numerous groups and activities. The SCAR Expert Group on "Geodetic Infrastructure in Antarctica" (GIANT) serves as a counterpart of IAG SC 2.4f. M. Scheinert co-chairs GIANT as well as chairs the GIANT project "Gravity Field". Furthermore, several group members are involved in the initiation and set-up of the new SCAR Scientific Research Program "Instabilities and Thresholds in Antarctica" (INSTANT). Within INSTANT regional gravity field information in Antarctica serves a number of questions to be investigated (e.g. paleo modelling, tectonic and geological interpretation, inversion for bathymetry and subglacial topography).

Future plans and activities

Future activities are well defined following the "Terms of Reference". Since any Antarctic activity call for a long-term preparation the main points to be focused on do not change. New surveys will be promoted, nevertheless, due to the huge logistic efforts of Antarctic surveys, coordination is organized well in advance and on a broad international basis. Within AntGG, the discussion on methods and rules of data exchange is in progress and has to be further pursued. Compilations of metadata and databases have to cover certain aspects of gravity surveys in Antarctica (large-scale airborne surveys, ground-based relative gravimetry, absolute gravim-etry at coastal stations). The main goal to deliver a grid of terrestrial gravity data was fulfilled by the publication of a first grid in 2016 (Scheinert et al. 2016). Updates and enhancements are anticipated as reported above.

With regard to new gravity surveys in Antarctica, aerogravimetry provides the most powerful tool to survey larger areas. In this context, airborne gravimetry forms a core observation technique within an ensemble of aerogeophysical instrumentation. Further airborne missions may help not only to fill in the polar data gap in its proper sense, but also all remaining gaps over Antarctica.

Selected conferences with participation of AntGG members / with relevance to AntGG

- IUGG General Assembly, Prague, 23 June – 01 July, 2015.
- XII International Symposium on Antarctic Earth Sciences, Goa, 13-17 July, 2015.
- ESA Living Planet Symposium, Prague, 9-13 May 2016.
- SCAR Open Science Conference, Kuala Lumpur, 22-26 August 2016.
- 1st Joint Commission 2 and IGFS Meeting, Thessaloniki, 19-23 September 2016.
- AGU Fall Meetings (2015, 2016) and EGU General Assemblies (2016, 2017).
- International Workshop "Airborne Geodesy and Geophysics with Focus on Polar Applications", Dresden, 19-21 April 2017.
- IUGG General Assembly, Montreal (Canada), 08–18 July 2019.
- XIII International Symposium on Antarctic Earth Sciences, Goa, 13-17 July, 2015.
- International Symposium on Antarctic Earth Sciences (ISAES) XIII, Incheon (South Korea), 28 July – 02 August 2019
- XXXVI SCAR Meeting and Open Science Conference (online, originally to take place in Hobart, Australia), August 2020
- EGU General Assemblies 2020, 2021 (virtual conferences)
- AGU Fall Meetings 2019, 2020

References

Eisermann, H., G. Eagles, A. Ruppel, E. C. Smith, W. Jokat (2020): Bathymetry Beneath Ice Shelves of Western Dronning Maud Land, East Antarctica, and Implications on Ice Shelf Stability. Geophysical Research Letters, 47(12), e2019GL086724, https://doi.org/10.1029/2019GL086724

MacGregor, J. A. et al. (2021): The scientific legacy of NASA's Operation IceBridge. Reviews of Geophysics. First published 03 May 2021. https://doi.org/10.1029/2020RG000712

Morlighem, M., E. Rignot, T. Binder, D. Blankenship, R. Drews, G. Eagles, O. Eisen, F. Ferrac-cioli, R. Forsberg, P. Fretwell, V. Goel, J. S. Greenbaum, H. Gudmundsson, J. Guo, V. Helm, C. Hofstede, I. Howat, A. Humbert, W. Jokat, N. B. Karlsson, W. S. Lee, K. Matsuoka, R. Millan, J. Mouginot, J. Paden, F. Pattyn, J. Roberts, S. Rosier, A. Ruppel, H. Seroussi, E. C. Smith, D. Steinhage, B. Sun, M. R. van den Broeke, T.

D. van Ommen, M. van Wessem & D. A. Young (2020): Deep glacial troughs and stabilizing ridges unveiled beneath the mar-gins of the Antarctic ice sheet. Nature. Geoscience. 13, 132–137. https://doi.org/10.1038/s41561-019-0510-8

Pappa, F., J. Ebbing, F. Ferraccioli (2019): Moho Depths of Antarctica: Comparison of Seismic, Gravity, and Isostatic Results. Geochemistry,Geophysics, Geosystems, 20(3): 1629-1645. https://doi.org/10.1029/2018GC008111

Scheinert, M., P. Zingerle, T.Schaller, R. Pail, M. Willberg (2021): Towards an updated, en-hanced regional gravity field solution in Antarctica. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-9873, https://doi.org/10.5194/egusphere-egu21-9873

Zingerle, P., R. Pail, M. Scheinert, T. Schaller (2019): Evaluation of terrestrial and airborne gravity data over Antarctica – A generic approach, Journal of Geodetic Science, 9:29-40, doi: 10.1515/jogs-2019-0004

Zingerle, P., R. Pail, M. Willberg, M. Scheinert (2021): A partition-enhanced least-squares collo-cation approach (PE-LSC). Journal of Geodesy (in revision).

Sub-commission 2.5: Satellite Altimetry

Chair: *Xiaoli Deng (Australia)*
Vice Chair: *C.K. Shum (U.S.A.)*

Overview

Over the period of 2019-2021, research activities of the IAG sub-commission 2.5 focused on integrated use of altimetry and space geodetic techniques and their applications in climate change analysis. These include global and coastal sea level changes, monitoring surface water levels over inland water bodies, new applications, development of the retracking algorithm, validation and calibration of altimetry data from both conventional and new satellite altimetry missions. The sub-commission also contributed to establish new study and working groups. The contributions below represent the group work by following members:

Prof Ole Andersen (DTU, Denmark)
Prof Li-Feng Bao (Chinese Academy of Sciences, China)
A/Prof Xiaoli Deng (The University of Newcastle, Australia)
Dr Luciana Fenoglio-Marc (University of Bonn, Germany)
Prof Cheinway Hwang (National Yang Ming Chiao Tung University, Taiwan)
A/Prof Tao-Yong Jin (Wuhan University, China)
Prof Chung-Yen Kuo (National Cheng Kung University, Taiwan)
Prof Jürgen Kusche (University of Bonn, Germany)
A/Prof Hyongki Lee (University of Houston, United States)
Dr Fukai Peng (Sun Yat-Sen University, China)
Prof David Sandwell (Scripps Institution of Oceanography, United States)
Prof C. K. Shum (Ohio State University, United States)
Dr Walter H. F. Smith (NOAA, United States)

Most members have made significant contributions to research and applications of satellite altimetry and been the co-authors of a publication by a large group of International Altimetry Team (2021). The publication provides a comprehensive description of interdisciplinary altimetry enabled science and applications, reporting on ESA's "25 Years of Progress in Radar Altimetry" Symposium, held at Ponta Delgada, São Miguel Island, Azores Archipelago, Portugal, 24-29 September 2018.

Altimetry study and working groups

A Mean Sea Surface (MSS) topography working group led by Prof David Sandwell started in September 2020. The group members include researchers from Scripps Institution of Oceanography, CLS, DTU, NOAA, SIO and NYCU. The regular meetings have been held to discuss several challenging issues of (1) cross-comparisons between MSS models from CLS, DTU and RADS, (2) understanding the large MSS difference between existing models in the Arctic and the Kuroshio and the Gulf Stream, and (3) the use of ICESAT-2 altimetry for the recovery of ocean topography.

The SC2.5 sub-commission has proposed following study groups:

- SC25.1: High-resolution altimetry for geodetic, oceanographic, cryosphere and hydrology studies (HRA), chaired by Dr Luciana Fenoglio-Marc and Prof Ole Baltazar Andersen.

The mapping of the surface water elevation (SWE) at high resolution in space and time has been a goal of the ocean and the hydrology scientific communities. Global observations of high spatial and temporal resolution are required to understand the climate-related oceanic and hydrologic dynamics, which involve small-scale processes and their interaction with larger-scale dynamics. However, spatial scales smaller than 150 km still cannot be globally observed, even with different satellite constellations. The Surface Water and Ocean Topography Mission (SWOT), to be launched in 2022, will give a unique contribution by providing observational evidence of unobserved wavelengths closing the observational gap between 100 and 15 km wavelength. As such, HRA is to investigate the developments allowed by high-resolution altimetry in 1D and 2D fields, to provide a forum for discussion and to encourage innovative interdisciplinary scientific research and applications.

- SC25.2: Synergistic applications of satellite altimetry with other satellite sensors/physical models, chaired by A/Prof Hyongki Lee.

  Satellite altimetry is a mature geodetic technique successfully providing surface elevation changes over, not only ocean, but also inland water bodies, ice-sheets/glaciers and topographic lands, with advances in waveform retracking and new technologies such as Synthetic Aperture Radar (SAR) and SAR-interferometric (SARIn) modes altimeters. In particular, satellite altimetry has been also used to augment existing monitoring network or to derive new estimates with data from other satellite sensors or a physical model, especially over terrestrial surfaces. Therefore, this is to promote innovative usage of altimetry data synergistically integrated with data obtained from other satellite sensors (e.g., optical/SAR imaging sensors, GRACE/GRACE-FO, CYGNSS, etc.) and physical models in order to advance scientific studies and real world applications.

- SC25.3: International Altimeter Service (IAS), chaired by Prof C.K. Shum and A/Prof Xiaoli Deng.

  IAS is to pool together international resources in satellite altimetry. It aims to provide a forum for broad scientific consensus on intricate altimetry low to high level data processing algorithms, to complement existing altimetry data processing entities, to provide a mission- and agency-independent forum for potentially improved altimetry data processing and data product access, to encourage innovative, new and interdisciplinary scientific research and applications of satellite altimetry. The IAS proposed development was presented by C.K. Shum, Xiaoli Deng, and Remko Scharroo, during the IUGG Symposia, Palais des Congrès in Montréal, Québec, Canada, July 9, 2019; and discussed in the First Meeting of the IAG Executive Committee, 2019–2023, on July 18, 2019. The IAS development plan was also presented at the Second Meeting of the IAG Executive Committee, 2019–2023, by C.K. Shum, Xiaoli Deng, and Remko Scharroo, during the American Geophysical Union Meeting on December 7, 2019. The planned activities are to be accomplished during the next two years.

Mean sea surface topography and marine gravity field

Prof Sandwell’s team has assessed the ability of ICESat-2 (the Ice, Cloud and land Elevation Satellite 2) photon height data to recover oceanographic signals ranging from surface gravity waves to the marine geoid using data over a tropical Pacific box in both wavenumber and space domains (Yu et al., 2021). Data were analysed in three bands: long wavelengths (20–500 km), intermediate wavelengths (3–20 km) and short wavelengths (15 m–3 km). Results show that an ICESat-2 single track can recover the marine geoid at wavelengths >20 km which is similar to the best radar altimeter data. The wavelength and propagation direction of surface gravity waves are sometimes well resolved by using a combination of the strong and weak beams, which are separated by 90 m. Higher than expected power was found in the 3–20 km wavelength band where geoid and ocean signals should be small. This artificial power is caused by the projection of 2D surface waves with ∼300 m wavelengths into longer wavelengths (5–10 km) because of the 1D sampling along the narrow ICESat-2 profile. Thus, ICESat-2 will not provide major improvements to the geoid recovery in most of the ocean.

In conclusion, ICESat-2 is a highly capable instrument with the potential to yield new information about along-track surface waves over distances of 10 km or less. It will not provide major improvements for the geoid in the open ocean, where many years of radar altimeter observations are providing increasingly accurate global marine gravity maps approaching 12 km wavelength resolution. However, ICESat-2 data may be valuable in regions where surface gravity waves have low amplitude, and the broad radar altimeter waveforms are corrupted by land reflections in a 5 km radius.

The NYCU team led by Prof Cheinway Hwang has used altimeter data from multiple satellite missions to determine gravity anomalies in the South China Sea (Zhu et al., 2021), and has investigated the optimal method for gravity derivation from simulated sea surface heights of future SWOT mission (Yu et al, 2021).

New applications of altimetry

Altimeter gravity detection of undersea volcano eruptions

For the first time, altimeter-derived marine gravity field variations with high spatial resolution and accuracy were used to study the Nishinoshima volcanic activity. Prof Bao's team has computed three different periods with detrended Bouguer gravity anomalies, corresponding to before, during and after the volcanic eruption, and used a method called DEXP to interpret the magma distributions and motions beneath the Nishinoshima volcano (Li et al., 2021). The method is applied to yields fast 3D image of the source distribution at depth, and is characterized by high stability and resolution, thanks to the regular behavior of potential fields versus the altitude. During the observation period, the depths to the top of magmas of Nishinoshima were estimated to become shallower and less than 2 km which accords with the seismic results (Okada et al. 2016; Takagi and Nagaoka 2017). In addition, the results showed that the magma chambers reduced underlying Nishinoshima and in the western Nishinoshima while they decreased and then increased in the eastern, especially northeastern Nishinoshima. These implied that the magma motions are complicated with both vertical movements and magma transports during the volcanic eruption, and the magma chamber beneath Nishinoshima appears to be fed by the deeper magma storage system, mainly in eastern and northeastern Nishinoshima resulting from the westward subduction of the Pacific Plate beneath the Philippine Sea Plate. Finally, according to the continuous magma supplement in northeastern Nishinoshima, the Nishinoshima volcano may continue to be active in the future. These results enhanced our understanding of the Nishinoshima volcanic magma motions and dynamics. This study shows that satellite radar altimetry provides an innovative and viable tool to study subaqueous volcanism, and demonstrates the methodology for the first time, on the study of the 2013 Nishinoshima volcanic eruption.

Altimeter gravity detection of submarine plate tectonic motions

Submarine plate tectonic motions are important part of geodynamics and global change. According to the correspondence between mass migration and change of the earth's external gravity field, Li et al. (2020) analyze the submarine plate motion characteristics using global marine gravity field variations from 1995 to 2019 calculated by the altimetry data of different periods. The results show that the gravity anomalies change significantly at plate convergent boundaries, aseismic ridges, seamount groups and fault zones, but not at plate divergent boundaries. The vertical gravity gradients vary significantly in the Southwest Indian Ridge, Atlantic ridge and Middle Indian Ridge, as well as in the subduction zone of the western Pacific Ocean and some aseismic ridges, which spatial distributions are basically consistent with the terrain. The marine gravity field variations accurately reflected the submarine plate tectonic characteristics on the whole. Compared with gravity anomalies, vertical gravity gradient variations can more demonstrably reflect the submarine plate motions, especially in the mid-ocean ridge. The smaller the spreading rate is, the more significant the vertical gravity gradient variation is. In addition, the effects of the gravity field uncertainties on the results are discussed emphatically, the surface slope correction is one of the major factors.

Altimeter detection of elevation changes over mountain glaciers

Hwang et al. (2021) explore the potential of nadir-looking altimeters in detecting elevation changes over mountain glaciers. They developed an altimeter processing technique to detect long-term elevation changes near a glacier terminus and an icefield in Tanggula Mountains using altimeter data from the TOPEX/Poseidon (T/P), Jason-1 (J1), Jason-2 (J2), and Jason-3 (J3) altimeters. The altimeter-observed glacier thinning is confirmed by the direct elevation differences between the digital elevation models from the satel¬lite missions TanDEM-X and SRTM, and by the glacier area losses from Landsat images. The Cryosat-2 result shows the altitude effect of glacier change: the higher the glacier, the less it melts. A repeat altimeter can provide time-lapsed elevation measurements as a virtual glacier station to monitor glacier melt caused by climate change.

Sea levels

Sea level trends

Satellite altimetry and tide gauges are the two main techniques used to measure sea level. Due to the limitations of satellite altimetry, a high-quality unified sea level model from coast to open ocean has traditionally been difficult to achieve. Yang et al. (2021) proposes a fusion approach of altimetry and tide gauge data based on a deep belief network (DBN) method. Taking the Mediterranean Sea as the case study area, a progressive three-step experiment was designed to compare with the inverse distance weighted (IDW) method, the kriging (KRG) method and the curvature continuous splines in tension (CCS) method. The results show that the precision of the DBN method is better than that of the other three methods and is reduced by approximately 20% when the limited altimetry along-track data and in-situ tide gauge data are used. In addition, the distribution of satellite altimetry data and tide gauge data has a large effect on the other three methods but less impact on the DBN model. Furthermore, the sea level anomalies generated by the DBN model contain more spatial distribution information than others, which means the DBN can be applied as a more feasible and robust way to fuse these two kinds of sea levels.

Adaptive and accurate trend estimation of the sea level record is critically important for characterizing its nonlinear variations. Sea level change is a nonstationary or nonlinear process. The present modelling methods are difficult to accommodate nonlinear changes. All these problems affect the accuracy and adaptability of nonlinear trend estimation. Jin et al. (2021) propose a method called EMD-SSA, which effectively combines adaptive empirical mode decomposition (EMD) and singular spectrum analysis (SSA). First, the sea level change time series is decomposed by EMD to estimate the intrinsic mode functions. Second, the periodic or quasiperiodic signals in the intrinsic mode functions can be determined using Lomb-Scargle spectral analysis. Third, the numbers of the identified periodicities / quasi-periodicities are used as embedding dimensions of SSA to identify possible nonlinear trends. Then, the optimal nonlinear trend with the largest absolute Mann-Kendall rank is selected as the final trend for the sea level change. Based on a comprehensive experiment using simulated sea level change time series, we concluded that the EMD-SSA method can adaptively provide better estimate of the nonlinear trend in a realistic sea level change time series with consistency or high accuracy.

Karimi and Deng (2020) estimated the sea level rise around Australia using a new approach to account for low frequency climate signals. They investigated the impact of climate modes on sea level variations and trends around Australia using altimetry data, climate indices, and sea level records from tide gauge stations. The spectral analyses of the climate indices and tide gauge data suggest that a low frequency signal with a period of 11 years emerges during the mid 1980s. Since the 25-year satellite altimetry record is yet too short to detect low frequency signals, their effect on the estimation of regional sea level trend is unknown. Therefore, Karimi and Deng (2020) estimated the sea level trend with consideration of this signal and using a two-step method. All signals with periods shorter than 7.5 years are first removed from sea level time series and then the trend is estimated using the parametric model that includes the 11-year signal. The average sea level trend for around Australia is estimated as 3.85±0.15 mm/year during the period of 1993-2018.

Sea-level budget, vertical motion, sea-level acceleration and deltaic study

Research on holistic sea-level budget adjustments using robust statistical models have been conducted (İz & Shum, 2020a, 2020b; İz, Yang & Shum, 2020a). Novel studies conflating altimeter and tide gauge records to estimate vertical land motion and geocentric coastal sea-level have been reported (İz et al., 2019; İz, Yang & Shum, 2020b). İz & Shum (2020c) reported on the certitude of the estimates of reported global sea-level uniform acceleration using satellite altimetry (1992–2020) and tide gauge data. The results of robust uncertainty analysis considered the unmodeled errors by prior studies including the long-period signals induced presumably by the 18.6-year lunar nodal tides induced sub-harmonics, with periodicities at 55.8-, 75.5-year, suggested that one should exercise prudence on the certainty of estimated uniform sea-level accelerations using satellite altimetry or tide gauge data during the altimetry era (İz & Shum, 2020c).

A sea-level study, published in *Proceedings of the National Academy of Sciences* (Becker et al. 2019), conducted a robust estimate of water-level changes in the Ganges–Brahmaputra–Meghna delta, the largest deltaic region and one of nations with the highest population density in the world. The deltaic regime is primarily driven by continental freshwater dynamics, vertical land motion, and sea-level rise. Through a dataset from 101 gauges, water-level evolution was reconstructed since the 1970s and the results show that the water-level variations across the delta increased slightly faster, at ∼3 mm/yr, than the global mean sea-level rise (∼2 mm/yr). By combining satellite altimetry and water-level reconstruction, that maximum expected rates of delta subsidence since the 1990s are estimated to be ranging from 1 to 7 mm/yr. By 2100, even under a greenhouse gas emission mitigation scenario (RCP4.5), the subsidence could double the projected sea-level rise, making it reaches 85 to 140 cm across the delta (Becker et al. 2019).

Monitoring inland water bodies

Model-aided Altimetry-based River Level Forecasting System for Mekong Basin

The research team led by A/Prof Hyongki Lee in Houston developed a freely accessible and model-aided satellite altimeter-based daily water level forecasting system for Mekong River (MR) and Mekong Delta (MD) (Chang et al., 2019). This system and toolkit have been delivered to SERVIR-Mekong and end-user agencies such Mekong River Commission (MRC). The daily forecasting system is developed using the forecasting rating curve generated from (1) 10-day repeat Jason-2 derived water level changes at upstream virtual stations and the Tonle Sap Lake, (2) daily river discharges at upstream Virtual Stations (VSs) obtained from VIC hydrologic model, and (3) historic in situ water levels at the locations where the forecasting is to be performed. In order to simulate ocean tide influences on water levels, a sum of 5-term sinusoidal function is used. They have performed 10-day or longer “pseudo-forecasting” at 11 locations in MD for the years of 2011 and 2012 and obtained promising forecasting skill with mean absolute error (MAE) of less than or about 0.10 m and excellent temporal agreement with observations from in situ gauges (Figure 23). The harnessing of freely available satellite altimetry data merged with easy to set up macroscale hydrologic model for flow prediction makes our model-aided satellite flood forecasting approach globally applicable for ungauged river basins and deltas.

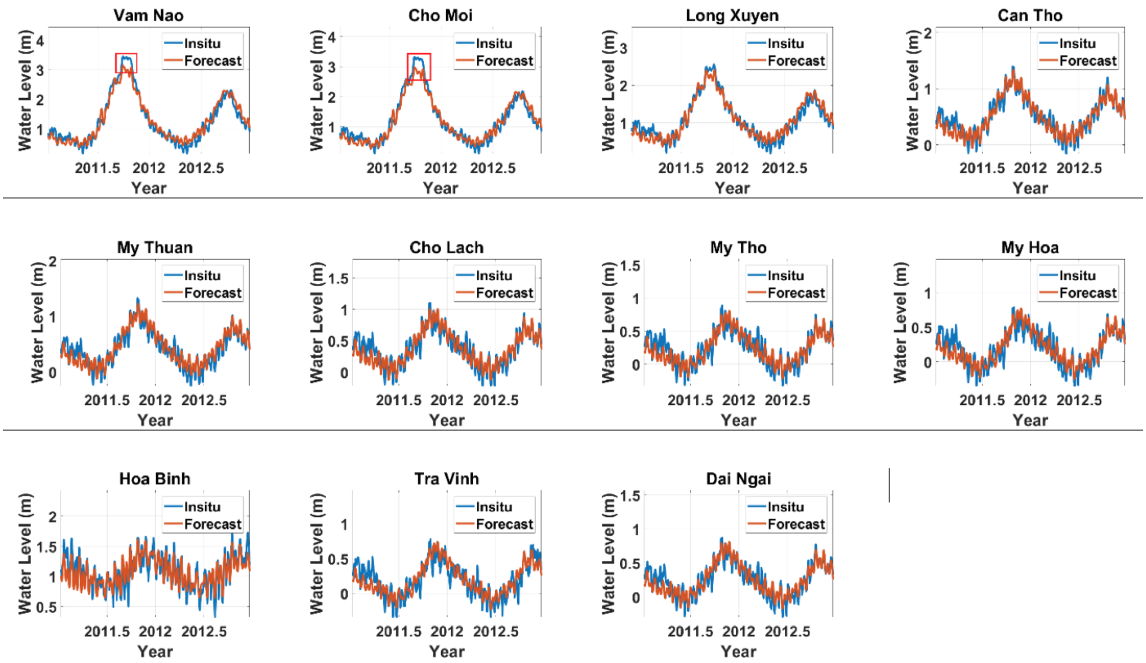


Figure 23. 10-day forecasted (orange) and in situ (blue) water levels from 2011 to 2012 at in-situ stations in MD.

Forecasting Inundation Extents using Rotated Empirical Orthogonal Function Analysis (FIER) and Altimetry-based River Level Forecasting System

FIER (Chang et al., 2020) has been developed to hindcast and forecast daily inundation extents using SAR images and historical and forecasted water levels or discharge. This video link (https://www.youtube.com/watch?v=J7jLpjd6KS0) animates forecasted daily inundation extents over Tonle Sap Lake (TSL) floodplains in Cambodia for Year 2019, generated with Sentinel-1 SAR imagery, Jason-2/3 altimetry, and multivariate ENSO index. The study is currently expanding the test region to the entire Lower Mekong with multiple hydrological contributors to the inundation of Lower Mekong. It is expected that the inundation in Lower Mekong would be mainly governed by flooding in Tonle Sap Lake, Mekong mainstem, and Mekong Delta (Chang et al., 2019). Indeed, from the Rotated Empirical Orthogonal Function (REOF) analysis, it is found that Mode 1 and Mode 2 represent Sentinel-1 intensity variations due to flooding of TSL and Mekong mainstem (at Kampong Cham), respectively. We also found that Mode 3 and Mode 4 are governed by flooding in Mekong Delta, specifically at My Thuan and Can Tho, respectively (Figure 24). Consequently, not only historical but also forecasted water levels (H) or streamflow (Q) over TSL, mainstem and Mekong Delta are necessary to apply FIER over Lower Mekong (Figure 25). Forecasted H over TSL can be obtained from the multivariate ENSO index (Chang et al., 2020). Forecasted H over mainstem (at Kampong Cham) can be obtained from publicly available Mekong River Commission (MRC)'s operational river level forecasting system. Forecasted H over Mekong Delta can be obtained from the flood forecasting system built with Jason-2/3 altimetry data and VIC-model (Figure 23; Chang et al., 2019). Alternatively, forecasted Q over Mekong Delta can also be generated from the Ensemble Learning Regression approach using satellite altimetry data developed by PI Lee's group (supported by NASA Water Resources Program) (*Kim et al., 2019*).

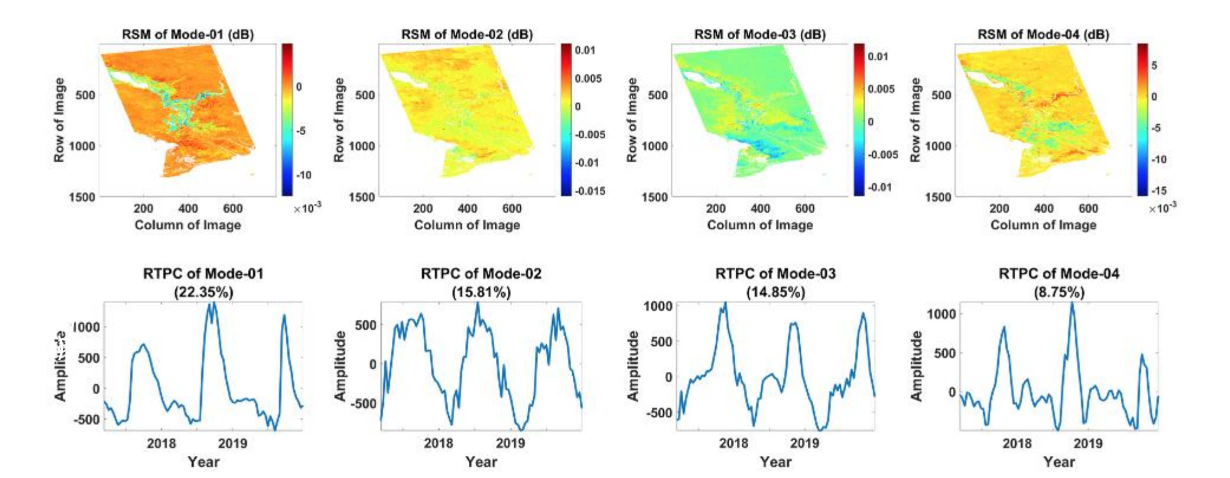


Figure 24. Spatial modes (top panels) and temporal components (bottom panels) from REOF analysis over Lower Mekong using Sentinel-1 images.

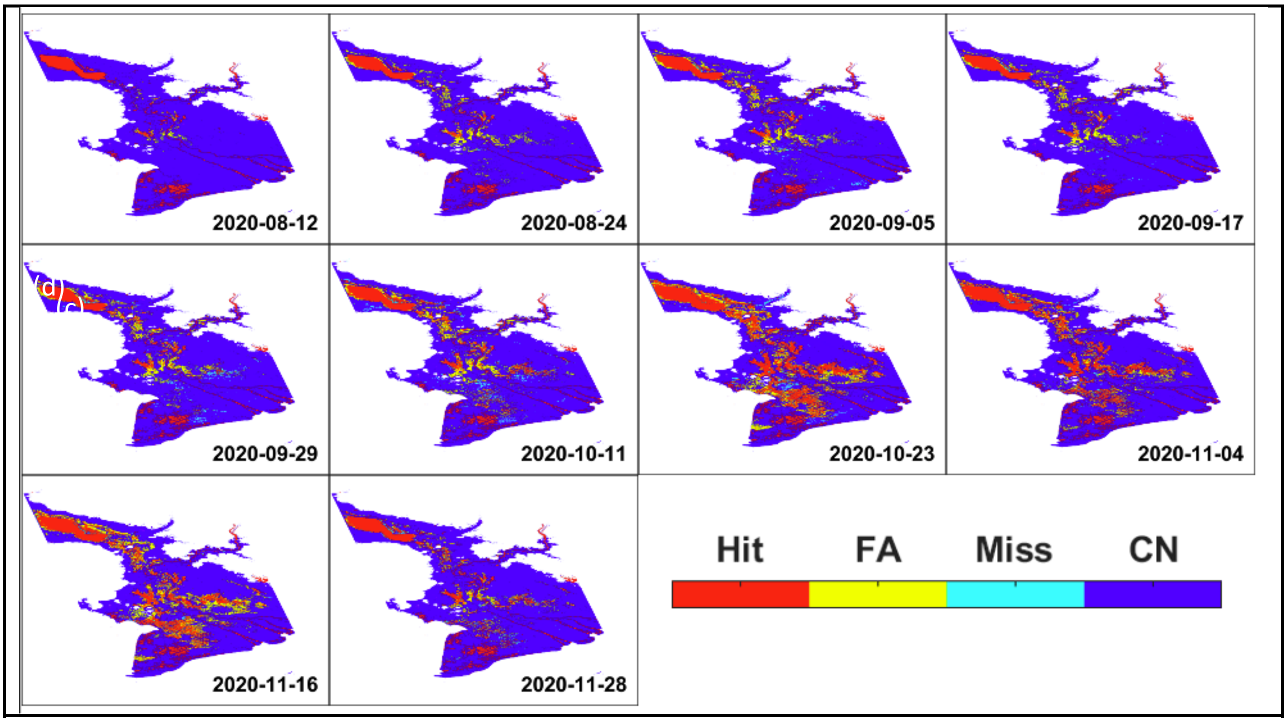


Figure 25. FIER-estimated flood inundation maps at selected dates over Lower Mekong compared with Sentinel-1 SAR-derived inundation maps. Altimetry-based river level forecasting system has been used with FIER.

Estimation of river discharges with Ensemble Learning Regression using altimetry data

Ensemble learning regression for estimating river discharges (ELQ) has been proven to be an effective method (Kim et al., 2019) compared to the previous method based on a power law relationship (at-a-hydraulic geometry, AHG) developed by Leopold and Maddock (1953) and the Manning's equation (Manning, 1889). ELQ has been successfully applied to estimate the river discharges at the Brazzaville station in the Congo Basin using water level changes from multiple Envisat virtual stations. ELQ, one of the machine learning techniques, trains individual base learner and then linearly combines them, which leads to more accurate estimates of river discharges.

Similar to other continental river basins, the water management in the Mekong River Basin (Figure 26) has been experiencing difficulty due to insufficient stream gauges. Here, we apply ELQ to the Mekong River in order to estimate daily discharges at decommissioned or temporarily discontinued in situ stations using Envisat altimetry data (Kim et al., 2020). The ELQ-derived discharges have been compared with a previous method based on a rating curve, which is $M_1 = a_1 \cdot (H - H_{min} + d_{min})^{\frac{5}{3}} + b_1$ (hereinafter Model 1) (Rantz et al., 1982), and a_i and b_i are parameters to be calibrated with in-situ discharges (Figures 27 and 28).

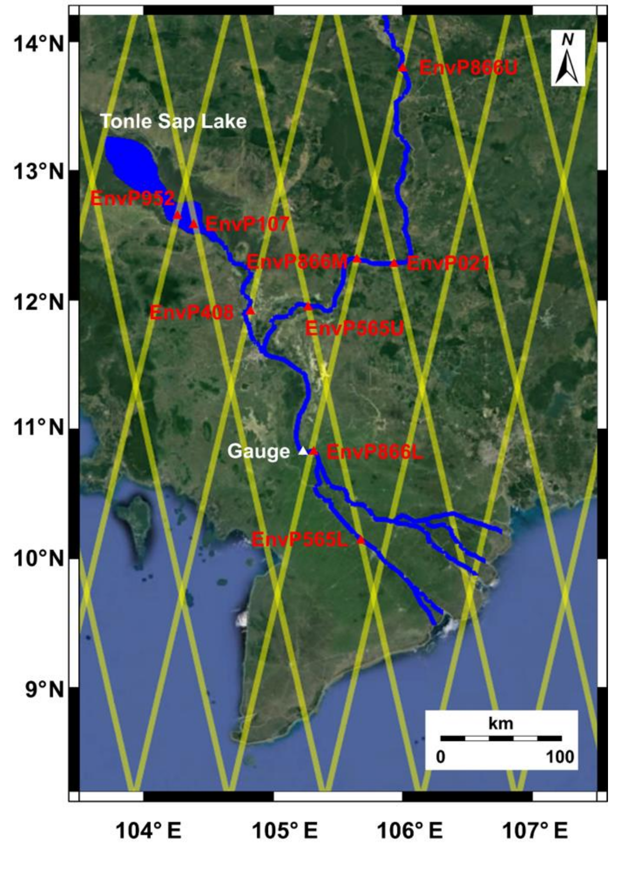


Figure 26. Map of the lower Mekong River with Envisat altimetry ground tracks. The white and red triangles indicate the in-situ gauge at Tan Chau and Envisat virtual stations, respectively. Yellow lines are Envisat altimetry ground tracks.

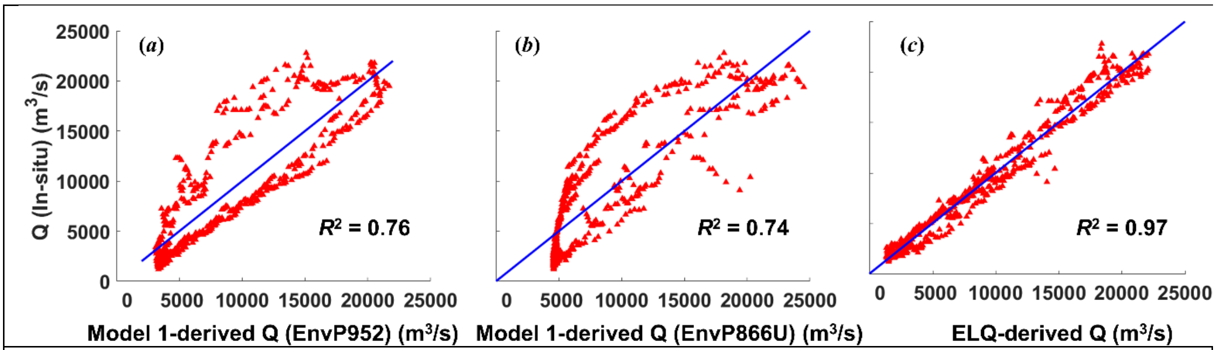


Figure 27. Performance comparison of (*a*) the Model 1-derived *Q* using EnvP952, (*b*) Model-derived *Q* using EnvP866U, and (*c*) ELQ-derived *Q* at Tan Chau station.

It is expected that this method can be used to provide discharge estimates at in situ stations along the Mekong River which are decommissioned or discontinued due to instrument failures.

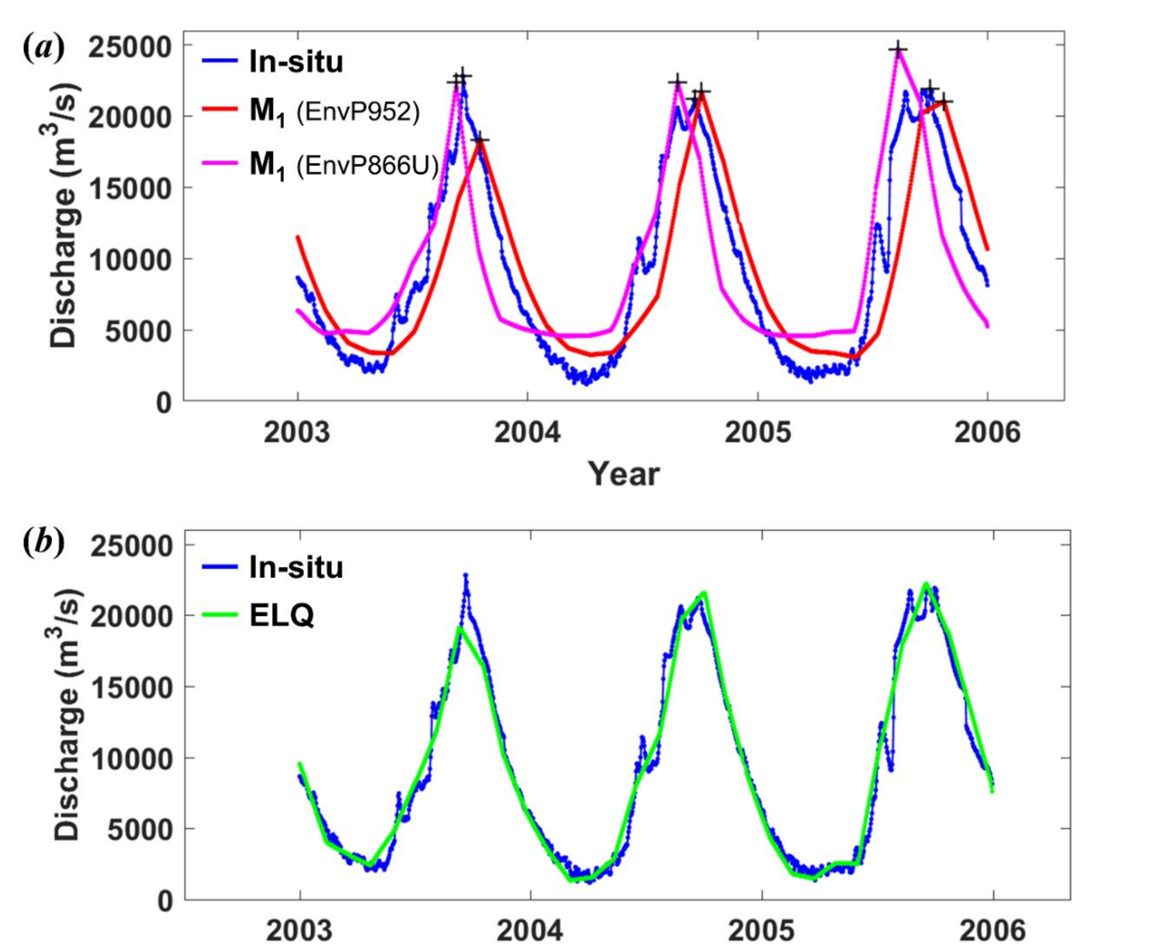


Figure 28. Comparison between the estimated *Q* and in-situ *Q* at Tan Chau station using (*a*) Model 1 and (*b*) ELQ. '+' signs in (*a*) indicate peak dates of discharges in Model 1-derived *Q* and in-situ *Q*.

In Germany, Dr Fenoglio's team also used the improved altimeter heights and the river slope evaluated from two intersections of the same satellite track to study the hydrodynamics of the river. River discharge is a key variable to quantify the water cycle and its flux. First river discharge is evaluated from water level and slope. Various methods have been used, included the empirical rating curve method which looks for a relationship between altimeter height and discharge from a nearby in-situ station, the semi-empirical Bjerklie method and the physically-based method based on hydraulic equations. The normalized RMSE of altimetric and in-situ discharge is found to be between 3 and 7% for the rating curve methos, while using the altimeter-derived slope and heights the semi-empirical Bjerklie method the normalised RMSE is higher and around 20% (Fenoglio et al., 2021).

Altimetry Data Processing for Inland Water Bodies Using Web Application

Markert et al. (2019) introduced an open-source web application (https://altex.servirglobal.net/) to access and explore Jason-2/3 altimetry datasets for use in water level monitoring, named the Altimetry Explorer (AltEx, Figure 29). The back-end of this web application is based on the automation method of Okeowo et al. (2017) led by Lee's group. This web application, along with its relevant REST API, facilitates access to altimetry data for analysis, visualization, and impact. The data provided through AltEx is validated using thirteen gauges in the Amazon Basin from 2008 to 2018 with an average Nash-Sutcliffe Coefficient and RMSE of 0.78 and 1.2 m, respectively.

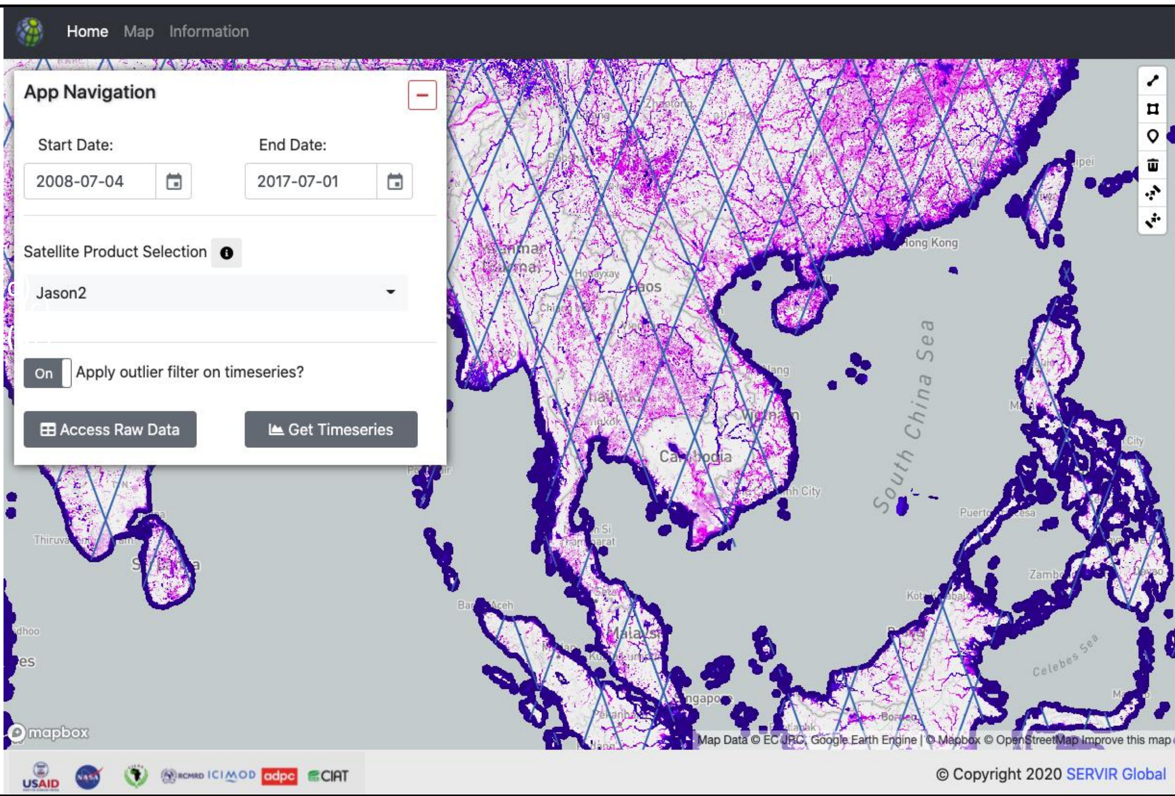


Figure 29. Interface of Altimetry Explorer (https://altex.servirglobal.net/)

Satellite altimetry applications on lakes in China and on global rivers

Studies on regional differences of lake volume evolutions across China, and on refuting that the volume of China's lakes were under-estimated using Landsat images and altimetry have been published (Zhang et al. 2019; 2020a). A review study published in *Earth Science Reviews*, synthesized the trends, patterns, and mechanisms on the response of the Tibetan Plateau lakes to anthropogenic climate change (Zhang et al. 2020b).

A new and comprehensive decadal river elevation climate data records using multi-mission radar altimeter data for global rivers wider than 1 km, were generated for the hydrologic community, and published in *Earth System Science Data* (Coss et al. 2020). The data product is hosted at the Ohio State University (https://go.osu.edu/altimeterVirtualStations) for visualizations and river water-level data download, and at NASA JPL/PODDAC.

Kao et al. (2019) assessed the performance of CryoSat-2 and SARAL/AltiKa radar altimetry retrieved water-level over Tibetan lakes and sea level in coastal region of Taiwan. Lee et al. (2020) evaluated and improved *in situ* GNSS-Reflectometry altimetry sea level in coastal Taiwan.

Deng et al. (2021) tested the capability of retracked CryoSat-2 data (both SARIn mode and LRM) by different retrackers for monitoring surface water levels of plateau lakes. A case study has been conducted for two small lakes (<52 km^2 per lake) in Tibet and an inland lake in Yunnan, China. CryoSa-2 L2 LRM and L1B SARIn-mode data from 2011 to 2018 have been used to monitor water level variations of Dianchi Lake and two lakes of Gemang Co and Zhangnai Co in Tibetan Plateau (TP), respectively (Figure 30). In addition to official data estimated from ICE (for LRM) and WWMFW (for SARIn) retrackers, we have retrieved the water surface heights referred to the EGM2008 geoid through retracking CryoSat-2 20 Hz waveforms using different retrackers, including ALES and MBP (for LRM), as well as PPT, OCOG and APD-PPT (for SARIn). Of these retrackers, the APD-PPT is newly proposed in this study, which combines the adaptive peak detection method with the PPT. The lake level is determined via the median value and standard deviation computed from the outlier-free and unbiased surface heights along each track. The time series of lake levels has been generated and its trend has been estimated for each lake over the study period.

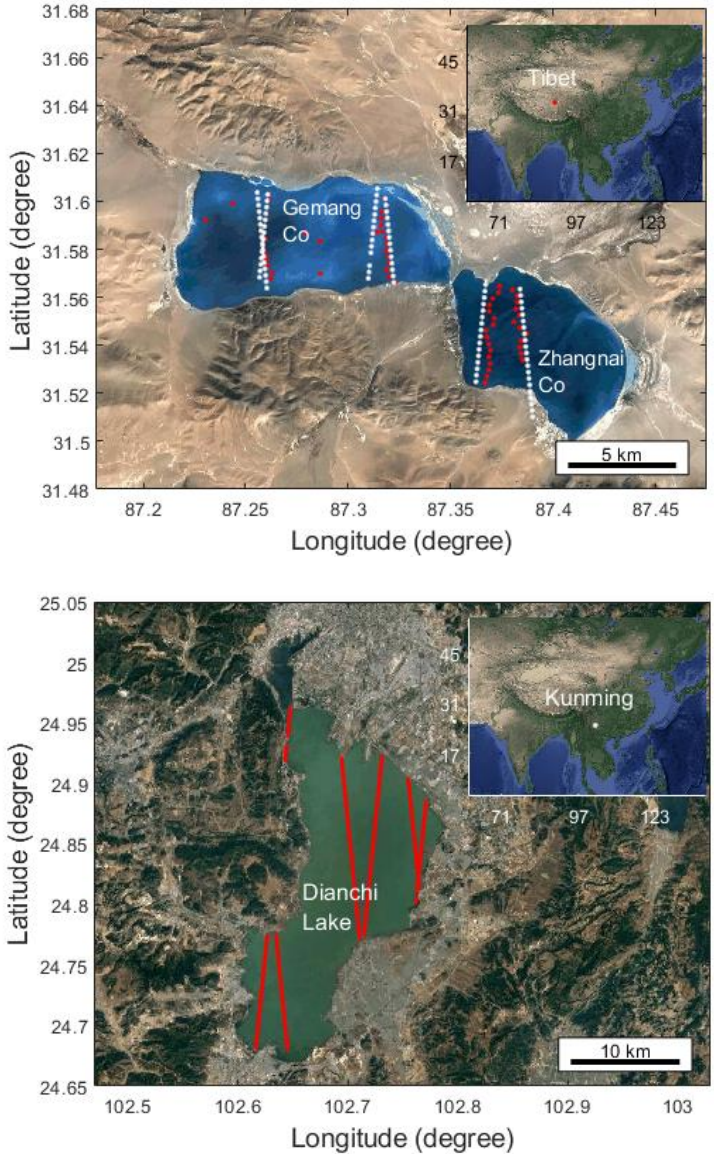


Figure 30. Top: TP lakes Gemang Co (left) and Zhangnai Co (right) overlapped with one cycle of CryoSat-2 SARIn-mode ground tracks in 2016. The white-dot lines are the nominal ground tracks, while the red dots are the corresponding slope-corrected ground tracks when considering off-nadir measurements. Note that some off-nadir measurements are located on land, but have been deleted during the data editing process. Bottom: Dianchi Lake, China, overlapped with one cycle of CryoSta-2 LRM ground tracks (in red) in 2011.

The lake level estimations are indirectly validated against those from Jason-2 in TP and from in situ data in Dianchi Lake, both showing good agreement with strong correlation coefficients >0.74 (Figures 31 and 32). The results of this paper suggest that the official ICE retracker for LRM data and APD-PPT retracker for SARIn-mode waveforms are the most appropriate retrackers over Dianchi Lake and TP lakes, respectively. The trend estimates of the time series derived by both retrackers are 61.0±10.8 mm/yr for Gemang Co and Zhangnai Co in TP, and 30.9±64.9 mm/yr for Dianchi Lake, indicating that the lake levels over three lakes were continuously rising over the study period. The results of this study show that CryoSat-2 SARIn-mode data can be used for monitoring many small lakes that have not been measured by other altimetry missions in TP.

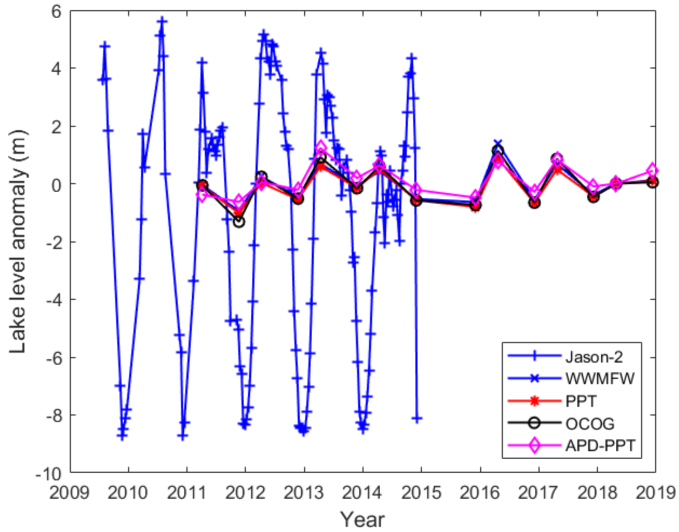


Figure 31. Validation of lake level variations derived from CryoSat-2 against those from Jason-2 over Zhangnai Co. The lake level anomaly is computed by subtracting a median value of lake levels between 2011 and 2015 from each lake level.

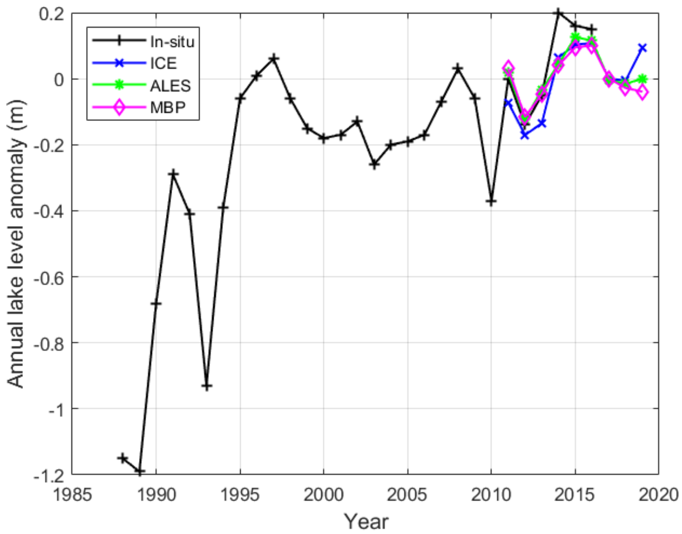


Figure 32. Validation of variations of annual lake level anomalies derived from CryoSat-2 LRM against those from in situ gauge data in Dianchi Lake from 2011 to 2016.

Retracking, calibrating and validating of altimetry data

Innovative processing and retracking for SAR mode waveforms

Dr. L. Fenoglio's main research topic is water level change in coastal and inland water derived from an integrated use of space geodetic techniques and its application to climate change analysis. Innovative processing and retracking have been developed for SAR mode waveforms with the SAMOSA+ and SAMOSA++ retrackers (Dinardo et al. 2018, 2020) and with the Signal Model Involving Numerical Convolution (SINC/SINCS), a fast convolution based waveform model for conventional and unfocused SAR altimetry (Buchhaupt et al., 2018).

Further on, the sub-waveform Spatio Temporal Altimetry Retracker (STAR) in LRM mode (Roscher et al., 2017) is adapted to the SAR mode retracker STARS (STAR for SAR) by using SINCS as the waveform model (Uebbing et al., 2021). The TUDaBo processor developed in-house and accessible in GPOD (http://gpod.eo.esa.int) includes the Reduce Synthetic Aperture Radar (RDSAR), Synthetic Aperture Radar (SAR Delay Doppler) unfocused and Range Migration Compensation (RMC). The model SINCS-OV accounts in SINCS for the vertical Motion of Wave Particles (VMWP) and increases the precision of the retracked parameters compared to standard SAR processing, as SAR precision depends on SWH and wave period (T_{02}) (Buchhaupt et al., 2020). In Figure 33, we notice an increase in the agreement between SAR and non-SAR processing when the SINCS-OV retracker is used.

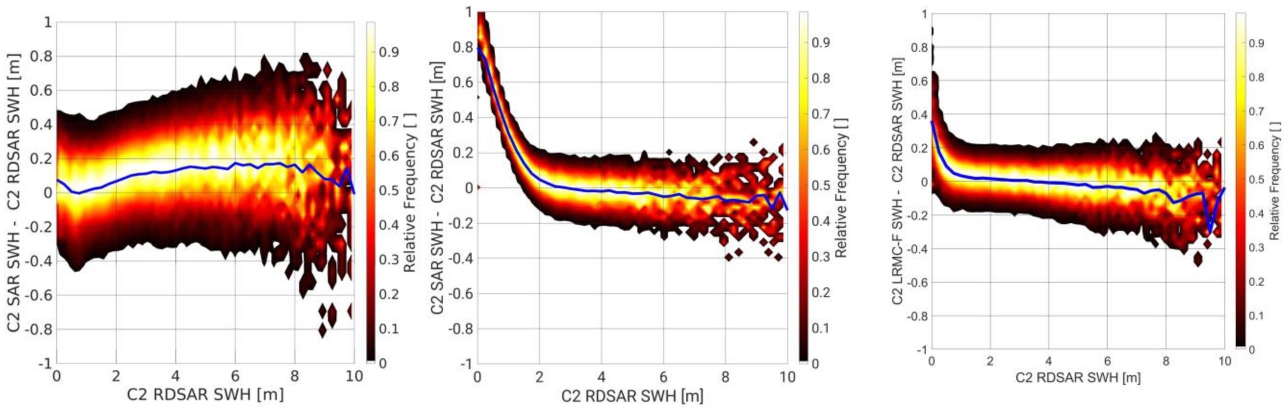


Figure 33. SWH 1-Hz differences between RDSAR and (left) Unfocused SAR CryoSat-2 SINCS, (middle) SAR SINCS-OV ZSK and (right) LRMC-F (right)

Cross-calibration of altimeter products and validation against in-situ and models

Dr Fenoglio's team has performed the cross-calibration of altimeter products and validation against in-situ and models. Dr Fenoglio is a member of validation teams and of study groups for current altimeter missions and of Mission Advisory Groups for future missions. The improvement near coast and in inland water of the SAR altimeter heights versus the LRM mode, was shown in Fenoglio et al., (2019, 2020) for CryoSat-2 and Sentinel-3. The validation of Sentinel-6 data has just started. The Fully Focused SAR Processed data in the implementation by Guccione et al. (2018) is evaluated as part of the expert group. FF-SAR is expected to increase the along-track spatial resolution to sub-meter level (Egido and Smith 2018). Data accuracy and precision improve with the enhanced unfocused SAR processing SAMOSA+ and SAMOSA++. The SAR waveform and noise floor are different from those in LRM and the surface water slope is a new observable. The geophysical parameters are still affected by land contamination and the accuracy decreases near coasts. The results by Fenoglio et al. (2020) show that SAMOSA+ and STAR products are the less noisy in the last 3 km from coast and are in best agreement with the ocean models (Figure 34).

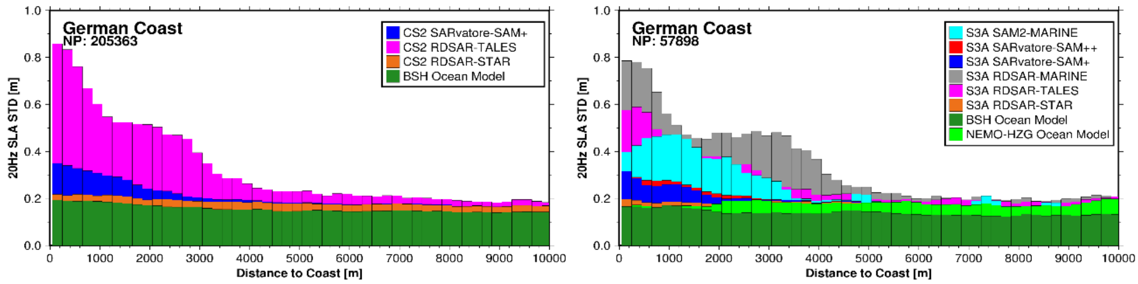


Figure 34. Standard deviation of CryoSat-2 (left) and Sentinel-3A (right) sea surface height anomaly in German Bight from altimeter products with SAMOSA+ and ++ retrackers and two ocean models until December 2018. The BSH (dark green) and the NEMO-WAM (light green) ocean models are corrected with ocean tide model TPXO8. NP is the number of common measurements selected for each dataset (Figure 25, Fenoglio et al., 2020).

In estuaries and in the Wadden intertidal sea the STD difference (STDD) is larger. At Otterndorf, in the Elbe estuary (Figure 35) in-situ and Sentinel-3A water heights corrected for all corrections have a STDD of 30 cm, which arises either from a variation in discharge or from errors in the ocean tide model TPX08 used to correct for the ocean tide. A visual inspection with the water level in the river part at the Elbe River at the gauge Neue Darchau supports this second option.

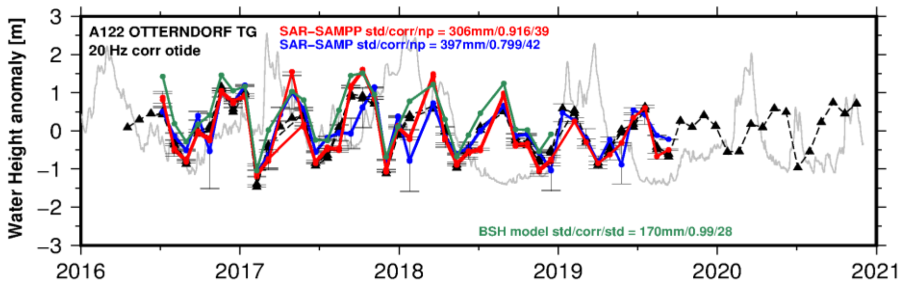


Figure 35. Otterndorf from Sentinel-3A and in-situ ocean tide correction applied from Fenoglio et al. 2020 (adapter Fig.10d in Fenoglio et al. 2020).

Schröder et al. (2019) show that the SAMOSA+ product is superior to the standard Copernicus data in rivers. Figure 35 gives the comparison of various processing with the Mainz in-situ data in the river Rhine. In that river, the STDD between water level and corresponding nearest gauge at each Virtual Gauge (VG) are between 0.10 m and 0.30 m in half of the 17 VGs. In Figure 36 (left) in-situ data and various altimeter products are compared in Mainz, the STDD is 10 cm. In summary, the mean STDD with in-situ data is 2-4 cm at sea, 10-20 cm in rivers and 30-50 cm in estuarine and intertidal zone.

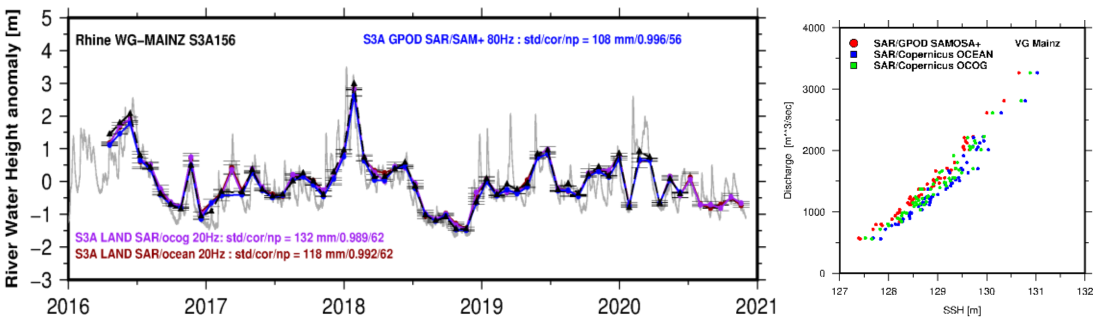


Figure 36. (left) Water level anomalies and (right) rating curve RC of in-situ discharge and VG water height in Mainz

Sentinel-3A for oceans at Southeast Asia

Idris et al. (2021) performed the assessment of altimetric data from Sentinel-3A satellite operating in Synthetic Aperture Radar (SAR) mode for sea level research studies and applications over the largest archipelagos at Southeast Asia. Both qualitative and quantitative assessments are conducted by analysing the physical shapes of waveforms, comparing with quasi-independent geoidal height data and independent tide gauge measurements. The results identified the percentage of ocean like and non-ocean like waveforms are 91% and 9%, respectively (Figure 37). Off 9% of non-ocean like waveforms, the major class is multi-peak (7%) followed by the quasi-specular waveforms (2%) observed near the coastline (<10 km). Ocean like waveforms typically appear beyond 500 m from the coastline. When comparing with geoidal heights and tide gauge measurements, the performance of sea levels from several retrackers are assessed. The SAMOSA+ retracker outperforms other retrackers (i.e., sub-waveform and modified threshold retrackers with 30%, 20% and 10%). That is, the standard deviation of differences against geoidal heights, and the temporal correlation against tide gauges are superior in most cases (Figure 38). In terms of root mean square error (RMSE), all retrackers are ranging with RMSE $\leq$20 cm.

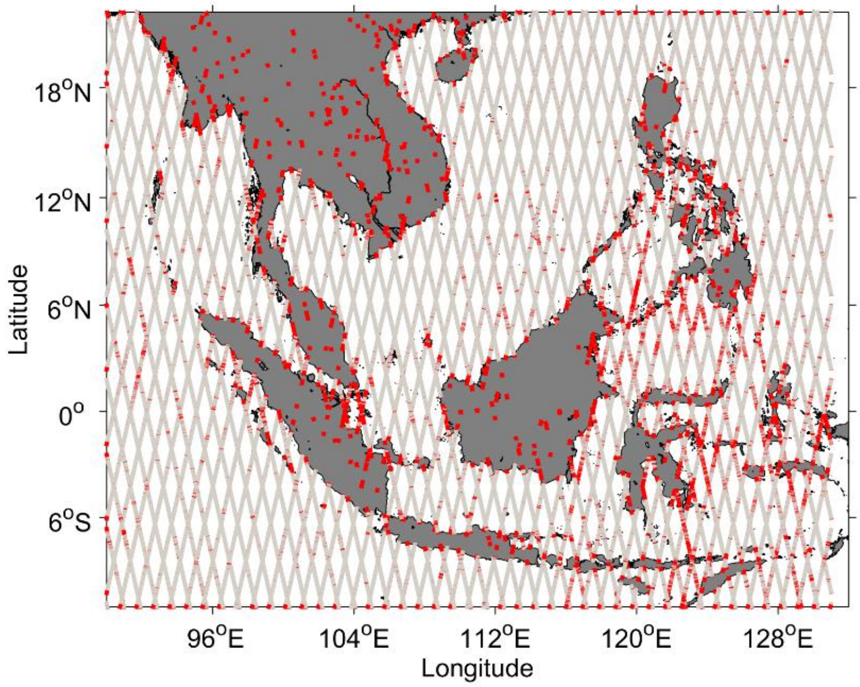


Figure 37. Spatial plot of waveform classes along the Sentinel-3A satellite tracks. The light grey and red colors show the ocean-like and non-ocean like waveforms, respectively. Note that the red marks on the land showing the waveforms over inland water.

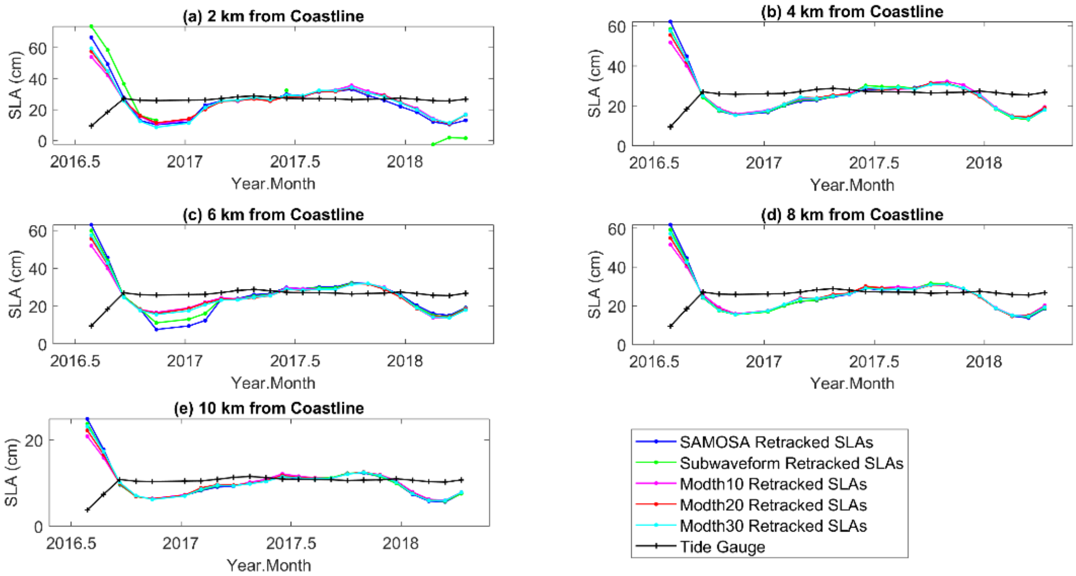


Figure 38. Time series of SLAs from several retrackers at the difference distance from the coastline. They are from pass 053 near Ko Lak tide gauge stations. The time series from Ko Lak station is also shown.

Data improvement and validation around Australia

Peng and Deng (2020a) examine the performance of their Brown-Peaky (BP) retracker on retrieving the backscatter coefficients, and then wind speeds, in coastal zones. Eight years of Jason-2 waveforms are reprocessed by the BP retracker. An empirical wind speed model is used to obtain the altimeter wind speeds based on the BP-derived backscatter coefficients. The validation of BP-derived wind speeds is conducted through comparisons with wind speeds from the *in situ* anemometer and Jason-2 official altimeter product. The along-track root mean square errors (RMSEs) and biases between altimeter and anemometer wind speed time series are calculated pointwise to evaluate the data quality. The orthogonal regression analysis is computed to evaluate the overall data quality. The validation results show that the BP-derived backscatter coefficients are highly correlated with the square of the off-nadir angles. By removing the correlation-induced error, the quality of BP-derived backscatter coefficients is comparable to that obtained from the three-parameter maximum likelihood estimator (MLE3). The improved backscatter coefficients are beneficial for retrieving reliable along-track wind speed observations, which allows for lower and smoother RMSEs and biases. The 1- and 2-Hz BP-derived wind speeds achieve similar performance, implying that the application of high rate altimeter wind speeds in coastal zones is possible. We also find that the altimeter wind speeds are significantly dependent on the sea state in the last 20-km distance to the coast, where the bias between altimeter and anemometer wind speeds increases remarkably and varies inversely with the offshore distance.

In Australia, Peng and Deng (2020b and 2020c) conducted studies in validation of sea level anomaly (SLA) data from Jason-1/2/3 and Sentinel-3A missions against in-situ data, as well as improvement of SLA data through retracking processes and improving the corrections. They analysed the precision of 20-Hz SLA estimates with three sets of SSB corrections (i.e. 1-Hz, 20-Hz and composite SSB models) within 100 km to the Australian coastline using 16 years of retracked Jason-1/2/3 data, by modified Brown-Peak (MBP), and 3 years of SAMOSA+ retracked Sentinel-3A data. Here they focused on removing the noise from 20-Hz SLA estimates via applying the intra-1-Hz and recalculated SSB corrections. The performance of SSB corrections on reducing the SLA noise was assessed. The SLA's precision was evaluated in the 1×1 km grids and presented in different coastal zones. The composite SSB correction, which was recomputed after removing the retracker-dependant correlated error in 20-Hz SLA, is found to achieve better performance than other SSB corrections in the study area. Applying the 20-Hz and composite SSB corrections has reduced noise by ~10% and ~13%, respectively, in the MBP-retracked 20-Hz Jason SLA estimates, while only ~2% of noise reduction is shown by applying the 1-Hz standard SSB correction (Figure 39). It is also found that the improvement of retracked Sentinel-3A SLA estimates by SSB corrections is very low (~3%), indicating a dedicated SSB correction model should be developed for the SAR mode altimeter.

As a result, the precision of composite SSB-corrected SLA estimates for all Jason missions can be retained at the level of 5.1±1.1 cm until 3 km from the Australian coast, which is slightly lower than that of Sentinel-3A (4.2±0.9 cm). The degradation within 3 km from the coast mainly corresponds to the along-track direction for MBP-retracked Jason SLA estimates, and the across-track direction for SAMOSA+ retracked Sentinel-3A SLA estimates, respectively.

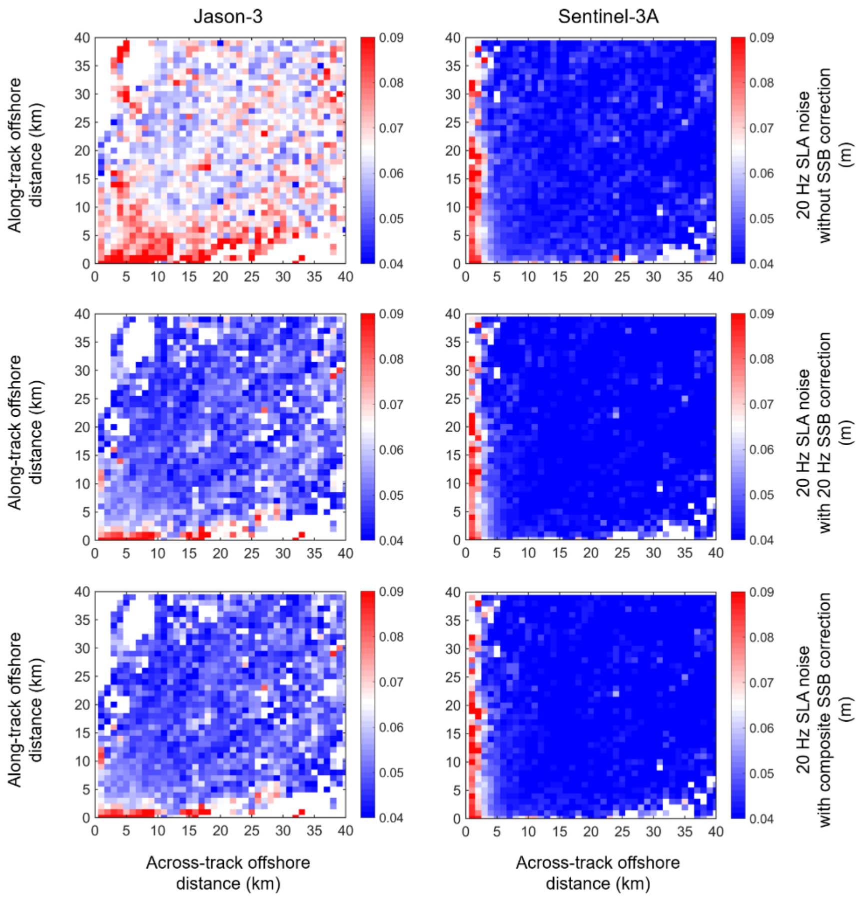


Figure 39. Noise level of Jason-3 MBP-retracked (left panel) and SAMOSA+ retracked Sentinel-3A (right panel) 20-Hz SLA estimates. Three cases are illustrated from top to bottom of the graph: 1) 20-Hz SLA estimates without SSB correction; 2) 20-Hz SLA estimates with 20-Hz SSB correction and 3) 20-Hz SLA estimates with composite SSB correction. The noise level is computed on 1×1 km grids depending on the offshore distance in the along-track (y-axis) and across-track (x-axis) directions. The median value of each grid is represented as an indication of the noise level. White pixels indicates there are no data available.

Peng and Deng (2020b) validate the Synthetic Aperture Radar (SAR) mode sea level anomalies (SLAs) of Sentinel-3A altimetry mission around the Australian coastal region using eight tide gauge sea level records and retracked Jason-3 datasets from a modified Brown-peaky (MBP) retracker. The MBP is a modified version of our existing Brownpeaky retracker aimed at enhancing BP's performance. They compared the noise of Sentinel-3A SLAs averaged across three posting rates (i.e. 1 Hz, 2 Hz and 4 Hz) with the 1 Hz noise of MBP-derived Jason-3

SLAs. At distances>10 km from the coast, the noise level of 1 Hz Sentinel-3A SLAs (~1.2 cm) is lower than that of the MBP-retracked Jason-3 SLAs (~1.7 cm). Moreover, the noise level of 2 Hz Sentinel-3A SLAs is comparable to that of the 1 Hz MBP-derived Jason-3 dataset, indicating that Sentinel-3A can provide precise SLAs at finer spatial scales. The Root Mean Square Error (RMSE) of differences between the tide gauge SLA time series and the equivalent SLA time series at each along-track altimeter point was used to assess pointwise data quality (Figure 40). For both Sentinel-3A and MBP-retracked Jason-3, the along-track RMSEs of 20 Hz SLAs vary between 0.05 m and 0.2 m. The mean and standard deviation (STD) of 1 Hz SLA differences at crossover points were computed for each individual altimetry mission to assess overall data quality. When compared with the crossover analysis results, the quality of Sentinel-3A SLAs is superior to that of the retracked Jason-3 dataset in terms of smaller STDs at crossover points (8.8 cm vs. 10.7 cm).

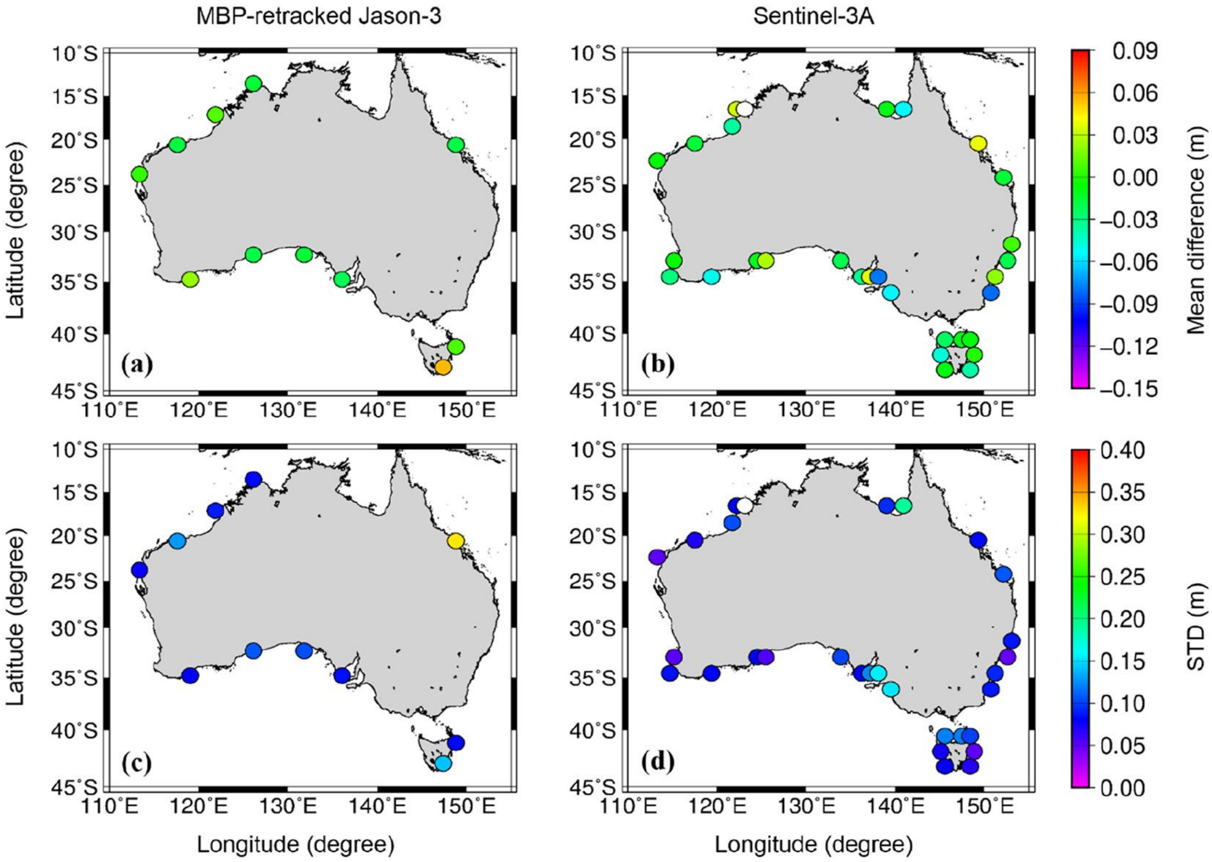


Figure 40. Mean and STD of SLA differences at crossover points within the 0–50 km coastal zone around Australia. The solid white circles in (b) and (d) indicate that the values (0.41 m and 0.67 m) were outside of the ranges shown in the colour bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Preparation for the future SWOT mission

In preparation to the future mission SWOT, data are simulated in the previous two mentioned regions. The goal of the SWOT mission is to detect small spatial scales in the ocean and to improve knowledge of hydrodynamic processes in the continuum coastal-estuary-rivers, which is not well observed from classical satellite altimetry. We have investigated in simulations the novelty of the mission for our regions. SWOT observations simulated at in-situ data locations from in-situ time-series were processed with the wavelet method to detect the signal registered by discrete SWOT observations. Figure 41 shows the signal in Helgoland and Ottendorf. SWOT 2D observations were simulated on the ocean by the JPL Ocean SWOT simulator using the ocean model SCHISM as input. Similarly, SWOT observations in the River Rhine were simulated by the Large Scale SWOT simulator applied to input water height of the hydrodynamic model Sobek. Figure 42 (right) shows that the simulated time-series in Mainz are denser than the Sentinel-3A altimeter time-series. Data resolution and decorrelation length scale of the on-board pre-processed estimates of SSH and spatially uncorrelated errors, are the dominant source of measurement errors on scales shorter than 100 km. Analysis for both the 1-day cycle and the 21-day science phase is planned in the two regions in collaboration with the SWOT Science Team in projects CONWEST-DYCO (coast and estuary), REFECCT (river) (https://swot.jpl.nasa.gov/people/142) and in project “SWOT Multi-sensor and Modeling approaches for monitoring the Multi-scale Coastal hydrodynamics” - 3MC by B. Laignel (University of Rouen, France). SWOT 3MC includes the comparison of the Seine and Elbe estuaries.

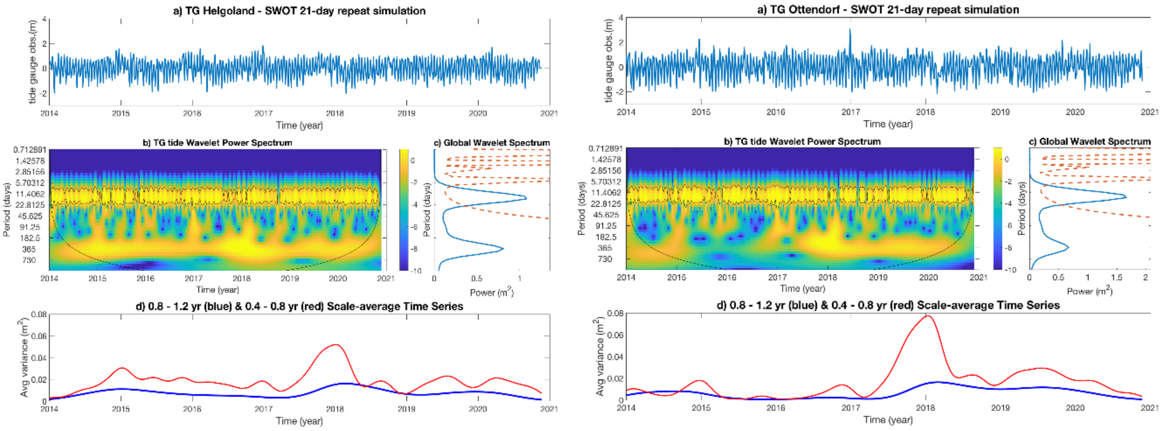


Figure 41. Wavelet analysis of 1D-SWOT 5-day simulated from Helgoland (top) and Ottendorf (bottom) in-situ gauge

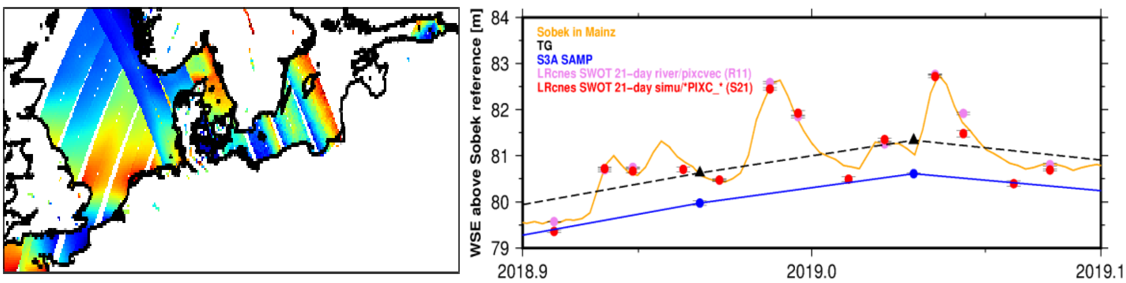


Figure 42. SWOT 2D simulation of WSE using the SCHISM ocean model and the JPL Ocean Simulator (left). SWOT 2D simulation of WSE on Rhine River nearby the Mainz river gauge using Large Scale Hydrology simulator (right).

Selected relevant publications during the period 2019 - 2021

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J.U., Ballu, V., Durand, F., Le Cozannet, G., Saiful Islam, AKM., Calmant, S., Shum, C. (2020) Water level changes, subsidence, and sea level rise in the Ganges-Brahmaputra-Meghna delta, Proc. National Academy of Sciences, 117(4), doi:10.1073/pnas.1912921117.

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio, L., Shah, R., Almar, R., Andersen, O., Birol, B., Bonnefond, P., Bouffard, J., Calafat, F., Cardellach, E., Cipollini, P., Le Cozannet, G., Dufau, C., Fernandes, J., Frappart, F., Garrison, J., Gommenginger, G., Han, G., Høyer, J.L. , Kourafalou, V., Leuliette, E., Li, Z., Loisel, H. , Madsen Skovgaard, K., Marcos, M., Melet, A., Meyssignac, B., Pascual, A., Passaro, M., Ribó, S., Scharroo, R., Song, T., Speich, S., Wilkin, J., Woodworth, P., Wöppelmann, G. (2019) Requirements for a Coastal Hazards Observing System, in Frontiers in Marine Science, Coastal Ocean Processes, Front. Mar. Sci., doi.org/10.3389/fmars.2019.00348

Buchhaupt, C., Fenoglio-Marc, L., Becker, M., Kusche, J. (2020). Impact of Vertical Water Particle Motions on Fully-Focused SAR Altimetry, Advanced Space Research Special Issue 25 Years of Progress in Radar Altimetry, doi.org/10.1016/j.asr.2020.07.015.

Chang, C.-H., H. Lee, F. Hossain, S. Basnayake, S. Jayasinghe, F. Chishtie, D. Saah, H. Yu, K. Sothea, D.D. Bui, (2019) A model-aided satellite altimetry based flood forecasting system for Mekong River, Environmental Modelling & Software, 112, 112-127.

Chang, C.-H., H. Lee, D. Kim, E. Hwang, F. Hossain, F. Chishtie, S. Jayasinghe, S. Basnayake, (2020) Hindcast and forecast of daily inundation extents using satellite SAR and altimetry data with rotated empirical orthogonal function analysis: case study in Tonle Sap Lake Floodplain, Remote Sensing of Environment, 241, 111732.

Coss, S., Durand, M., Yi, Y., Jia, Y.Y., Guo, Q., Tozzulo, S., Shum, C., Frasson, R., Allen, G., Calmant, S., Pavelsky, T. (2020) Global river radar altimetry time series (GRRATS): New decadal river elevation climate data records for the hydrologic community, Earth System Science Data, 12, 127–150, doi:10.5194/essd-2019-84.

Deng, X., Ren-Bin, W., Peng, F., Yong, Y., & Nan-Ming, M. (2021). Retracking Cryosat-2 Data in SARIn and LRM Modes for Plateau Lakes: A Case Study for Tibetan and Dianchi Lakes. Remote Sensing, 13(6), 19 pages. doi:10.3390/rs13061078

Dinardo, S., Fenoglio, L., Becker, M., Scharroo, R., Fernandes, M. J., Staneva, J., Grayek, S., Benveniste, J., (2020) A RIP-based SAR Retracker and its application in North East Atlantic with Sentinel-3, Advances in Space Research, Special Issue 25 Years of Satellite Altimetry, doi.org/10.1016/j.asr.2020.06.004.

Du, T.L.T., H. Lee, D.D. Bui, B. Arheimer, H.-Y. Li, J. Olsson, S.E. Darby, J. Sheffield, D. Kim, E. Hwang, (2020) Streamflow prediction in "geopolitically ungauged" basins using satellite observations and regionalization at subcontinental scale, Journal of Hydrology, 588, 125016.

Fenoglio-Marc, L., Zahkavova, E., Gärtner, M., Zohidov, B., Dinardo, S., and Duong, Q. (2021) Discharge of the river Rhine from multi-sensor data from empirical and physical methods, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13857, https://doi.org/10.5194/egusphere-egu21-13857.

Fenoglio, L., Dinardo, S., Buchhaupt, C., Uebbing, B., Scharroo, R., Kusche, J., Becker, M. and Benveniste, J. (2019) Calibrating CryoSat-2 and Sentinel-3A sea surface heights along the German coast, In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, doi.org/10.1007/1345_2019_73.

Fenoglio, L., Dinardo, S., Uebbing, B., Buchhaupt, C., Gärtner, M., Staneva, J., Becker, M., Klos, A., Kusche, J. (2020). Advances in NE-Atlantic coastal Sea Level Change Monitoring from Delay Doppler Altimetry, Adv. Space Res., doi.org/10.1016/j.asr.2020.10.041.

Fenoglio-Marc L., Buchhaupt C. (2021). TUDaBo a SAR Processing Prototype for GPOD, Altimetry coastal and Open Ocean Performance. Algorithm Theoretical Basis Document, ESA, EOEP-SEOM-EOPS-TN-17-046

Gharineiat, Z., & Deng, X. (2020). Spectral Analysis of Satellite Altimeter and Tide Gauge Data around the Northern Australian Coast. Remote Sensing, 12(1), 16 pages. doi:10.3390/rs12010161

International Altimetry team, (2021). Altimetry for the future: Building on 25 years of progress. Advances in Space Research, https://doi.org/10.1016/j.asr.2021.01.022

Hossain, F., Bonnema, M. Srinivasan, M., Beighley, E., Andral, A. Doorn, B., Jayaluxmi, I., Jayasinghe, S., Kaheil, Y., Fatima, B., Elmer, N., Fenoglio, L., Bales, J., Lefevre, F., Legrand, S., Brunel, D., and Le Traon, P.Y. (2020). The Early Adopter Program for the Surface Water Ocean Topography Satellite Mission: Lessons Learned in Building User Engagement during the Pre-launch Era. Bull. Amer. Meteor. Soc. N. 101, doi.org/10.1175/BAMS-D-19-0235.1.

Hwang, C, SH Wei, YS Cheng, A Abulaitijiang, OB Andersen, NF Chao, HY Peng, KH Tseng, and JC Lee (2021). Glacier and lake level change from TOPEX-series and Cryosat-2 altimeters in Tanggula: comparison with satellite imagery, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 32.

Idris, N. H., Vignudelli, S., & Deng, X. (2021). Assessment of retracked sea levels from Sentinel-3A Synthetic Aperture Radar (SAR) mode altimetry over the marginal seas at Southeast Asia. International Journal of Remote Sensing, 42(4), 1535-1555. doi:10.1080/01431161.2020.1836427

İz, H. Bâki, Yang, T.Y., Shum, C, Kuo, C.Y. (2019) Optimal mathematical and statistical models to estimate vertical crustal movements using satellite altimetry and tide gauge data, J. Geodetic Science, doi:10.1515/jogs-2019-0014.

İz, H. Bâki, Shum, C. (2020a) Year by year closure adjustment of global mean sea level budget, inclusive of lumped snow, water vapor, and permafrost mass components, J. Geod. Sci, 10, 83–90, doi:10.1515/jogs-2020-0109.

İz, H. Bâki, Shum, C. (2020b) A statistical protocol for a holistic adjustment of global sea level budget, J. Geodetic Science, 10, 1–6, doi:10.1515/jogs-2020-0001.

İz, H. Bâki, Shum, C. (2020c) The certitude of a global sea level acceleration during the satellite altimeter era, J. Geod. Sci., 10, 29–40, doi:10.1515/jogs-2020-0101.

İz, H. Bâki, Yang, T.Y., Shum, C. (2020a) Rigorous adjustment of the global mean sea level budget during

2005-2015, Jl. of Geodesy and Geodynamics, doi:10.1016/j.geog.2020.03.001.
İz, H. Bâki, Shum, C., Yang, T.Y. (2020b) Conflation of satellite altimetry and tide gauge records at coast, J. J. Geodetic Science, 10:62–68, doi:10.1515/jogs-2020-0113.
Jin, T.Y., M. Xiao, W. Jiang, C.K. Shum, Ding, H., C-Y Kuo, J. Wan (2021). An Adaptive Method for Nonlinear Sea Level Trend Estimation by Combining EMD and SSA. Earth and Space Science, 8, doi:10.1029/2020EA001300
Kao, H.C., Kuo, C.Y., Tseng, K.H., Shum, C., Tseng, T.P., Jia, Y.Y., Yang, T.Y., Ali, A.A., Yi, Y., Hussain, D. (2019) Assessment of Cryosat-2 and SARAL/AltiKa Altimetry for Measuring Inland Water and Coastal Sea Level Variations: A Case Study on Tibetan Plateau Lake and Taiwan Coast, Marine Geodesy, doi:10.1080/01490419.2019.1623352,
Karimi, A. A., Deng, X., & Andersen, O. B. (2019). Sea Level Variation around Australia and Its Relation to Climate Indices. Marine Geodesy, 42(5), 469-489. doi:10.1080/01490419.2019.1629131
Karimi, A. A., Baltazar Andersen, O., & Deng, X. (2020). Mean Sea Surface and Mean Dynamic Topography Determination from Cryosat-2 Data around Australia. Advances in Space Research. doi:10.1016/j.asr.2020.01.009
Karimi, A. A., & Deng, X. (2020). Estimating sea level rise around Australia using a new approach to account for low frequency climate signals. Advances in Space Research, 65, 2324-2338. doi:10.1016/j.asr.2020.02.002
Kim, D., H. Lee, C.-H. Chang, D.D. Bui, S. Jayasinghe, S. Basnayake, F. Chistie, E. Hwang (2019). Daily river discharge estimation using multi-mission radar altimetry data and Ensemble Learning Regression in lower Mekong River Basin, Remote Sensing, 11, 2684, doi:10.3390/rs11222684.
Kim, D., H. Lee, E. Beighley, R.M. Tshimanga (2019). Estimating discharges for poorly gauged river basin using ensemble learning regression with satellite altimetry data and a hydrologic model, Advances in Space Research, doi:10.1016/j.asr.2019.08.018.
Kim, D., H. Yu, H. Lee, E. Beighley, M. Durand, D.E. Alsdorf, E. Hwang (2019). Ensemble learning regression for estimating river discharges using satellite altimetry data: central Congo River as a test-bed, Remote Sensing of Environment, 221, 741-755.
Klos, A., Kusche, J., Fenoglio-Marc, L., Bos, M., Bogusz, J. (2019) Introducing a vertical land motion model for improving estimates of sea level rates derived from tide gauge records affected by earthquakes. GPS Solut., 23: 102. doi.org/10.1007/s10291-019-0896-1.
Lee, C.M., Kuo, C.Y., Sun, J., Tseng, T.P., Chen, K.H., Lan, W.H., Shum, C., Ali, T., KChing, K.E., Chu, P., Jia, Y.Y. (2019) Evaluation and improvement of coastal GNSS reflectometry sea level variations from existing GNSS stations in Taiwan, Adv. Space Res., 63, 1280–1288, doi:10.1016/j.asr.2018.10.039.
Li, Q., Bao, L. & Shum, C.K. (2021), Altimeter-derived marine gravity variations reveal the magma mass motions within the subaqueous Nishinoshima volcano, Izu–Bonin Arc, Japan. J Geod 95, 46, https://doi.org/10.1007/s00190-021-01488-7.
LI, Q., L. Bao, & C.K. Shum (2020). Altimeter-derived marine gravity variation studies the submarine plate tectonic motions, Chinese Journal of Geophysics (in Chinese), 63(7): 2506-2515, doi: 10.6038/cjg2020N0436
Markert, K.N., S.T. Pulla, H. Lee, A.M. Markert, E.R. Anderson, M.A. Okeowo, A.S. Limaye (2019). AltEx: An open source web application and toolkit for accessing and exploring altimetry datasets, Environmental Modelling & Software, 117, 164-175.
Peng, F., & Deng, X. (2020a). Validation of Wind Speeds From Brown-Peaky Retracker in the Gulf of Mexico and East Coast of North America. IEEE Transactions on Geoscience and Remote Sensing, 58(8), 5793-5803. doi:10.1109/tgrs.2020.2970443
Peng, F., & Deng, X. (2020b). Validation of Sentinel-3A SAR mode sea level anomalies around the Australian coastal region. Remote Sensing of Environment, 237, 16 pages. doi:10.1016/j.rse.2019.111548
Peng, F., & Deng, X. (2020c). Improving precision of high-rate altimeter sea level anomalies by removing the sea state bias and intra-1-Hz covariant error. Remote Sensing of Environment, 251, 13 pages. doi:10.1016/j.rse.2020.112081
Sandwell, D.T., H. Harper, B. Tozer and W. H. F. Smith (2019) Gravity Field Recovery from Geodetic Altimeter Missions, 10.1016/j.asr.2019.09.011.
Schroeder, S., Springer, A., Kusche, A., Uebbing, B., Fenoglio, L., Diekkrueger, B., Pomeon, T. (2019). Niger discharge from radar altimetry: bridging gaps between gauge and altimetry time series Hydrol. Earth Syst. Sci., 23, 4113–4128, 2019 https://doi.org/10.5194/hess-23-4113-2019
Seifi, F., X. Deng and O. B. Andersen (2019) Assessment of the Accuracy of Recent Empirical and Assimilated Tidal Models for the Great Barrier Reef, Australia, Using Satellite and Coastal Data, Remote Sens. 2019, 11, 1211; doi:10.3390/rs11101211.
Seifi, F., Deng, X., & Ole Baltazar, A. (2019). UoNGBR: A Regional Assimilation Barotropic Tidal Model for the Great Barrier Reef and Coral Sea Based on Satellite, Coastal and Marine Data. Remote Sensing, 11(19), 22 pages. doi:10.3390/rs11192234
Staneva J., Wahle K., Koch W., Behrens A., Fenoglio-Marc L., Stanev E. (2016) Coastal flooding: impact of

waves on storm surge during extremes. A case study for the German Bight. Natural Hazards and Earth System Sciences, doi:10.5194/nhess.2016-227

Tozer, B., D. T. Sandwell, W.H.F. Smith, C. Olson, J. R. Beale, and P. Wessel (2019) Global bathymetry and topography at 15 arc seconds: SRTM15+, Earth and Space Science (in review)

Uebbing, B., Buchhaupt, C., Stolzenberger, S., Fenoglio, L., Kusche, J., and Dinardo, S.: Improving coastal altimetry results using the Spatio Temporal Altimetry Retracking for SAR (STARS), EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-3046, https://doi.org/10.5194/egusphere-egu21-3046, 2021.

Yang, Lianjun, Taoyong Jin, Xianwen Gao, Hanjiang Wen, Tilo Schöne, Mingyu Xiao, Hailan Huang (2021). Sea Level Fusion of Satellite Altimetry and Tide Gauge Data by Deep Learning in the Mediterranean Sea. Remote Sensing. 13, 908. https://doi.org/10.3390/rs13050908

Yao Yu, David T Sandwell, Sarah T Gille, Ana Beatriz Villas Bôas (2021), Assessment of ICESat-2 for the recovery of ocean topography, Geophysical Journal International, 226 (1), 456-467, https://doi.org/10.1093/gji/ggab084

Yu, DC, C Hwang, OB Andersen, ETY Chang, and L Gaultier (2021). Gravity recovery from SWOT altimetry using geoid height and geoid gradient, Remote Sensing of Environment, under revision, 2021

Yuan, T., H. Lee, H. Yu, H.C. Jung, A. Madson, Y. Sheng, E. Beighley (2019), Mapping forested floodplain topography using InSAR and radar altimetry, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12, 5189-5198.

Zhang, G.Q., Yao, T.D., Chen, W.F., Zheng, G.X., Shum, C., Yang, K., Piao, S.L., Sheng, Y.W., Yi, S., Li, J.L., O'Reilly, C.M., Qi, S.H., Shen, S.S. P., Zhang, H.B., Jia, Y.Y. (2019) Regional differences of lake evolution across China from 1960s to 2015, Remote Sens. of Environ., doi:10.1016/j.rse.2018.11.038, 221, 386–404.

Zhang, G.Q., Chen, W.F., Zheng, G.X., Xie, H.J., Shum, C. (2020a) Are China's water bodies (lakes) underestimated? Proceedings of the National Academy of Sciences, doi:10.1073/pnas.1922250117.

Zhang, G.Q., Yao,T .D., Xie, H.J., Yang, K., Zhu, L.P., Shum, C., Bolch, T., Yi, S.A., Allen, S., Jiang, L.G., Chen, W.F., Ke. C.Q., (2020b) Response of Tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms, Earth-Sci. Reviews, 208, 103269, doi:10.3390/geosciences9100415.

Zhu, C, J Guo, J Gao, X Liu, C Hwang, A Yu, J Yuan, B Ji, B Guan (2020). Marine gravity determined from multi-satellite-GM/ERM altimeter data over the South China Sea: SCSGA V1.0, Journal of Geodesy, 94 (5), https://doi.org/10.1007/s00190-020-01378-4.

Sub-commission 2.6: Gravity Inversion and Mass Transport in the Earth System

Chair: *Wei Feng (China)*
Vice Chair: *Roelof Rietbroek (Netherlands)*

Overview

Sub-commission 2.6 promotes and supports scientific research concerning spatial and temporal variations of gravity related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. The sub-commission is accompanied by a steering committee consisting of the members Cheinway Hwang, Vincent Humphrey, Jürgen Kusche, Maxime Mouyen, Jürgen Muller, John Reager, Wenbin Shen, Wenke Sun, and Bert Wouters. The members of the steering committee cover all relevant aspects from the various applications of space gravimetry on geodesy, hydrology, solid Earth, oceanography, and cryosphere, the mass transport inferred from terrestrial and space gravimetry. A working group focusing on the geodetic observations and physical interpretations in the Tibet has been established.

Activities and publications during the period 2019-2021

International Collaboration

A Sino-European international team (lead by the chair of SC2.6) supported by the International Space Science Institute (ISSI) and ISSI-Beijing was established in 2020 for gravity field modelling and improving our understanding of mass transport in the Earth system in the context of the GRACE and GRACE-FO missions. This international team project is an extension of the COST-G ISSI team supported by ISSI.

Figure 43 First round table meeting for the Sino-European international team organized by the Commission-2 president in Bern (16-17 Jan., 2020)

Satellite Gravimetry

Several terrestrial water storage anomaly (TWSA) reconstruction methods were proposed to bridge the gap between GRACE and GRACE-FO or infer the TWSA in the pre-GRACE era, e.g. using SLR data (Löcher and Kusche, 2021), Swarm POD data (Richter et al.2021), or using statistical reconstructions (Li et al. 2021). A recent study also tried to understand how, in the future, one could validate GRACE-FO or successor missions with optical clocks linked by fibre networks (Schröder et al., 2021). Another direction of recent work is creating a global reanalysis of terrestrial water storage via assimilating GRACE data into a hydrological model, with one of the final objectives being able to provide GRACE-based drought estimates (Gerdener et al., 2020) at 50 km resolution. In addition, the performance of GRACE mascon solutions was investigated for seismic studies (Zhang et al., 2019, Zhang et al., 2020).
In the framework of the Greenland Ocean ice sheet interaction project (funded by the German BMBF), S. Stolzenberger (with R. Rietbroek and J. Kusche), is working on modelling the effects of meltwater fluxes to the ocean circulation. A crucial aspect is the validation of the simulations with geodetic observations (Figure 44).

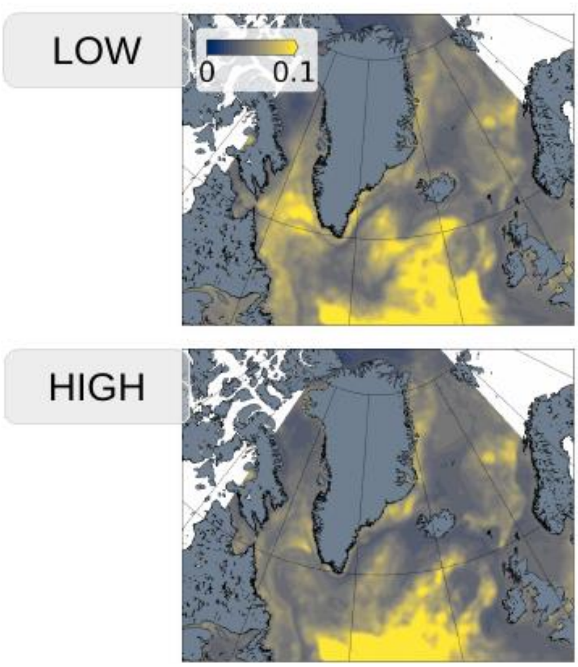


Figure 44 Root mean square error of sea surface height changes from an ocean model forced with meltwater (two different resolutions), and from a joint inversion (from B. Uebbing, Bonn) of GRACE and altimetry. Source: Stolzenberger et al. 2021 (EGU2021 https://doi.org/10.5194/egusphere-egu21-8225, 2021)

Ground gravimetry

Mouyen et al. (2019) conducted a preliminary investigation of the dual-Superconducting Gravimeter (SG) configuration in the Low Noise Laboratory in Rustrel (France) with a focus on groundwater redistributions in karstic aquifer. The two SGs are located about 400 m depth apart, one in an underground tunnel, the other one at the surface, roughly right above the underground SG. They evaluated the complementary attraction of the ground water on both SGs This work was continued under the lead of Séverine Rosat and Jacques Hinderer at Strasbourg. In addition, artificial intelligence methods, specifically deep neural networks, were used to predict groundwater level variations from rainfall and other meteorological data, and to explain gravity residual in SG time series recorded at the Onsala Space Obersvatory (Våge, 2020).

The group led by Cheinway Hwang established an absolute gravity site (Wanlong) to monitor gravity changes due to infiltrations and groundwater changes in the Pingtung Alluvial Fan, southern Taiwan for 1.5 years since May 2019. The annual peak-to-peak gravity change here was 135 μgal. A monsoonal rain in May 2020 introduced large gravity changes lasting for 3 days. Unlike the steady increase of groundwater level, the gravity values underwent three stages of changes: a rapid rise, followed by nearly zero changes for few days, and finally a gentle rise consistent with the rise of groundwater level. The gravity experiment showed that absolute gravity observations can verify the process of surface water infiltrated into an unsaturated zone to recharge the saturated zone, and can determine depth-dependent specific yields. In addition, inversion of sediment mass redistribution in a landsliding area was done in Taiwan from joint photogrammetry and gravimetry (Mouyen et al., 2020). Since only gravity can really sense mass, one can get more reliable quantification of erosion than with optic methods alone. However, the gravity survey remains a practical challenge. Small and cheap gravity sensors (MEMS gravimeter) may prove useful for such studies in the near future.

Meetings

Several members (R. Rietbroek, V. Humphrey, B. Wouters, J. Kusche) of the SC2.6 have contributed, both on an organizational level and in the forms of scientific content and keynote lectures, to the workshop initiated by the Inter-Commission Committee on Geodesy for Climate Research (ICCC) which was online held in March 2021. The workshop covered topics, closely related to the mass transport theme of the SC2.6, such as the use of (satellite) gravity and deformation data to study changes in hydrology, the cryosphere, and the ocean. Furthermore, during the 2021 general assembly of the EGU, commission members have been active as session conveners and presenters.

- S. Stolzenberger, R. Rietbroek, C. Wekerle, B. Uebbing, J. Kusche, Greenland meltwater effects in geodetic and oceanographic data, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021
- M. O. Willen, B. Uebbing, M. Horwath, J. Kusche, Constraining the contributions of ice sheets to sea-level rise in a global inversion framework, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021
- R. Rietbroek, T. Frederikse , I. Sasgen, Keynote lecture: A tango between ice and sea level, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021
- V. Humphrey, Keynote lecture: Climate models for geodesy, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021
- P. Khapikova, V. Humphrey, C. Frankenberg, Evaluating CMIP6 soil water storage with GRACE satellite observations, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021
- M. O. Willen, T. Broerse, A. Groh, B. Wouters, P. Kuipers Munneke, M. Horwath, M. R. van den Broeke, L. Schröder, Time dependent contributions to the mass balance of Antarctic drainage systems from satellite geodesy and model products, IAG-ICCC workshop “Geodesy for Climate Research”, March 29-31 2021

References

Mouyen, M., Longuevergne, L., Chalikakis, K., Mazzilli, N., Ollivier, C., Rosat, S., et al. (2019). Monitoring of groundwater redistribution in a karst aquifer using a superconducting gravimeter. E3S Web Conf., 88. https://doi.org/10.1051/e3sconf/20198803001

Zhang, L., Yi, S., Wang, Q., Chang, L., Tang, H., & Sun, W. (2019). Evaluation of GRACE mascon solutions for small spatial scales and localized mass sources. Geophysical Journal International, 218(2), 1307–1321. https://doi.org/10.1093/gji/ggz198

Chen, K.-H., Hwang, C., Chang, L.-C., Tsai, J.-P., Yeh, T.-C. J., Cheng, C.-C., et al. (2020). Measuring aquifer specific yields with absolute gravimetry: Result in the Choushui River Alluvial Fan and Mingchu Basin, central Taiwan. Water Resources Research, 56(9), e2020WR027261. https://doi.org/10.1029/2020WR027261

Gerdener, H., Engels, O., & Kusche, J. (2020). A framework for deriving drought indicators from the Gravity Recovery and Climate Experiment (GRACE). Hydrol. Earth Syst. Sci., 24(1), 227–248. https://doi.org/10.5194/hess-24-227-2020

Löcher, A., & Kusche, J. (2020). A hybrid approach for recovering high-resolution temporal gravity fields from satellite laser ranging. Journal of Geodesy, 95(1), 6. https://doi.org/10.1007/s00190-020-01460-x

Mouyen, M., Steer, P., Chang, K.-J., Le Moigne, N., Hwang, C., Hsieh, W.-C., et al. (2020). Quantifying sediment mass redistribution from joint time-lapse gravimetry and photogrammetry surveys. Earth Surface Dynamics, 8(2), 555–577. https://doi.org/10.5194/esurf-8-555-2020

Våge, M. (2020). Groundwater and gravity modelling using recurrent neural networks Master's thesis in Complex Adaptive Systems. Retrieved from https://odr.chalmers.se/handle/20.500.12380/302274

Zhang, L., Tang, H., Chang, L., & Sun, W. (2020). Performance of GRACE Mascon Solutions in Studying Seismic Deformations. Journal of Geophysical Research: Solid Earth, 125(10), e2020JB019510. https://doi.org/https://doi.org/10.1029/2020JB019510

Li, F., Kusche, J., Chao, N., Wang, Z., & Löcher, A. (2021). Long-Term (1979-Present) Total Water Storage Anomalies Over the Global Land Derived by Reconstructing GRACE Data. Geophysical Research Letters, 48(8), e2021GL093492. https://doi.org/10.1029/2021GL093492

Richter, H. M. P., Lück, C., Klos, A., Sideris, M. G., Rangelova, E., & Kusche, J. (2021). Reconstructing GRACE-type time-variable gravity from the Swarm satellites. Scientific Reports, 11(1), 1117. https://doi.org/10.1038/s41598-020-80752-w

Schröder, S., Stellmer, S., & Kusche, J. (2021). Potential and scientific requirements of optical clock networks for validating satellite-derived time-variable gravity data. Geophysical Journal International, 226(2), 764–779. https://doi.org/10.1093/gji/ggab132

Commission 3 – Earth Rotation and Geodynamics

https://com3.iag-aig.org/

President: Janusz Bogusz (Poland)
Vice-President: Chengli Huang (China)

Structure

Sub-Commission 3.1:	Earth Tides and Geodynamics
Sub-Commission 3.2:	Volcano Geodesy (joint with IAVCEI)
Sub-Commission 3.3:	Earth Rotation and Geophysical Fluids
Sub-Commission 3.4:	Cryospheric Deformation (joint with IACS)
Sub-Commission 3.5:	Seismogeodesy (joint with IASPEI)
Joint Study Group 3.1:	Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment (joint with IAG Commissions 1 and 2)
Joint Working Group 3.1:	Improving Theories and Models of the Earth's Rotation (joint with IAU)
Joint Working Group 3.2:	Global combined GNSS velocity field (joint with IAG Commissions 1 and 2)

Overview

This report presents the activities of the entities of Commission 3 for the reporting period 2019-2021. The Commission consists of 5 Sub-Commissions, 2 Joint Working Groups and Joint Study Groups. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research related to monitoring, explaining and numerically describing dynamic changed within Earth system. Sub-Commission 3.1 (Earth Tides and Geodynamics) addresses direct and indirect tidal phenomena that affect the position of fiducial sites and have to be corrected to provide accurate spatial referencing. Sub-Commission 3.2 (Volcano Geodesy) addresses explosion in the quality and quantity of volcano geodetic data, which has created a need for new approaches to data analysis, interpretation, and modelling required for data fusion and joint interpretation, both between geodetic datasets and with other types of volcano monitoring results. Sub-Commission 3.3 (Earth Rotation and Geophysical Fluids) addresses the space-time variation of atmospheric pressure, seafloor pressure and the surface loads associated with the hydrological cycle, and Earth's (mainly elastic) responses to these mass redistributions. Sub-Commission 3.4 (Cryospheric Deformation) addresses past and present changes in the mass balance of the Earth's glaciers and ice complexes which both induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Sub-Commission 3.5 (Seismogeodesy) addresses studying the plate boundary deformation zones and integration of geodetic and seismological monitoring of seismically active areas by increasing and/or developing infrastructures dedicated to broadband observations from the seismic wave band to the permanent displacement. Commission 3 interacts with Global Geodetic Observing System (GGOS), other Commissions and Services of the IAG as well as with other organizations such as the International Astronomical Union (IAU), International Association of Seismology and Physics of the Earth's Interior (IASPEI), International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and International Association of Cryospheric Sciences (IACS). Because of pandemic situation the on-site activities in 2019-2021 were very limited, however on-line activities of the Commission 3 entities were significant and described in details in the following part of this report.

Sub-commission 3.1: Earth Tides and Geodynamics

Chair: *Carla Braitenberg (Italy)*
Vice-Chair: *Séverine Rosat (France)*

Terms of Reference

SC 3.1 addresses the entire range of Earth tidal phenomena and dynamics of the Earth, both on the theoretical as well as on the observational level. The Earth tide affects many types of high precision instrumentation, be it measurements of position, deformation, potential field or acceleration. The tidal phenomena influence both terrestrial and satellite-borne acquisitions. The tidal potential is a driving force that can be accurately calculated, and the tidal response observable as deformation and variations in Earth orientation and rotation parameters gives information on Earth's rheology. Instruments sensitive enough to detect the tidal signal, record a large range of periodic and aperiodic phenomena as ocean and atmospheric tidal loading, ocean, atmospheric and hydrospheric non-tidal effects, deformation related to the earthquake cycle and even to gravitational waves, as well as plate tectonics and intraplate deformation. The periods range from seismic normal modes over to the Earth tides and the Chandler Wobble and beyond, ending at the nutation period. Thus, the time scales range from seconds to years and for the spatial scales from local to continental dimensions. The improvements in gravimetric instrumentation leads to the use of gravimetry as a tool to detect underground mass changes, as naturally occurring hydrologic draughts or fluids injected into the underground for the purpose of temporary storage or for other purposes. The Earth must be studied as a dynamic system through the study of the global gravity field and its temporal variations, and the global and local deformation at the surface in order to define the Earth's internal structure and dynamics.

Summary of the Sub-commission's activities during the period 2019-2021

Meetings:

- Organization of the 19th International Symposium on Geodynamics and Earth Tides that will be held June 22-26, 2021 in Wuhan, China.
- Participation in the organization of the sessions
- Organization of the call and the committee for the assignment of the Melchior Medal 2021.

<u>Website</u>: http://get2020.csp.escience.cn/dct/

Sessions:

- **Session 1: Tides and non-tidal loading**
  - Conveners: Jean-Paul Boy, Heping Sun, Hartmut Wziontek, David Crossley
- **Session 2: Geodynamics and the earthquake cycle**
  - Conveners: Severine Rosat, Kosuke Heki, Thomas Jahr, Wenke Sun
- **Session 3: Variations in Earth rotation**
  - Conveners: Chengli Huang, Harald Schuh, Ben Chao, Janusz Bogusz
- **Session 4: Time variable gravity and mass redistribution**
  - Conveners: Cheinway Hwang, Carla Braitenberg, Holger Steffen, Wei Feng
- **Session 5: Monitoring of subsurface fluids**
  - Conveners: Jacques Hinderer, Jaakko Makinen, Yoichi Fukuda, Giuliana Rossi
- **Session 6: New technology and software development**
  - Conveners: Olivier Francis, Jürgen Müller, Hannu Ruotsalainen, Zhongkun Hu

Special sessions at international meetings: EGU 2019, 2020, 2021; AGU 2019, 2020, 2021.

Editorial activities: support and promotion in the role as Editor of themes related to the SC 3.1 in the journal Pure and Applied Geophysics.

Peer-reviewed publications:

Abdelfettah, Y., Hinderer, J., Calvo, M., Dalmais, E., Maurer, V., Genter, A., 2020. Using highly accurate land gravity and 3D geologic modeling to discriminate potential geothermal areas: Application to the Upper Rhine Graben, France, Geophysics, Society of Exploration Geophysicists, 85 (2), pp.G35-G56. 10.1190/geo2019-0042.1

Arana, D., Oliveira Camargo, P., E. Cassola Molina, D. Blitzkow, Ana Cristina Oliveira Cancoro de Matos, et al.. 2020. The Impact of Atmospheric Correction on Brazilian Earth Tide Models. Pure and Applied Geophysics, Springer Verlag, 177 (9), pp.4377-4389. Doi:10.1007/s00024-020-02486-0

Boy, J.-P., Barriot, J.-P., Förste, C., Voigt, C., Wziontek, H., 2020. Achievements of the First 4 Years of the International Geodynamics and Earth Tide Service (IGETS) 2015-2019. International Association of Geodesy Symposia, doi:10.1007/1345_2020_94

Canuel, B., S. Abend, P. Amaro-Seoane, F. Badaracco, Q. Beaufils, A. Bertoldi, K. Bongs, P. Bouyer, C. Braxmaier, W. Chaibi, N. Christensen, F. Fitzek, G. Flouris, N. Gaaloul, S. Gaffet, C. L. Garrido Alzar, R. Geiger, S. Guellati-Khelifa, K. Hammerer, J. Harms, J. Hinderer, J. Junca, S. Katsanevas, C. Klempt, C. Kozanitis, M. Krutzik, A. Landragin, I. Làzaro Roche, B. Leykauf, Y.-H. Lien, S. Loriani, S. Merlet, M. Merzougui, M. Nofrarias, P. Papadakos, F. Pereira, A. Peters, D. Plexousakis, M. Prevedelli, E. Rasel, Y. Rogister, S. Rosat, A. Roura, D. O. Sabulsky, V. Schkolnik, D. Schlippert, C. Schubert, L. Sidorenkov, J.-N. Siemß, C. F. Sopuerta, F. Sorrentino, C. Struckmann, G. M. Tino, G. Tsagkatakis, A. Viceré, W. von Klitzing, L. Woerner, X. Zou, 2020. ELGAR - a European Laboratory for Gravitation and Atom-interferometric Research, Class. Quantum Grav., 37, 225017 https://doi.org/10.1088/1361-6382/aba80e

Carabajal, C. & J.-P. Boy, 2020. Lake and reservoir volume variations in South America from radar altimetry, ICESat laser altimetry, and GRACE time-variable gravity, Advances in Space Research, doi:10.1016/j.asr.2020.04.022

Carabajal, C. & J.-P. Boy, 2020. ICESAT-2 ALTIMETRY AS GEODETIC CONTROL, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIII-B3-2020, pp.1299-1306. Doi:10.5194/isprs-archives-XLIII-B3-2020-1299-2020

Chaffaut, Q., Hinderer, J., Masson, F., Viville, D., Bernard, J.-D. et al.. 2020. Continuous Monitoring with a Superconducting Gravimeter As a Proxy for Water Storage Changes in a Mountain Catchment, International Association of Geodesy Symposia, doi:10.1007/1345_2020_105

Cheraghi, H., Hinderer, J., S. Abdoreza Saadat, J.-D. Bernard, Y. Djamour, et al., 2019. Stability of the Calibration of Scintrex Relative Gravimeters as Inferred from 12 Years of Measurements on a Large Amplitude Calibration Line in Iran. Pure and Applied Geophysics, Springer Verlag, doi:10.1007/s00024-019-02300-6

Gillet, N., Dumberry, M. & S. Rosat, 2020. The limited contribution from outer core dynamics to global deformations at the Earth's surface, Geophys. J. Int., 224, 216-229, https://doi.org/10.1093/gji/ggaa448

Hinderer, J., Hector, B., Riccardi, U., Rosat, S., Boy, J.-P., Calvo, M., Littel, F. and J.-D. Bernard, 2020. A study of the monsoonal hydrology contribution using a 8-yr record (2010-2018) from superconducting gravimeter OSG-060 at Djougou (Benin, West Africa), Geophys. J. Int., 221, 431 – 439, doi: 10.1093/gji/ggaa027

Hinderer, J., Riccardi, U., Rosat, S., Boy, J.-P., Hector, B., Calvo, M., Littel, F., Bernard, J.-D., 2020. A study of the solid earth tides, ocean and atmospheric loadings using an 8-year record (2010-2018) from superconducting gravimeter OSG-060 at Djougou (Benin, West Africa), J. Geodyn., 134, https://doi.org/10.1016/j.jog.2019.101692

Majstorovic, J., Rosat, S. & Y. Rogister, 2019. Earth's spheroidal motion induced by a gravitational wave in flat space-time, Phys. Rev. D., 100, 044048, 10.1103/PhysRevD.100.044048

Majstorovic, J., Rosat, S., Lambotte, S. and Y. Rogister, 2019. Testing performances of the optimal sequence estimation and autoregressive method in frequency domain for estimating eigenfrequencies and zonal structure coefficients of low-frequency normal modes, Geophys. J. Int., 216, 1157-1176, https://doi.org/10.1093/gji/ggy483

Mémin, A., Ghienne, J.-F., Hinderer, J., Roquin, C. & M. Schuster, 2020. The Hydro-Isostatic Rebound Related to Megalake Chad (Holocene, Africa): First Numerical Modelling and Significance for Paleo-Shorelines Elevation. Water, MDPI, 12 (11), pp.3180. doi:10.3390/w12113180

Mémin, A., Boy, J.-P., Santamaria-Gomez, A., 2020. Correcting GPS measurements for non-tidal loading, GPS Solutions, 24 (2), 10.1007/s10291-020-0959-3

Mouyen, M., Longuevergne, L., Chalikakis, K., Mazzilli, N., Ollivier, C., Rosat, S., Hinderer, J., Champollion, C., 2019. Monitoring of groundwater redistribution in a karst aquifer using a superconducting gravimeter, E3S Web of Conf., 88, 03001, https://doi.org/10.1051/e3sconf/20198803001

Mouyen, M., Steer, P., Chang, K.-J., Le Moigne, N., Hwang, C., Hsieh, W.-C., Jeandet, L., Longuevergne, L., Cheng, C.-C., Boy, J.-P., Masson, F., 2020. Quantifying sediment mass redistribution from joint time-lapse gravimetry and photogrammetry surveys, Earth Surface Dynamics, European Geosciences Union, 8 (2), pp.555-577, doi:10.5194/esurf-8-555-2020

Nicolas, J., Verdun, J., Boy, J.-P., Bonhomme, L., Asri, A. et al. 2021. Improved Hydrological Loading Models in South America: Analysis of GPS Displacements Using M-SSA. Remote Sensing, MDPI, GNSS for Geosciences, 13 (9), pp.1605, doi:10.3390/rs13091605

Rosat, S., Boy, J.-P., Bogusz, J. and A. Klos, 2020. Inter-Comparison of Ground Gravity and Vertical Height Measurements at Collocated IGETS Stations. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, https://doi.org/10.1007/1345_2020_117

Rosat, S., Gillet, N., Boy, J.-P., Couhert, A. & M. Dumberry, 2021. Interannual variations of degree 2 from geodetic observations and surface processes, Geophys. J. Int., 225(1), 200-221, doi: 10.1093/gji/ggaa590

Schäfer, F., Jousset, P., Güntner, A., Erbas, K., Hinderer, J., Rosat, S., Voigt, C., Schöne, T. and R. Warburton, 2020. Performance of three iGrav superconducting gravity meters before and after transport to remote monitoring sites, Geophys. J. Int., 223, 2, 959-972, https://doi.org/10.1093/gji/ggaa359

Tiwari, V. & J. Hinderer, 2020. Gravity Field, Time Variations from Surface Measurements. Encyclopedia Solid Earth Geophysics 2nd edition.

Vitagliano, E., Riccardi, U., Piegari, E., Boy, J.-P., Di Maio, R., 2020. Multi-Component and Multi-Source Approach for Studying Land Subsidence in Deltas, Remote Sensing, MDPI, 12 (9), pp.1465. doi:10.3390/RS12091465

Ziegler, Y., Lambert S, Nurul Huda I, Bizouard C., Rosat, S., 2020. Contribution of a joint Bayesian inversion of VLBI and gravimetric data to the estimation of the Free Inner Core Nutation and Free Core Nutation resonance parameters, Geophys. J. Int., 222, 2, 845-860, https://doi.org/10.1093/gji/ggaa181

Braitenberg, C., 2021. Gravity, in: Encyclopedia of Geology. Elsevier, pp. 706–718. https://doi.org/10.1016/B978-0-08-102908-4.00182-X

Braitenberg C., Pivetta T., Barbolla D. F., Gabrovsek F., Devoti R., Nagy I. (2019). Terrain uplift due to natural hydrologic overpressure in karstic conduits. Scientific Reports, 9:3934, 1-10, doi.:10.1038/s41598-019-38814-1.

Delvaux, D., Maddaloni, F., Tesauro, M., Braitenberg, C., 2021. The Congo Basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data. Global and Planetary Change 198, 103407. https://doi.org/10.1016/j.gloplacha.2020.103407

Kaban, M.K., Delvaux, D., Maddaloni, F., Tesauro, M., Braitenberg, C., Petrunin, A.G., El Khrepy, S., 2021. Thickness of sediments in the Congo basin based on the analysis of decompensative gravity anomalies. Journal of African Earth Sciences 179, 104201. Alvarez O., Gimenez M., Folguera A., Chaves C. A. M., Braitenberg C. (2019). Reviewing megathrust slip behavior for recent Mw>8.0 earthquakes along the Peru-Chilean margin from satellite GOCE gravity field derivatives. Tectonophysics, Volume 769, 20 October 2019, 228188, https://doi.org/10.1016/j.tecto.2019.228188

Migliaccio. F., M. Reguzzoni, K. Batsukh, G. M. Tino, G. Rosi, F. Sorrentino, C. Braitenberg, T. Pivetta, D. F. Barbolla, S. Zoffoli (2019) MOCASS: a satellite mission concept using Cold Atom Interferometry for measuring the Earth gravity Field, Surveys in Geophysics, 40(5), 1029-1053.

Motta J. G., de Souza Filho C. R., Carranza E. J. M., Braitenberg C. (2019). Archean crust and metallogenic zones in the Amazonian Craton sensed by satellite gravity data. Scientific Reports, 9:2565, 1-10, doi:10.1038/s41598-019-39171-9.

Pail, R., Bamber, J., Biancale, R., Bingham, R., Braitenberg, C., Eicker, A., Flechtner, F., Gruber, T., Güntner, A., Heinzel, G., Horwath, M., Longuevergne, L., Müller, J., Panet, I., Savenije, H., Seneviratne, S., Sneeuw, N., Dam, T. van and Wouters, B. (2019). Mass variation observing system by high low inter-satellite links (MOBILE) – a new concept for sustained observation of mass transport from space, Journal of Geodetic Science, 9(1), 48–58, doi:10.1515/jogs-2019-0006.

Pastorutti A., Braitenberg C. (2019) A geothermal application for GOCE satellite gravity data: modelling the crustal heat production and lithospheric temperature field in Central Europe, Geophysical Journal International, 219, 1008–1031, https://doi.org/10.1093/gji/ggz344.

Pivetta T., Braitenberg C. (2020). Sensitivity of gravity and topography regressions to earth and planetary structures. Tectonophysics, 774, 228299, doi:10.1016/j.tecto.2019.228299,

Reguzzoni M., Migliaccio F., Batsukh K., (2021) : Gravity field recovery and error analysis for the MOCASS mission proposal based on cold atom interferometry, Pure and Applied Geophysics, accepted, in press-

Rossi, G., Pastorutti, A., Nagy,I., Braitenberg, C., Parolai, S., 2021. Recurrence of fault-valve behavior in a continental collision area: evidence from tilt/strain measurements in Northern Adria, Front. Earth Sci.,doi: 10.3389/feart.2021.641416

Tadiello, D. and Braitenberg, C.: Gravity modeling of the Alpine lithosphere affected by magmatism based on seismic tomography, Solid Earth, 12, 539–561, https://doi.org/10.5194/se-12-539-2021, 2021.

Zahorec, P., Papčo, J., Pašteka, R., Bielik, M., Bonvalot, S., Braitenberg, C., Ebbing, J., Gabriel, G., Gosar, A., Grand, A., Götze, H.-J., Hetényi, G., Holzrichter, N., Kissling, E., Marti, U., Meurers, B., Mrlina, J., Nogová, E., Pastorutti, A., Scarponi, M., Sebera, J., Seoane, L., Skiba, P., Szűcs, E., Varga, M., 2021. The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. Earth Syst. Sci. Data Discuss. 2021, 1–72. https://doi.org/10.5194/essd-2020-375

Sub-commission 3.2: Volcano Geodesy

Joint with IAVCEI

Chair: *Emily Montgomery-Brown (USA)*
Vice-Chair: *Alessandro Bonforte (Italy)*

Summary of the Sub-commission's activities during the period 2019-2021

A meeting of the Commission has been held in Portland on 7 and 8 October, 2020 together with the CONVERSE Research Coordination Network ("How to respond to (pre)eruptive volcanic activity for highest scientific return?"). During this meeting, the activities of the commission were discussed and future actions were planned. The pandemic reduced all the activities since the beginning of 2020. As a major effect, the pandemic forced the commission to cancel the plans for an October 2020 workshop in Yellowstone. However, the volcano-geodesy commission organized a virtual meeting on December 15 and 16 at two different times to meet colleagues participating from different time zones. Upcoming activities were discussed for upcoming meetings and a modelling exercise was planned in two parts, an initial virtual exercise in 2021 followed by an in-person exercise when in-person meetings resume. The website was rebuilt from scratch in late 2020/early 2021 after it was corrupted. We contributed to the IAG Highlights report with a series of highlights featured on our website, including a discussion of volcano monitoring during the pandemic.

Meetings and Special Sessions:

- 2019 EGU General Assembly: From slow-spreading to rapid mass-movements in alpine and volcano-tectonic settings. Advances on monitoring, modelling and risk management (8 oral presentations, 16 poster presentations);
- 2019 EGU General Assembly: Volcanic Processes: Tectonics, Deformation, Geodesy, Unrest (20 oral presentations, 27 poster presentations);
- 2019 AGU Fall Meeting: Improving Volcano Deformation Interpretations with Integrated Multidisciplinary Data. (8 Abstracts);
- 2020 Cities on Volcanoes: Volcano deformation: data integration, models, ambiguities and implications for eruption forecasting;
- 2021 IAVCEI Assembly: Global applications of Volcano Geodesy.

Peer-reviewed publications:

Alparone, S., Bonforte, A., Gambino, S., Guglielmino, F., Obrizzo, F., & Velardita, R. (2019). Dynamics of Vulcano Island (Tyrrhenian Sea, Italy) investigated by long-term (40 years) geophysical data. *Earth-Science Reviews*, *190*, 521-535.

Anantrasirichai, N., Biggs, J., Albino, F., & Bull, D. (2019). A deep learning approach to detecting volcano deformation from satellite imagery using synthetic datasets. *Remote Sensing of Environment*, *230*, 111179.

Anderson, K. R., Johanson, I. A., Patrick, M. R., Gu, M., Segall, P., Poland, M. P., ... & Miklius, A. (2019). Magma reservoir failure and the onset of caldera collapse at Kīlauea Volcano in 2018. *Science*, *366*(6470).

Azzaro, R., Bonforte, A., D'Amico, S., Guglielmino, F., & Scarfì, L. (2020). Stick-slip vs. stable sliding fault behaviour: A case-study using a multidisciplinary approach in the volcanic region of Mt. Etna (Italy). *Tectonophysics*, *790*, 228554.

Battaglia, Maurizio; Alpala, Jorge A.; Alpala, Rosa L.; Angarita, Mario; Arcos, Dario; Euillades, Leonardo; Euillades, Pablo; Muller, Cyril; Medina, Lourdes Narváez (2020). Monitoring Volcanic Deformation. Encyclopedia of Geology, 2nd edition, Elsevier.

Beauducel, F., Peltier, A., Villie, A., & Suryanto, W. (2020). Mechanical imaging of a volcano plumbing system from GNSS unsupervised modeling. Geophysical Research Letters, 47, e2020GL089419. https://doi.org/10.1029/2020GL089419

Bonforte, A., Guglielmino, F., & Puglisi, G. (2019). Large dyke intrusion and small eruption: The December 24, 2018 Mt. Etna eruption imaged by Sentinel-1 data. *Terra Nova*, *31*(4), 405-412.

Boixart, G., Cruz, L. F., Miranda Cruz, R., Euillades, P. A., Euillades, L. D., & Battaglia, M. (2020). Source Model for Sabancaya Volcano Constrained by DInSAR and GNSS Surface Deformation Observation. Remote Sensing, 12(11), 1852.

Cayol V., A. Peltier A., J.L. Froger, F. Beauducel, Monitoring of Volcano deformation, in Hazards and Monitoring of Volcanic Activity, Volume 2, Sismology, deformation and remote sensing, ISTE Science Publishing LTD, in the press 2021.

Camacho, A.G., Prieto, J.F., Ancochea, E., Fernández, J., 2019. Deep volcanic morphology below Lanzarote, Canaries, from gravity inversion: New results for Timanfaya and implications. Journal of Volcanology and Geothermal Research, 369, 64-79, doi: 10.1016/j.jvolgeores.2018.11.013.

Camacho, A.G., Fernández, J., 2019. Modeling 3D free-geometry volumetric sources associated to geological and anthropogenic hazards from space and terrestrial geodetic data. Remote Sens., 11(17), 2042; doi: 10.3390/rs11172042.

Camacho, A.G., Fernández, J., Samsonov, S.V., Tiampo K.F., Palano, M., 2020. Multisource 3D modelling of elastic volcanic ground deformations. Earth and Planetary Science Letters, 547C, 116445. https://doi.org/10.1016/j.epsl.2020.116445.

Camacho, A.G., Prieto, J.F., Aparicio, A., Ancochea, E., Fernández, J., 2021. Upgraded GROWTH 3.0 software for structural gravity inversion and application to El Hierro (Canary Islands). Computers & Geosciences, 150, 104720 https://doi.org/10.1016/ j.cageo.2021.104720.

Delgado, F. (2021). Rhyolitic volcano dynamics in the Southern Andes: Contributions from 17 years of InSAR observations at Cordón Caulle volcano from 2003 to 2020. *Journal of South American Earth Sciences*, *106*, 102841.

Escayo, J., Fernández, J., Prieto, J.F., Camacho, A.G., Palano, M., Aparicio, A., Rodríguez-Velasco, G., Ancochea, E., 2020. Geodetic study of the 2006-2010 ground deformation in La Palma (Canary Islands): observational results. Remote Sens., 12, 2566; doi:10.3390/rs12162566.

Fernández, J., Escayo, J., Hu, Z., Camacho, A.G., Samsonov, S.V., Prieto, J.F., Tiampo, K.F., Palano, M., Mallorquí, J.J., Ancochea, E., 2021. Detection of volcanic unrest onset in La Palma, Canary Islands, evolution and implications. Scientific Reports, 11:2540, https://doi.org/10.1038/s41598-021-82292-3.

Gailler L., J.F. Lénat and F. Donndaieu, Monitoring of gravimetry, in Hazards and Monitoring of Volcanic Activity, Volume 3, Fluids, gravity, magnetic and electrical methods, ISTE Science Publishing LTD, in the press 2021.

Greco, F., Bonforte, A., Carbone, D., & Messina, A. A. (2019, January). Results from 10 years of absolute gravity measurements at Mt. Etna volcano (Italy). In *Geophysical Research Abstracts* (Vol. 21).

Hamling, I. J. (2020). InSAR observations over the Taupō Volcanic Zone's cone volcanoes: insights and challenges from the New Zealand volcano supersite. *New Zealand Journal of Geology and Geophysics*, 1-11.

Hill, D. P., Montgomery-Brown, E. K., Shelly, D. R., Flinders, A. F., & Prejean, S. (2020). Post-1978 tumescence at Long Valley caldera, California: a geophysical perspective. *Journal of Volcanology and Geothermal Research*, *400*, 106900.

Hickey, J., Lloyd, R., Biggs, J., Arnold, D., Mothes, P., & Muller, C. (2020). Rapid localized flank inflation and implications for potential slope instability at Tungurahua volcano, Ecuador. *Earth and Planetary Science Letters*, *534*, 116104.

Jiang, Y., & González, P. J. (2020). Bayesian Inversion of Wrapped Satellite Interferometric Phase to Estimate Fault and Volcano Surface Ground Deformation Models. *Journal of Geophysical Research: Solid Earth*, *125*(5), e2019JB018313.

Jones, R. J., D. S. Stamps, C. Wauthier, E. Saria (2019), Evidence for slip on a border fault triggered by magmatic processes in an immature continental rift, *Geochemistry Geophysics Geosystems*, DOI: 10.1029/2018GC008165.

Kintner, J. A., C. Wauthier, C. J. Ammon (2019), InSAR and Seismic Analyses of the 2014-15 Earthquake Sequence near Bushkan, Iran: Growth of an Anticline, *Geophysical Journal International*, ggz065, DOI: https://doi.org/10.1093/gji/ggz065.

Lechner, H. N., C. Wauthier, G. P. Waite, R. Escobar-Wolf (2019), Magma storage and diking revealed by GPS geodesy at Pacaya volcano, Guatemala, *Bulletin of Volcanology*, DOI: 10.1007/s00445-019-1277-x.

Lundgren, P., Girona, T., Bato, M. G., Realmuto, V. J., Samsonov, S., Cardona, C., ... & Aivazis, M. (2020). The dynamics of large silicic systems from satellite remote sensing observations: The intriguing case of Domuyo volcano, Argentina. *Scientific reports*, *10*(1), 1-15.

Mattia, M., Bruno, V., Montgomery-Brown, E., Patanè, D., Barberi, G., & Coltelli, M. (2020). Combined Seismic and Geodetic Analysis Before, During, and After the 2018 Mount Etna Eruption. *Geochemistry, Geophysics, Geosystems*, *21*(9), e2020GC009218.

Miguelsanz, L., González, P.J., Tiampo, K:F., Fernández, J., 2021. Tidal influence on seismic activity during the 2011-2013 El Hierro volcanic unrest. Tectonics, 40, e2020TC006201. https://doi.org/10.1029/2020TC006201.

Montgomery-Brown, E. K., & Miklius, A. (2021). Periodic dike intrusions at Kı-lauea volcano, Hawai'i. *Geology*, *49*(4), 397-401.

Morales Rivera, A. M., Amelung, F., Albino, F., & Gregg, P. M. (2019). Impact of crustal rheology on temperature-dependent viscoelastic models of volcano deformation: Application to Taal Volcano, Philippines. *Journal of Geophysical Research: Solid Earth*, *124*(1), 978-994.

Neal, C. A., Brantley, S. R., Antolik, L., Babb, J. L., Burgess, M., Calles, K., ... & Damby, D. (2019). The 2018 rift eruption and summit collapse of Kīlauea Volcano. Science, 363(6425), 367-374.

Patrick, M. R., Houghton, B. F., Anderson, K. R., Poland, M. P., Montgomery-Brown, E., Johanson, I., ... & Elias, T. (2020). The cascading origin of the 2018 Kīlauea eruption and implications for future forecasting. *Nature Communications*, *11*(1), 1-13.

Peltier, A., V. Ferrazzini, A. Di Muro, P. Kowalski, N. Villeneuve, N. Richter, O. Chevrel, J. L. Froger, A. Hrysiewicz, M. Gouhier, et al. (2020). Volcano Crisis Management at Piton de la Fournaise (La Réunion) during the COVID-19 Lockdown, Seismol. Res. Lett. XX, 1–15, doi: 10.1785/0220200212.

Sigmundsson, F., Pinel, V., Grapenthin, R., Hooper, A., Halldórsson, S. A., Einarsson, P., ... & Yamasaki, T. (2020). Unexpected large eruptions from buoyant magma bodies within viscoelastic crust. *Nature communications*, *11*(1), 1-11.

Silverii, F., Montgomery-Brown, E. K., Borsa, A. A., & Barbour, A. J. (2020). Hydrologically Induced Deformation in Long Valley Caldera and Adjacent Sierra Nevada. *Journal of Geophysical Research: Solid Earth*, *125*(5), e2020JB019495.

Reath, K., M. Pritchard, M. Poland, F. Delgado, S. Carn, D. Coppola, S. Ebmeier, E. Rumpf, S. Henderson, S. Baker, P. Lundgren, R. Wright, J. Biggs, T. Lopez, C. Wauthier, S. Moruzzi, A. Alcott, R. Wessels, B Andrews, J. Griswold, S. Ogburn, S. Loughlin, F. Meyer, M. Pavolonis, D. Schneider, G. Vaughan, M. Bagnardi (2019), Thermal, deformation, and degassing remote sensing time series (A.D. 2000-2017) at the 47 most active volcanoes in Latin America: Implications for Volcanic Systems, *Journal of Geophysical Research*, DOI: 10.1029/2018JB016199.

Ripepe, M., Lacanna, G., Pistolesi, M., Silengo, M. C., Aiuppa, A., Laiolo, M., ... & Delle Donne, D. (2021). Ground deformation reveals the scale-invariant conduit dynamics driving explosive basaltic eruptions. *Nature communications*, *12*(1), 1-8.

Segall, P. (2019). Magma chambers: what we can, and cannot, learn from volcano geodesy. *Philosophical Transactions of the Royal Society A*, *377*(2139), 20180158.

Smittarello, D., Cayol, V., Pinel, V., Froger, J. L., Peltier, A., & Dumont, Q. (2019). Combining InSAR and GNSS to track magma transport at basaltic volcanoes. Remote Sensing, 11(19), 2236.

Smittarello, D., Cayol, V., Pinel, V., Peltier, A., Froger, J. L., & Ferrazzini, V. (2019). Magma propagation at Piton de la Fournaise from joint inversion of InSAR and GNSS. Journal of Geophysical Research: Solid Earth, 124(2), 1361-1387.

Stephens, K.J., C. Wauthier, R. Bussard**, M. Higgins, P. LaFemina (2020), Assessment of mitigation strategies for tropospheric phase contributions to InSAR time-series datasets over two Nicaraguan volcanoes, *Remote Sensing*, DOI: https://doi.org/10.3390/rs12050782.

Sun, J., C. Wauthier, K. Stephens*, M. Gervais, G. Cervone, P. LaFemina, M. Higgins (2020), Automatic detection of surface deformation by volcanic sources using deep learning, *Journal of Geophysical Research: Solid Earth*, DOI: https://doi.org/10.1029/2020JB019840.

Trottini, M., Vigo, I., Vargas-Alemañy, J.A., García-García, D., Fernández, J., 2020. On the Construction of Bootstrap Confidence Intervals for Estimating the Correlation Between Two Time Series Not Sampled on Identical Time Points. Mathemathical Geosciences, DOI: 10.1007/s11004-021-09947-9.

Tung, S., K. Katzenstein, T. Masterlark, J. Lei, C. Wauthier, D. Petley (2019), Sensitivities of Geodetic Source Analyses to Elastic Crust Heterogeneity Constrained by Seismic Tomography for the 2017 M_w 6.5 Jiuzhaigou, China, Earthquake, *Seismological Research Letters*, DOI: https://doi.org/10.1785/0220180272.

Vajda Peter, P. Zahorec, C.A. Miller, H. Le Mével, J. Papčo, A.G. Camacho, 2021Novel treatment of the deformation–induced topographic effect for interpretation of spatiotemporal gravity changes: Laguna del Maule (Chile) Journal of Volcanology and Geothermal Research vol.414 (June 2021) 107230, https://doi.org/10.1016/j.jvolgeores.2021.107230

Vajda Peter, I. Foroughi, P. Vaníček, R. Kingdon, M. Santos, M. Sheng, M. Goli, 2020 Topographic gravimetric effects in earth sciences: Review of origin, significance and implications. Earth-Science Reviews, vol 211 (Dec 2020), 103428, https://doi.org/10.1016/j.earscirev.2020.103428

Vajda Peter, P. Zahorec, J. Papčo, D. Carbone, F. Greco, M. Cantarero, 2020 Topographically predicted vertical gravity gradient field and its applicability in 3D and 4D microgravimetry: Etna (Italy) case study. Pure and Applied Geophysics, 177(7): 3315–3333, https://doi.org/10.1007/s00024-020-02435-x

Vajda Peter, Pavol Zahorec, Dušan Bilčík, Juraj Papčo, 2019, Deformation–induced topographic effects in interpretation of spatiotemporal gravity changes: Review of approaches and new insights. Surveys in Geophysics, 40:1095–1127 https://doi.org/10.1007/s10712-019-09547-7

Wauthier, C., D. C. Roman, M. P. Poland (2019), Modulation of seismic activity in Kīlauea's upper East Rift Zone by summit inflation and deflation, *Geology*, DOI: https://doi.org/10.1130/G46000.1.

Xu, W., Xie, L., Aoki, Y., Rivalta, E., & Jónsson, S. (2020). Volcano-wide deformation after the 2017 Erta Ale dike intrusion, Ethiopia, observed with radar interferometry. *Journal of Geophysical Research: Solid Earth*, *125*(8), e2020JB019562.

Xue, X., Freymueller, J., & Lu, Z. (2020). Modeling the posteruptive deformation at Okmok based on the GPS and InSAR time series: Changes in the shallow magma storage system. *Journal of Geophysical Research: Solid Earth*, *125*(2), e2019JB017801.

Sub-commission 3.3: Earth Rotation and Geophysical Fluids

Chair: *Jianli Chen (USA)*
Vice-Chair: *Michael Schindelegger (Germany)*

Members
- *Ben Chao (Chinese Taipei)*
- *Jianli Chen (USA)*
- *Tonie van Dam (Luxembourg)*
- *Henryk Dobslaw (Germany)*
- *Richard Gross (USA)*
- *Tim van Hoolst (Belgium)*
- *Erik Ivins (USA)*
- *Weijia Kuang (USA)*
- *Jolanta Nastula (Poland)*
- *Richard Ray (USA)*
- *David Salstein (USA)*
- *Michael Schindelegger (Germany)*
- *Ki-Weon Seo (Korea)*
- *Maik Thomas (Germany)*
- *Mike Watkins (USA)*
- *Yonghong Zhou (China)*
- *Leonid Zotov (Russia)*

Mass transport in the atmosphere-hydrosphere-mantle-core system, or the 'global geophysical fluids', causes observable geodynamic effects on broad time scales. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research that will lead to a better understanding of global mass transport processes and of the Earth's dynamic response. Angular momenta and the related torques, gravitational field coefficients, and geocenter shifts for all geophysical fluids are the relevant quantities. They are observed using global-scale measurements and are studied theoretically as well as by applying general circulation models; some of these models are already constrained by such geodetic measurements. The objective of the SC3.3 is to serve the scientific community by supporting research and data analysis in areas related to variations in Earth rotation, gravitational field and geocenter, caused by mass re-distribution within and mass exchange among the Earth's fluid sub-systems, i.e., the atmosphere, ocean, continental hydrosphere, cryosphere, mantle, and core along with geophysical processes associated with ocean tides and the hydrological cycle. SC 3.3 follows the program of activities defined by Commission 3. To promote the exchange of ideas and results as well as of analysis and modeling strategies, sessions at international conferences and topical workshops have been organized. In addition, SC 3.3 interacts with the sister organizations and services, particularly with the IERS Global Geophysical Fluids Centre and its operational component with four Special Bureaus (atmosphere, hydrology, ocean, combination) and its non-operational component for core, mantle, and tides.

Summary of the Sub-commission's activities during the period 2019-2021:

Meetings and Special Sessions:

On behalf of SC3.3, we have organized several sessions related to Earth Rotation and Geophysical Fluids at various scientific meetings and workshops, which include:

1) Session G04 Earth Rotation and Geodynamics at the 2019 IUGG General Assembly in Montreal, Canada (July 8-18, 2019). This is a joint session of SC3 sub-commissions, with Manabu Hashimoto (Japan) as convener, Janusz Bogusz (Poland), Jianli Chen (USA), Matt King (Australia) as co-conveners.
2) Session SE33 Global Mass Transport, Earth Rotation and Low-Degree Gravitational Change at the 2020 AOGS Annual Meeting to be held in Vivaldi Park, Hongcheon, Korea during June 28 – July 4, 2020, with Jianli Chen (USA) as convener and Richard Gross (USA), Michael Schindelegger (Germany), and Jolanta Nastula (Poland) as co-conveners.
   After much preparation, this meeting was cancelled due to the Covid-19 pandemic.
3) Session 3.1 Earth rotation, low-degree gravitational change and mass transport in geophysical fluids at the 2021 IAG General Assembly in Beijing, China during June 28 – July 2, with Jianli Chen (USA) as convener and José Ferrándiz (Spain), Richard Gross (USA), Michael Schindelegger (Germany). Henryk Dobslaw (Germany), Jin Li (China) as co-conveners.
   This session is jointly organized with IAG Inter-Commission Committee on "Geodesy for Climate Research" (ICCC).

In addition, SC3.3 has actively participated the online workshop series organized by ICCC, led by Henryk Dobslaw (Germany) and Jolanta Nastula (Poland).

Related peer-reviewed publications co-authored by SC members (incomplete list):

Chen, J.L., Ries, J.C., & Tapley, B.D. (2021). Low-degree gravitational changes from Earth rotation and GRACE and GRACE Follow-On, *J. Geod.* 95:38, DOI: 10.1007/s00190-021-01492-x.

Seo, K.-W., Kim, J.-S., Youm, K.-H., Chen, J.L., Wilson, C.R. (2021). Secular Polar Motion observed by GRACE, *J Geod.* 95:40, https://doi.org/10.1007/s00190-021-01476-x.

Chao, B. F. and Yu, Y., 2020. Variation of the equatorial moments of inertia associated with a 6-year westward rotary motion in the Earth. Earth and Planetary Science Letters, 542:116316, doi:10.1016/j.epsl.2020.116316.

Dill, R., Dobslaw, H., Hellmers, H., Kehm, A., Bloßfeld, M., Thomas, M., Seitz, F., Thaller, D., Hugentobler, U., Schönemann, E. (2020): Evaluating Processing Choices for the Geodetic Estimation of Earth Orientation Parameters with Numerical Models of Global Geophysical Fluids. - Journal of Geophysical Research: Solid Earth, 125, 9, e2020JB020025.

Śliwińska, J., Nastula, J., Dobslaw, H., Dill, R. (2020): Evaluating Gravimetric Polar Motion Excitation Estimates from the RL06 GRACE Monthly-Mean Gravity Field Models. - Remote Sensing, 12, 6, 930. https://doi.org/10.3390/rs12060930

Xu, C. Y., & Chao, B. F. (2019). Seismic effects on the secular drift of the Earth's rotational pole. Journal of Geophysical Research: Solid Earth, 124, 6092– 6100. https://doi.org/10.1029/2018JB017164

Chen, J.L., Wilson, C.R., Kuang, W., & Chao, B.F. (2019). Interannual oscillations in Earth rotation. *J. Geophys. Res.* Solid Earth, 124. https://doi.org/10.1029/2019JB018541

Kuang, W., B.F. Chao, J.L. Chen, Reassessment of electromagnetic core-mantle coupling and its implications to decadal polar motion, *Geodesy and Geodynamics*, https://doi.org/10.1016/j.geog.2019.06.003, 2019.

Nastula, J., Winska, M., Sliwinska, J., and Salstein, D., 2019. Hydrological signals in polar motion excitation - Evidence after fifteen years of the GRACE mission. Journal of Geodynamics, 124:119–132, doi:10.1016/j.jog.2019.01.014.

Dill, R., Dobslaw, H. (2019): Seasonal Variations in Global Mean Sea-Level and Consequences on the Excitation of Length-of-Day Changes. - Geophysical Journal International, 218, 2, 801-816. https://doi.org/10.1093/gji/ggz201

Dill, R., Dobslaw, H., Thomas, M. (2019): Improved 90-day Earth orientation predictions from angular momentum forecasts of atmosphere, ocean, and terrestrial hydrosphere. - Journal of Geodesy, 93, 3, 287-295. https://doi.org/10.1007/s00190-018-1158-7

Sub-commission 3.4: Cryospheric Deformation

Joint with IACS

IAG co-Chair:	*Jeff Freymueller (USA)*
IACS co-Chair:	*Bert Wouters (NDL)*
Vice-Chair:	*Natalya Gomez (CDN)*

Terms of Reference

This Sub-Commission is organized jointly with IACS. Past and present changes in the mass balance of the Earth's glaciers and ice sheets induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Geodetic observations that validate, or may be assimilated into, models of glacial isostatic adjustment (GIA) and/or constrain models of changes in present-day ice masses through measurements of elastic rebound are of paramount importance, as are "paleo-geodetic" observations like the history of relative sea level. Present-day ice mass changes induce an immediate elastic deformation of the Earth, while the integrated history of mass changes induces an additional viscoelastic deformation. Traditionally, these have been considered separately, which is a good approximation for long-ago load changes and regions of high mantle viscosity. In regions of low mantle viscosity (e.g. West Antarctica and Iceland), the present-day and recent past load changes must be modeled together as the rapid viscoelastic relaxation is substantial and not easily separated from the immediate elastic changes. In all cases, present-day geometric measurements (e.g., uplift rates) measure the sum of elastic and viscoelastic deformations, and these components cannot be separated without additional models or observations. Present-day gravity changes have a different sensitivity to the elastic and viscoelastic components. In addition, it is now clear that 1-D Earth models are no longer sufficient for many problems, but 3-D models pose computational challenges, and careful inter-comparison of 3-D models is required to better understand model differences. Reference frames of GIA models are likely computed in the center of mass of the solid Earth frame, while the International Terrestrial Reference Frame (ITRF) is defined with origin at the center of mass of Earth system (including all fluids). This means a frame origin transformation is required to allow direct comparison to measurements in ITRF and ambiguity currently exists over the exact transformation between the two. This SC has a long history as part of IAG. At the Montreal IUGG, it was decided to make this a joint sub-commission with IACS. Within IAG, SC3.4 historically has focused on resolving technical measurement issues. With the new cross-Association sub-commission, we will have a better opportunity to enhance collaboration and dissemination of these measurements within the glaciological community.

Summary of the Sub-commission's activities during the period 2019-2021:

Thus far, most of our activities have been carried out in cooperation with other groups having similar goals. In addition, the pandemic has hampered many of our plans, including the organization of workshops. As a result, the main activity completed so far is the organization of a virtual seminar series jointly with colleagues representing the World Climate Research Program (WCRP) and measurements of Paleo Sea-level (PALSEA). This monthly seminar series has drawn over 100 participants worldwide to each seminar so far, with two more set to run this summer. The series is designed to lead up to an upcoming PALSEA workshop in September (https://palseagroup.weebly.com/2021-meeting.html), which will include a focus on topics of strong interest to SC3.4. The interest in the seminar series has been strong enough that we plan to resume it in the fall/winter.

We hope that the PALSEA workshop can be used to nucleate working groups that will lead us toward the accomplishment of two of the SC3.4 goals:

- Develop an online archive of 1D and 3D Earth rheological models to enhance dissemination and inter-comparison of these models. The IRIS Earth Models Collaboration (http://ds.iris.edu/ds/products/emc/) offers a promising suite of tools and archive capability, and they are eager to work with us. The IRIS EMC includes open-source software tools for dealing with their model format, and we will try to encourage development of tools to compare and use these viscosity models, and to transform seismic velocity models into effective viscosity models.
- Contribute to and continue an effort to benchmark 3D GIA modeling approaches, similar to the benchmarking exercise done a few years ago for 1D codes. We will coordinate with Jacky Austermann, who is leading the PALSEA effort, to find synergies and help to continue this important effort.
- *WCRP/PALSEA/IAG Seminar Series:* Bob Kopp *(*March 9, https://mediaspace.msu.edu/media/WCRP_PALSEA_IAG%20Seminar%20Series%20March%209%3A%20Bob%20Kopp/1_6ippoj4p); Wouter van der Wal (April 13, https://mediaspace.msu.edu/media/WCRP+PALSEA+IAG+Seminar+Series+April+13A+Wouter+van+der+Wal/1_q629m876); Aimee Slangen and Fiamma Straneo (May 11, https://mediaspace.msu.edu/media/WCRP+PALSEA+IAG+Seminar+Series+May+11A+Aimee+Slangen+and+Fiamma+Straneo/1_49ig5vbf).
- AGU Fall meeting 2020: Sessions G012 (poster) and G013 (oral): Linking Cryosphere and the Solid Earth: From Sea Level Changes and Geodetic Time Series to Earth Rheology Session conveners: Rebekka Steffen, Jeff Freymueller, Natalya Gomez, Lambert Caron, 31 abstracts submitted. This session was organized together with JSG3-1.
- EGU General Assembly 2021 (vEGU21): Session 3.1: Geodesy for Climate Change, Session conveners: Roelof Rietbroek, Carmen Boening, Henryk Dobslaw, Anna Klos, Bert Wouters, 16 abstracts submitted.
- IAG Scientific Assembly 2021: Sessions 3.2: Observations and modeling of deformation related to changing ice, Session conveners: Jeff Freymueller, Natalya Gomez, Rebekka Steffen, Erik Ivins, Bert Wouters and Hansheng Wang, 12 abstracts submitted. This session is organized together with JSG3-1.

Sub-commission 3.5 : Seismo-Geodesy

Joint with IASPEI

Chair: *Jean-Mathieu Nocquet (France)*
Co-chair: *Takuya Nishimura (Japan)*

Overview

During the past decade, progresses in geodetic techniques together with seismological analysis have progressively allowed to monitor ground motion over a broad frequency range from milliseconds to decades, in the context of a wide spectrum of slow and rapid slip modes observed at faults worldwide. SC 3.5 is a joint IAG-IASPEI initiative aiming at facilitating the cooperation between the geodetic and the seismological communities to improve our current understanding of the different seismic processes. Its objectives are to encourage the development of high quality observation networks at plate boundaries for monitoring and early warning, promote technical innovation for improved monitoring of fault behavior, foster joint geodetic and seismological studies of faults. SC 3.5 started on January 2020. SC 3.5 builds upon the experience of the former SC 3.5 WEGENER initiative to continue as a framework for geodetic cooperation in the study of plate boundary zones.

Summary of the Sub-commission's activities during the period 2019-2021

Meetings:

WEGENER Session at EGU 2019 (7-12 April 2019)

A session "Monitoring and modelling of geodynamics and crustal deformation: progress during 38 years of the WEGENER initiative" has been organized by the WEGENER group (Conveners: Haluk Ozener, Matthias Becker, Sara Bruni, Susanna Zerbini) together with the Geodynamics and Seismology divisions. It gathered 21 contributions (https://meetingorganizer.copernicus.org/EGU2019/session/30377)

WEGENER Session at EGU 2020 (4-8 May 2020)

Wegener session at EGU 2020 (Conveners: Sara Bruni, Takuya Nishimura, Jean-Mathieu Nocquet, Haluk Ozener, Susanna Zerbini) was hold virtual and gathered 22 presentations. https://meetingorganizer.copernicus.org/EGU2020/orals/35342. The session included contributions in new observational development, separation of contributions in geodetic time series, integration of active tectonics studies and geodesy to understand the role of faults at the regional scale and on the use of geodesy in seismic hazard assessment.

Seismo-geodesy Session at vEGU2021 (19-30 April 2021)

SC 3.5 organized a virtual session "Seismo-geodesy : integrating geodetic/seismological observations and analysis to probe the behavior of faults " co-sponsored by IUGG and the seismology division (https://meetingorganizer.copernicus.org/EGU21/session/39916). The session gathers 26 contributions addressing the following topics:

- Slow Slip Events: geodetic and seismological signatures
- Post-seismic slip and aftershocks
- Faults: from observation to models
- Improving geodetic analysis to probe fault behavior

Wegener 20th general Assembly – Marrakech, Morocco.

Wegener is planned to continue its activities under the umbrella of IAG-IASPEI, as a meeting organized every two years offering a space for collaborative discussion and presentation of research. Due to the pandemics, the forthcoming 20th general assembly to be hold in Marrakech has to be postponed to Fall 2022. (https://wegener2021.sciencesconf.org/)

Web site.

A dedicated web site has been started https://iag-seismogeodesy.github.io/

Seismo-geodesy highlights & trends.

The contributions received at meeting session, together with feedbacks provided by the community highlight several trends in seismo-geodesy, that might help to define specific actions of SC 3.5 in future. Study of earthquakes is steadily improving thanks to the availability of high quality observations networks in place at the time of the earthquake. For crustal earthquakes, very rapid analysis of Synthetic Aperture Radar data and Optical images now makes earthquakes precise characterization significantly faster, within a few days, sometimes hours after the event. Similarly, both seismological and geodetic signatures of slow slip at faults are better documented both during the interseismic and post-seismic periods. Advances in seafloor observations also promote monitoring of slow slip in the subduction zone. Active research is carried out to develop new analysis methods. Among them Machine Learning approaches are rapidly growing and are promising. Separation of non-tectonic contributions in geodetic time series remains a challenge for longer term signals. In addition to geodesy and seismology, active tectonics also would deserve to be included in the general scope of the Seismo-geodesy sub-commission. Integrating active tectonic would allow to enlarge the time scale of fault behavior from the earthquake to 10^2-10^5 years. This contribution becomes even more important in the context where the use of geodetic data to probabilistic seismic hazard assessment is rapidly growing.

Joint Study Group 3.1: Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment

With IAG Commissions 1 and 2

Chair: *Rebekka Steffen (Sweden)*
Co-Chair: *Erik R. Ivins (US)*

The Joint Study Group (JSG) on "Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment" is joint with IAG Commissions 1 (Reference Frames) and 2 (Gravity Field). The goal of the JSG is to allow cross fertilization of models, data and conceptual frameworks of the geodynamics and glacial isostatic adjustment (GIA) communities with the development of an interdisciplinary approach to better determine the Earth's internal rheological structure. We have invited the following researchers to be active members of the group:

- Kristel Chanard (France)
- Mark Hoggard (Australia)
- Paula Koelemeijer (UK)
- Harriet Lau (US)
- Tanghua Li (Singapore)
- Glenn Milne (Canada)
- Bart Root (Netherlands)
- Andrew Schaeffer (Canada)
- Kate Selway (Australia)
- Bernhard Steinberger (Germany)
- Doug Wiens (US)

Activities during the period 2019-2021

Development of goals and establishment of group: The group was newly formed, and objectives had to be developed, which were approved at the IAG Council Meeting in December 2019. The objectives follow the goal of the JSG to increase collaboration between different geoscientific disciplines (geodesy, geodynamics, seismology, mineral physics, applied geophysics). GIA Training School: A Training School on GIA was organized by SERCE (Solid Earth Responses and influences on Cryospheric Evolution) as part of SCAR (Scientific Community on Antarctic Research) and POLENET (Polar Earth Observing Network) as part of the Antarctica Network (ANET) both funded by The National Science Foundation (NSF) with additional funding from the International Association of Cryospheric Sciences (IACS), the European Geosciences Union (EGU), and DTU Space. The training school was held at the headquarter of Lantmäteriet in Gävle (Sweden). The chair of the JSG was involved in the organization, and the chair, co-chair and several team members were invited as lectures. 42 students attended the Training School in-person and several were able to attend the lectures virtually. The lectures during the Training School covered various topics on GIA modelling, ice sheet modelling and their observations. In addition, one day was dedicated to an excursion where the students were able to see the consequences of land uplift. AGU Fall Meeting 2020 Session: JSG 3.1 and SC 3.4 (Cryospheric Deformation) co-organized a session on "Linking Cryosphere and the Solid Earth: From Sea Level Changes and Geodetic Time Series to Earth Rheology" at the AGU Fall Meeting 2020. We received 30 abstracts and more than 100 participants attended the online session during the AGU Fall Meeting. Invited speakers were Kate Selway (Australia) and Volker Klemann (Germany). IASPEI Newsletter: The JSG has a large focus on seismology and geodynamics. Thus, a strong connection with IASPEI (International Association of Seismology and Physics of the Earth's Interior) was planned. To achieve this, an article about the JSG was published in the IASPEI newsletter in February 2021. First Group Meeting: A short first group meeting was organized on February 24th, 2021, where almost all group members were able to attend. The meeting was held online and gave us the possibility to discuss further steps. We also decided to create a Slack workspace to ease the communication within the group (JSG3.1-GIA). IAG General Assembly 2021 Session: JSG 3.1 and SC 3.4 (Cryospheric Deformation) co-organized a session on "Observations and modeling of deformation related to changing ice loads" at the General Assembly of the IAG 2021. In addition to the chairs and co-chairs of both IAG groups, Hansheng Wang from the Chinese Academy of Sciences in Wuhan was invited to join the convener team.

Relevant peer-reviewed publications by Joint Study Group members 2019-2021 (group members are in bold; alphabetically order)

Adhikari, S., **Ivins, E.R.**., Larour, E., Caron, L., Seroussi, H. (2020): A kinematic formalism for tracking ice–ocean mass exchange on the Earth's surface and estimating sea-level change. *The Cryosphere* 14, doi: 10.5194/tc-14-2819-2020.

Austermann, J., Chen, C.Y., **Lau, H.C.P.**, Maloo, A.C., Latychev, K. (2020): Constraints on mantle viscosity and Laurentide ice sheet evolution from pluvial paleolake shorelines in the western United States. *Earth and Planetary Science Letters* 532, doi: 10.1016/j.epsl.2019.116006.

Bartholet, A., **Milne, G.A.**, Latychev, K. (2020): Modelling sea-level fingerprints of glaciated regions with low mantle viscosity. *Earth System Dynamics Discussion*, doi: 10.5194/esd-2020-72. In review.

Bedrosian, P.A., Schwarz, G., **Selway, K.**, Wawrzyniak, P., Yang, D. (2021): Special issue "Studies on electromagnetic induction in the earth: recent advances and future directions". *Earth Planets Space* 73, doi: 10.1186/s40623-020-01336-6.

Bredow, E., **Steinberger, B.**, Gassmöller, R., Dannberg, J. (2020): Mantle Convection and Possible Mantle Plumes beneath Antarctica - Insights from Geodynamic Models and Implications for Topography. *Geological Society, London, Memoirs* 56, doi: 10.1144/M56-2020-2.

Caron, L., **Ivins, E.R.** (2020): A baseline Antarctic GIA correction for space gravimetry. *Earth and Planetary Science Letters* 531, doi: 10.1016/j.epsl.2019.115957.

Celli, N.L., Lebedev, S., **Schaeffer, A.J.**, Gaina, C. (2020): African cratonic lithosphere carved by mantle plumes. *Nature Communications* 11, doi: 10.1038/s41467-019-13871-2.

Celli, N.L., Lebedev, S., **Schaeffer, A.J.**, Ravenna, M., Gaina, C. (2020): The upper mantle beneath South America and the South Atlantic Ocean from waveform tomography with massive datasets, *Geophysical Journal International* 221, doi: 10.1093/gji/ggz574.

Emry, E.L., Nyblade, A.A., Horton, A., Hansen, S.E., Julià, J., Aster, R.C., Huerta, A.D., Winberry, J.P., **Wiens, D.A.**, Wilson, T.J. (2020): Prominent thermal anomalies in the mantle transition zone beneath the Transantarctic Mountains. *Geology* 2020, doi: 10.1130/G47346.1.

Estève, C., Audet, P., **Schaeffer, A.J.**, Schutt, D.L., Aster, R.C., Cubley, J. (2020): The upper mantle structure of northwestern Canada from teleseismic body wave tomography. *Journal of Geophysical Research: Solid Earth* 125, doi: 10.1029/2019JB018837.

Foster, A., Darbyshire, F., **Schaeffer, A.** (2020): Anisotropic structure of the central North American Craton surrounding the Mid-Continent Rift: Evidence from Rayleigh waves. *Precambrian Research* 342, doi: 10.1016/j.precamres.2020.105662.

Ghelichkhan, S., Fuentes, J.J., **Hoggard, M.J.**, Richards, F.D., Mitrovica, J.X. (2021): The precession constant and its long-term variation. *Icarus* 358, doi: 10.1016/j.icarus.2020.114172.

Gosselin, J.M., Audet, P., **Schaeffer, A.J.**, Darbyshire, F.A., Estève, C. (2020): Azimuthal anisotropy in Bayseian surface wave tomography: application to northern Cascadia and Haida Gwaii. *Geophysical Journal International* 224, doi: 10.1093/gji/ggaa561.

Gradmann, S., **Steffen, R.** (2021): Crustal-Scale Stress Modelling to Investigate Glacially Triggered Faulting. In: Steffen, H., Olesen, O., Sutinen, R. (eds), On glacially triggered faulting. *Cambridge University Press*. In press.

Hamlington, B.D., A.S. Gardner, **E. Ivins**, J.T.M. Lenaerts, J.T. Reager, et al. (2020) Understanding of contemporary regional sea-level change and the implications for the future. *Review of Geophysics* 58, doi: 10.1029/2019RG000672.

Ivins, E.R., L. Caron, S. Adhikari, E. Larour, M. Scheinert, (2020) A linear viscoelasticity for decadal to centennial time scale mantle deformation. *Reports on Progress in Physics* 83, doi:10.1088/1361-6633/aba346.

Ivins, E.R., van der Wal, W., Wiens, D.A., Lloyd, A., Caron, L. (2021): Antarctic upper mantle rheology. In: Martin, A.P., van der Wal, W., The Geochemistry and Geophysics of the Antarctic Mantle. *Geological Society London Memoirs*. In press.

Jones, T., R. Maguire, P. van Keken, J. Ritsema & **P. Koelemeijer** (2020). Subducted oceanic crust as the origin of seismically slow lower mantle structures. Progress in Earth and Planetary Science 7, doi:10.1186/s40645-020-00327-1.

Koelemeijer, P. (2021). Towards consistent seismological models of the core-mantle boundary landscape. In press, AGU monograph "Mantle Convection and Surface Expressions", edited by Marquardt, Ballmer, Cottaar & Konter, doi:10.1002/9781119528609.ch9.

Kuchar, J., **Milne, G.**, Hill, A., Tarasov, L., Nordman, M. (2020): An investigation into the sensitivity of postglacial decay times to uncertainty in the adopted ice history. *Geophysical Journal International* 220, doi: 10.1093/gji/ggz512.

Larour, E., Adhikari, S., Frederikse, T., Caron, L., Hamlington, B., Schlegel, N.-J., **Ivins, E.**, Kopp, R., Morlighem, M., Nowicki, S., (2020) SSM-SLPS: geodetically compliant Sea-Level Projection System for the Ice-sheet and Sea-level System Model v4.17. *Geoscientific Model Development* 13, doi:105194/gmd-13-4925-2020.

Lau, H.C.P., Holtzmann, B.K. (2019): "Measures of Dissipation in Viscoelastic Media" Extended: Toward Continuous Characterization Across Very Broad Geophysical Time Scales. *Geophysical Research Letters* 46, doi: 10.1029/2019GL083529.

Lau, H.C.P., Holtzmann, B.K., Havlin, C. (2020): Toward a Self-Consistent Characterization of Lithospheric Plates Using Full-Spectrum Viscoelasticity. *AGU Advances* 1, doi: 10.1029/2020AV000205.

Li, T., Wu, P., Wang, H., Steffen, H., Khan, N. S., Engelhart, S. E., Vacchi, M., Shaw, T.A., Peltier, W.R., Horton, B.P. (2020): Uncertainties of glacial isostatic adjustment model predictions in North America associated with 3D structure. *Geophysical Research Letters* 47, doi: 10.1029/2020GL087944.

Lloyd, A.J., **Wiens, D.A.**, Zhu, H., Tromp, J., Nyblade, A.A., Aster, R.C., Hansen, S.E., Dalziel, I.W.D., Wilson, T.J., **Ivins, E.R.**, O'Donnell, J.P. (2020): Seismic Structure of the Antarctic Upper Mantle Imaged with Adjoint Tomography. *Journal of Geophysical Research: Solid Earth* 125, doi: 10.1029/2019JB017823.

Lucas, E.M., Soto, D., Nyblade, A.A., Lloyd, A.J., Aster, R C., **Wiens, D.A.**, O'Donnell, J.P., Stuart, G.W., Wilson, T.J., Dalziel, I.W.D., Winberry, J.P., Huerta, A.D. (2020): P- and S-wave velocity structure of central West Antarctica: Implications for the tectonic evolution of the West Antarctic Rift System. *Earth and Planetary Science* Letters 546, doi: 10.1016/j.epsl.2020.116437.

Lucas, E.M., Nyblade, A.A., Lloyd, A.J., Aster, R C., **Wiens, D.A.**, O'Donnell, J.P., Stuart, G.W., Wilson, T.J., Dalziel, I.W.D., Winberry, J.P., Huerta, A.D. (2021): Seismicity and Pn velocity structure of central West Antarctica. *Geochemistry, Geophysics, Geosystems* 22, doi: 10.1029/2020GC009471.

Mitrovica, J.X., Austermann, J., Coulson, S., Creveling, J.R., **Hoggard, M.J.**, Jarvis, G.T., Richards, F.D. (2020): Dynamic topography and ice age paleoclimate. *Annual Review of Earth and Planetary Sciences*, 48, doi: 10.1146/annurev-earth-082517-010225.

Munier, R., Adams, J., Brandes, C., Brooks, G., Dehls, J., Gibbons, S.J., Hjartardóttir, Á.R., Hogaas, F., Johansen, T.A., Kvaerna, T., Mattila, J., Mikko, H., Müller, K., Nikolaeva, S.B., Ojala, A., Olesen, O., Olsen, L., Palmu, J.-P., Ruskeeniemi, T., Ruud, B.O., Sandersen, P.B.E., Shvarev, S.V., Smith, C.A., Steffen, H., **Steffen, R.**, Sutinen, R., Tassis, G. (2020): International database of Glacially Induced Faults. *PANGAEA*, doi: 10.1594/PANGAEA.922705.

Naif, S., **Selway, K.**, Murphy, B.S., Egbert, G., Pommier, A. (2021): Electrical conductivity of the lithosphere-asthenosphere system. *Physics of the Earth and Planetary Interiors* 313, doi: 10.1016/j.pepi.2021.106661.

Nield, G.A., King, M.A., **Steffen, R.**, Blank, B. (2020): A global, spherical, finite-element model for postseismic deformation using ABAQUS. *Geoscientific Model Development Discussion*, doi: 10.5194/gmd-2020-107. In review.

Pan, L., Powell, E.M., Latychev, K., Mitrovica, J.X., Creveling, J.R., Gomez, N., **Hoggard, M.J.**, Clark, P.U. (2021): Rapid postglacial rebound amplifies global sea level rise following West Antarctic Ice Sheet collapse. *Science Advances* 7, doi: 10.1126/sciadv.abf7787.

Pisarska-Jamroży, M. G., Belzyt, S., Börner, A., Hoffmann, G., Hüneke, H., Kenzler, M., Obst, K., Rother, H., Steffen, H., **Steffen, R.**, van Loon, T. (2019): The sea cliff at Dwasieden: soft-sediment deformation structures triggered by glacial isostatic adjustment in front of the advancing Scandinavian Ice Sheet. *DEUQUA Special Publication* 2, doi: 10.5194/deuquasp-2-61-2019.

Reusen, J.M., **Root, B.C.**, Szwillus, W., Fullea, J., van der Wal, W. (2020): Long-Wavelength Gravity Field Constraint on the Lower Mantle Viscosity in North America. *Journal of Geophysical Research: Solid Earth* 125, doi: 10.1029/2020JB020484.

Richards, F.D., **Hoggard, M.J.**, White, N.J., Ghelichkhan, S. (2020): Quantifying the relationship between short-wavelength dynamic topography and thermomechanical structure of the upper mantle using calibrated parameterization of anelasticity. *Journal of Geophysical Research: Solid Earth* 125, doi: 10.1029/2019JB019062.

Root, B.C. (2020): Comparing global tomography-derived and gravity-based upper mantle density models. *Geophysical Journal International* 221, doi: 10.1093/gji/ggaa091.

Rovira-Navarro, M., van der Wal, W., Barletta, V.R., **Root, B.C.**, Sandberg Sørensen, L. (2020): GRACE constraints on Earth rheology of the Barents Sea and Fennoscandia. *Solid Earth* 11, doi: 10.5194/se-11-379-2020.

Selway, K., Smirnov, M. Y., Beka, T., O'Donnell, J. P., Minakov, A., Senger, K., Faleide, J.I., Kalscheuer, T. (2020): Magnetotelluric constraints on the temperature, composition, partial melt content and viscosity of the upper mantle beneath Svalbard. *Geochemistry, Geophysics, Geosystems* 21, doi: 10.1029/2020GC008985.

Shen, W., **Wiens, D.A.**, Lloyd, A.J., Nyblade, A.A. (2020): A geothermal heat flux map of Antarctica empirically constrained by seismic structure. *Geophysical Research Letters* 47, doi: 10.1029/2020GL086955.

Shepherd, A., **Ivins, E**., Rignot, E. et al. (2020): Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* 579, doi: 10.1038/s41586-019-1855-2.

Steffen, H., **Steffen, R.** (2021): Indications on Glacially Triggered Faulting in Polar Areas. In: Steffen, H., Olesen, O., Sutinen, R. (eds), On glacially triggered faulting. *Cambridge University Press*. In press.

Steffen, R., Steffen, H., Weiss, R., Lecavalier, B.S., **Milne, G.A.**, Woodroffe, S.A., Bennike, O. (2020): Early Holocene Greenland-ice mass loss likely triggered earthquakes and tsunami. *Earth and Planetary Science Letters* 546, doi: 10.1016/j.epsl.2020.116443.

Steffen, R., Wu, P., Lund, B. (2021): Geomechanics of glacially triggered faulting. In: Steffen, H., Olesen, O., Sutinen, R. (eds), On glacially triggered faulting. *Cambridge University Press*. In press.

Szwillus, W., Ebbing, J., **Steinberger, B.** (2020): Increased density of large low-velocity provinces recovered by seismologically constrained gravity inversion. *Solid Earth* 11, doi: 10.5194/se-11-1551-2020.

Whitehouse P., **Milne G.**, Lambeck K. (2021): Glacial Isostatic Adjustment. In: Fowler A., Ng F. (eds), Glaciers and Ice Sheets in the Climate System. *Springer Textbooks in Earth Sciences, Geography and Environment*, doi: 10.1007/978-3-030-42584-5_15.

Wiens, D. A., Shen, W., Lloyd, A. J. (2021): The seismic structure of the Antarctic upper mantle. In: Martin, A.P., van der Wal, W., The Geochemistry and Geophysics of the Antarctic Mantle. *Geological Society London Memoirs*. In press.

Wu, P., **Steffen, R.**, Steffen, H., Lund, B. (2021): Glacial-isostatic adjustment models for earthquake triggering. In: Steffen, H., Olesen, O., Sutinen, R. (eds), On glacially triggered faulting. *Cambridge University Press*. In press.

Yousefi, M., **Milne, G.**, Li, S., Wang, K., Bartholet, A. (2020): Constraining interseismic deformation of the Cascadia subduction zone: New insights from estimates of vertical land motion over different timescales. *Journal of Geophysical Research: Solid Earth* 125, doi: 10.1029/2019JB018248.

Yousefi, M., **Milne, G.A.**, Latychev, K. (2021): Glacial isostatic adjustment of the Pacific Coast of North America: the influence of lateral Earth structure. *Geophysical Journal International* 226, doi: 10.1093/gji/ggab053.

Xiong, H., Zong, Y., **Li, T.**, Long, T., Huang, G., Fu, S. (2020): Coastal GIA processes revealed by the early to middle Holocene sea-level history of east China. *Quaternary Science Reviews* 233, doi: 10.1016/j.quascirev.2020.106249.

Joint Working Group 3.1: Improving Theories and Models of the Earth's Rotation

With IAU

Chair: José Ferrándiz (Spain)
Vice-Chair: Richard Gross (USA)

During this period, JWG 3.1 maintained its activity focusing on developing and proposing consistent updates of Earth rotation theories and models and their validation with the objective of achieving the accuracy and stability goals established by GGOS for reference frames. According to its terms of reference, the JWG aims at contributing to the implementation of the 2019 IAG Resolution 5 on Improvement of Earth Rotation Theories and Models, and the 2018 IAU Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames. Following the recommendations of the 2019 GGOS/IERS Unified Analysis Workshop, the priority tasks of building such models include:

- updating the amplitudes of the leading nutations of IAU2000 and testing shortened series for certain operational purposes,
- correcting the inconsistencies already known in precession-nutation models,
- testing the available FCN models and helping the relevant bodies consider whether or not the IERS should recommend FCN models for general purposes.

The development and publication of fully dynamically consistent theories capable of supporting and fully justifying those models is an even more demanding task that will require the maintenance of the activity until the end of the current 4-year term. Official approval for establishing the JWG ITMER by IAU Commission A2, Rotation of the Earth, was received in February 2020. Afterwards, the pandemic situation seriously affected the JWG activity. This unexpectedly long situation has produced some delay in the development of the foreseen work and did not allow holding any in-person meetings-of-opportunity due to the cancellation or change in format of most of the relevant events. For instance, Journées 2020, the latest in a series of meetings supported for decades by the IAG and IAU and which were re-started in 2017 thanks to the stimulus of the precedent IAU/IAG JWG 3.1 on Theory of Earth rotation and validation (TERV), was postponed sine die after some attempt at delaying it and was eventually cancelled. Other meetings were held using on-line formats like the EGU General Assemblies (GA) of 2020 and 2021. The EGU 2020 virtual session G3.1, co-organized by the SWG 1 chair, A. Escapa, received contributions related to the background of the JWG terms of reference, i.e., developing the outcomes of the precedent JWG TERV. The AGU 2020 Fall Meeting did not host a specific Earth rotation session organized with the participation of JWG members, unlike before; however, the GGOS session filled the gap by welcoming Earth rotation modelling and other related topics. At EGU 2021, a virtual session G3.3 on Earth rotation took place again, convened by Escapa together with other JWG members, and welcomed contributions in the scope of this JWG among others (https://meetingorganizer.copernicus.org/EGU21/session/39900). In the same EGU GA, the JWG organized a virtual meeting-of-opportunity open to all EGU registered attendees, the SPM7 (https://meetingorganizer.copernicus.org/EGU21/session/41591). On the other hand, in February 2021 IAU Commission A2 accepted a draft Resolution written by the JWG and submitted it to the IAU for consideration. If approved, it would favor the coordination between IAG and IAU regarding the improvement of Earth rotation in a consistent and effective way.

In spite of the difficulties, the JWG members and correspondents have been able to keep the outcomes of their research at a high level and have published and reported on a noticeable umber of valuable research results. Among them and from the perspective of the JWG terms of reference, a special mention must be made to the various sets of corrections to the precession-nutation models derived and proposed by different research groups led by JWG members. They confirm that achieving a reasonable improvement of those models is feasible at short term, as foreseen when the JGW was created. Finally, a good level of coordination with other IAG components, like GGOS, and with other WGs dealing with Earth rotation topics, in particular the IAU/IAG/IERS JWG on the Consistent realization of TRF, CRF, and EOP and the IERS WG on the second EOP Prediction Comparison Campaign which was recently inaugurated, has been kept through the existence of common members and correspondants.

Selected contributions by JWG members and correspondents

2021

Baenas T, Escapa A, Ferrándiz JM (2021) Secular changes in length of day: effect of the mass redistribution. Astronomy & Astrophysics, aa40356-21. https://doi.org/10.1051/0004-6361/202140356

Ding H, An Y, Shen WB (2021) New evidence for the fluctuation characteristics of intradecadal periodic signals in length-of-day variation. Journal of Geophysical Research: Solid Earth, 126, e2020JB020990. https://doi.org/10.1029/2020JB020990

Ferrándiz, JM, Juárez MA, Belda S, Baenas T, Modiri S, Heinkelmann R, Escapa A, Schuh H (2021) Assessing recently improved precession-nutation models, EGU GA 2021, EGU21-10180. https://doi.org/10.5194/egusphere-egu21-10180

Getino J, Escapa A, Ferrándiz JM, Baenas T (2021) The Rotation of the Nonrigid Earth at the Second Order. II. The Poincaré Model: Nonsingular Complex Canonical Variables and Poisson Terms. Astronomical Journal 161:232 (25pp) https://doi.org/10.3847/1538-3881/abdd1d

Hilton JL, Capitaine N, Chapront J, Ferrándiz JM, Fienga A, Fukushima T, Getino J, Mathews P, Simon J-L, Soffel M, Vondrak J, Wallace P, Williams J (2021) Correction to: Report of the International Astronomical Union Division I Working Group on Precession and the Ecliptic. Celes. Mech. Dynam. Astron. 133, 8. https://doi.org/10.1007/s10569-020-09998-w

Modiri S, Heinkelmann R, Belda S, Hoseini M, Korte M, Malkin Z, Ferrándiz JM, Schuh H (2021) A First Assessment of the interconnection between celestial pole offset and geomagnetic field variations, EGU General Assembly 2021, EGU21-7235. https://doi.org/10.5194/egusphere-egu21-7235

Nurul Huda I, Bizouard C, Allain D, Lambert S (2021) Polar motion resonance in the prograde diurnal band, Geophys J Int. https://doi.org/10.1093/gji/ggab113

Shih SA, Chao BF (2021) Inner core and its libration under gravitational equilibrium: Implications to lower-mantle density anomaly. Journal of Geophysical Research: Solid Earth, 126, e2020JB020541. https://doi.org/10.1029/2020JB020541

Triana SA, Trinh A, Rekier J, Zhu P, Dehant V (2021) The viscous and Ohmic damping of the Earth's free core nutation. Journal of Geophysical Research 126. https://doi.org/10.1029/2020JB021042

Zhang H, Shen WB (2021) Core–mantle topographic coupling: a parametric approach and implications for the formulation. Geophys J Int 225, 2060–2074. https://doi.org/10.1093/gji/ggab07

Zhu P, Triana SA, Rekier J, Trinh A, Dehant V (2021) Quantification of corrections for the main lunisolar nutation components and analysis of the free core nutation from VLBI-observed nutation residuals. J. Geodesy 95, 57 https://doi.org/10.1007/s00190-021-01513-9

2020

Baenas T, Escapa A, Ferrándiz JM (2020) Forced nutations of a two-layer Earth in canonical formulation with dissipative Hori-like kernel. Advances in Space Research 66:2646-2653. https://doi.org/1016/j.asr.2020.08.023

Baenas T, Escapa A, Ferrándiz JM (2020) Nutation of the non-rigid Earth: Effect of the mass redistribution. Astronomy & Astrophysics 643: A159. https://doi.org/10.1051/0004-6361/202038946

Bizouard C, Nurul Huda I, Ziegler Y, Lambert S (2020) Frequency dependence of the polar motion resonance, Geophys J Int 220, 753–758. https://doi.org/10.1093/gji/ggz463

Chao BF, Yu Y (2020) Variation of the equatorial moments of inertia associated with a 6-year westward rotary motion in the Earth, Earth and Planetary Science Letters, 542. https://doi.org/10.1016/j.epsl.2020.116316

Duan P, Huang C (2020) On the mantle-inner core gravitational oscillation under the action of the electromagnetic coupling effects. Journal of Geophysical Research: Solid Earth, 125, e2019JB018863. https://doi.org/10.1029/2019JB018863

Duan P, Huang CL (2020) Intradecadal variations in length of day and their correspondence with geomagnetic jerks. Nature Communications 11, 2273. https://doi.org/10.1038/s41467-020-16109-8

Ferrándiz JM, Al Koudsi D, Escapa A, Belda S, Modiri S, Heinkelmann R, Schuh H (2020) A First Assessment of the Corrections for the Consistency of the IAU2000 and IAU2006 Precession-Nutation Models. IAG Symposia. https://doi.org/10.1007/1345_2020_90

Ferrándiz JM, Escapa A, Baenas T, Belda S, Vigo I (2020) Effects of the observed Earth's oblateness variation on precession-nutation: A first assessment, EGU General Assembly 2020, EGU2020-16509. https://doi.org/10.5194/egusphere-egu2020-16509

Ferrándiz JM, Escapa A, Belda S, Baenas T, Modiri S, Heinkelmann R, Schuh H (2020) Improved Precession-Nutation Models: A First Assessment. AGU Fall Meeting 2020, G022-05. https://agu.confex.com/agu/fm20/meetingapp.cgi/Paper/755001

Ferrándiz JM, Gross RS; Escapa A, Getino J, Brzezinski A, Heinkelmann R (2020) Report of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation. IAG Symposia. https://doi.org/10.1007/1345_2020_103

Ferrándiz JM, Modiri S, Belda S, Barkin M, Bloßfeld M, Heinkelmann R and Schuh H (2020) Drift of the Earth's Principal Axes of Inertia from GRACE and Satellite Laser Ranging Data. Remote Sensing, 12(2):314. https://doi.org/10.3390/rs12020314

Guo Z, Shen, W. B (2020) Formulation of a triaxial three-layered Earth rotation: Theory and rotational normal mode solutions. Journal of Geophysical Research: Solid Earth, 125, e2019JB018571. https://doi.org/10.1029/2019JB018571

Malkin ZM (2020) Statistical Analysis of the Results of 20 Years of Activity of the International VLBI Service for Geodesy and Astrometry. Astron. Rep. 64, 168–188. https://doi.org/10.1134/S1063772920020043

Modiri S, Belda S, Hoseini M, Heinkelmann R, Ferrándiz JM, and Schuh H (2020) A new hybrid method to improve the ultra-short-term prediction of LOD. J Geodesy 94(2):23. https://doi.org/10.1007/s00190-020-01354-y

Nurul Huda I, Lambert S, Bizouard C, Ziegler Y (2020) Nutation terms adjustment to VLBI and implication for the Earth rotation resonance parameters, Geophys J Int, 220, 759–767. https://doi.org/10.1093/gji/ggz468

Nastula J, Chin TM, Gross R, Śliwińska J, Wińska M (2020) Smoothing and predicting celestial pole offsets using a Kalman filter and smoother. J Geodesy 94, 29. https://doi.org/10.1007/s00190-020-01349-9

Nastula J, Śliwińska J (2020) Prograde and Retrograde Terms of Gravimetric Polar Motion Excitation Estimates from the GRACE Monthly Gravity Field Models. Remote Sens. 12, 138. https://doi.org/10.3390/rs12010138

Schindelegger M, Harker A, Salstein D, Dobslaw H (2020) A multi-model assessment of sub-monthly polar motion and the associated ocean bottom pressure variability, EGU General Assembly 2020, EGU2020-7621. https://doi.org/10.5194/egusphere-egu2020-7621, 202

Sidorenkov N, Dionis E, Bizouard C, Zotov L (2020) Decadal fluctuations in Earth's rotation as evidences of lithospheric drift over the asthenosphere. In: Proceedings of the Journées 2019 "Astrometry, Earth Rotation, and Reference Systems in the GAIA era", Ed. C. Bizouard, pp. 243-247

Śliwińska J, Nastula J, Dobslaw H, Dill R (2020) Evaluating Gravimetric Polar Motion Excitation Estimates from the RL06 GRACE Monthly-Mean Gravity Field Models. Remote Sensing 12, 930. https://doi.org/10.3390/rs12060930

Śliwińska J, Wińska M, Nastula J (2020) Preliminary Estimation and Validation of Polar Motion Excitation from Different Types of the GRACE and GRACE Follow-On Missions Data. Remote Sens. 12, 3490. https://doi.org/10.3390/rs12213490

Stamatakos N, Salstein D, McCarthy D (2020) IERS Rapid Service/Prediction Center Use of Atmospheric and Ocean Angular Momentum for Earth Orientation, EGU General Assembly 2020, EGU2020-3738. https://doi.org/10.13168/AGG.2019.0030

Tercjak M, Gebauer A, Rajner M, Brzezinski A, Schreiber U (2020) On the Influence of Diurnal and Subdiurnal Signals in the Normal Vector on Large Ring Laser Gyroscope Observations. Pure Appl. Geophys. 177, 4217–4228. https://doi.org/10.1007/s00024-020-02484-2

Vondrák J, Ron C (2020) Determination of FCN parameters from different VLBI solutions, considering geophysical excitations. In: Proceedings of the Journées 2019 "Astrometry, Earth Rotation, and Reference Systems in the GAIA era", Ed. C. Bizouard, pp. 255-259

Vondrák J, Ron C (2020) Period and Q-factor of free core nutation, based on different geophysical excitations and VLBI solutions. Acta Geodyn. Geomater. 17, 207–215. https://doi.org/10.13168/AGG.2020.0015

Yu N, Chen G, Ray J, Chen W, Chao N (2020) Semi-decadal and decadal signals in atmospheric excitation of length-of-day. Earth and Space Science 7, e2019EA000976. https://doi.org/10.1029/2019EA000976

Zotov L, Bizouard C, Sidorenkov N, Shen WB, Guo ZL (2020) On the variability of the Chandler wobble. In: Proceedings of the Journées 2019 "Astrometry, Earth Rotation, and Reference Systems in the GAIA era", Ed. C. Bizouard, pp. 249-254

Zotov L, Bizouard C, Sidorenkov N, Ustinov A, Ershova T (2020) Multidecadal and 6-year variations of LOD. J Phys. Conf. Ser. 1705 012002. https://doi.org/10.1088/1742-6596/1705/1/012002

2019

Baenas T, Escapa A, Ferrándiz JM (2019) Precession of the non-rigid Earth: Effect of the mass redistribution. Astronomy & Astrophysics 626: A58. https://doi.org/10.1051/0004-6361/201935472

Puente V, Richard J-Y, Folgueira M, Capitaine N, Bizouard C (2019) Comparison of VLBI-based Luni-solar Nutation Terms. In: Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, vol. 24, 257–261.

Ron C, Vondrák J, Dill R, Chapanov Y (2019) Combination of geo-magnetic jerks with updated ESMGFZ effective angular momentum functions for the modelling of polar motion excitation. Acta Geodyn. Geomater. 16, 359–363. https://doi.org/10.13168/AGG.2019.0030

Joint Working Group 3.2: Global combined GNSS velocity field

With IAG Commissions 1 and 2

Chair: *Alvaro Santamaría-Gómez (France)*
Vice-Chair: *Roelof Rietbroek (Netherlands)*

Members:
Paul Rebischung (France)
Thomas Frederikse (USA)

Objectives of the Working Group:

This Working Group aims at combining and comparing available global GNSS velocity fields obtained by different groups from both network and PPP solutions. It continues the activities of former JWG3.2 with the inclusion of the last reprocessed solutions included for the ITRF2020 realization while also extending the scope to the horizontal component of the velocity field. GNSS velocities estimated by different groups usually differ due to GNSS data processing choices (applied corrections and noise level of the series), the completeness of the series, the removed position discontinuities, and the alignment to a terrestrial reference frame. The position discontinuities that populate the GNSS time series have probably the biggest impact on the velocity estimates. Even when using exactly the same GNSS position time series, it is common for different groups to provide different velocity estimates and uncertainties, mainly due to the different choices to treat position discontinuities. The main outcome of this Working Group will be a combined velocity field that takes into account the repeatability of the velocity estimates by the different groups. It is expected that the combined GNSS velocity field better reflects processing uncertainties and will be useful for the scientific community in the areas of tectonics, sea-level change, land subsidence and GIA modeling among others.

Program of activities:

Two global velocity field solutions are currently available from JPL and NGL. These two solutions, while using the same GNSS processing software (GIPSY in PPP mode) differ in some of the corrections applied and, importantly, also in the methodology used to estimate the station velocities from the time series. A third global velocity field is expected from the combined IGS solution, obtained from the recently finished third IGS reprocessing campaign. This solution constitutes the GNSS contribution to the future ITRF2020 and therefore, it will also serve as reference frame for the combined global velocity field. A fourth global velocity field is also expected to be available next year from the University of La Rochelle. The final combined global velocity field will include at least these four solutions, but additional global velocity field solutions will be included depending on availability and suitability.

Commission 4– Positioning and Applications

http://iag-comm4.survey.ntua.gr

President: Allison Kealy (Australia)
Vice President: Vassilis Gikas (Greece)

Structure

Sub-Commission 4.1:	Emerging Positioning Technologies and Augmentations
Sub-Commission 4.2:	Multi Frequency, Multi Constellation GNSS
Sub-Commission 4.3:	Atmospheric Remote Sensing
Sub-Commission 4.4:	GNSS Integrity and Quality Control
Special Study Group 4.1.1:	Positioning Using Smartphones
Joint Working Group 4.3.1:	Real-Time Ionosphere Monitoring and Modelling
Joint Working Group 4.3.4:	Validation of VTEC Models for High-Precision and High Resolution Applications

Overview

The primary mission objective of Commission 4 is to promote research that leverages current and emerging positioning techniques and technologies to deliver practical and theoretical solutions for GNSS smartphone positioning technologies, multi-frequency, multi-constellation GNSS, positioning integrity and quality, alternatives and backups to GNSS, sensor fusion, atmospheric sensing, modelling, and applications based on geodetic techniques. Commission 4 will carry out its work in close cooperation with the IAG Services and other IAG entities, as well as via linkages with relevant entities within scientific and professional organizations the International Federation of Surveyors (FIG), International Society for Photogrammetry and Remote Sensing (ISPRS) and the Institutes of Navigation (ION &RIN).

Recognizing the central role of Global Navigation Satellite Systems (GNSS) in providing the positioning requirements today and into the future, Commission 4 will focus on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for an increasing diversity of end-user applications. It also acknowledges the increasing levels of threat and vulnerabilities for GNSS only positioning and investigates technologies and approaches that address these. A significant part of Commission 4 activities is oriented towards the development of theory, strategies and tools for modeling and/or mitigating the effects of interference, signal loss and atmospheric effects, as they apply to precise GNSS positioning technology. In addition, technical and institutional issues necessary for developing backups to GNSS, integrated positioning solutions, automated processing capabilities and quality control measures, are also being addressed. Commission 4 also deals with geodetic remote sensing, using Synthetic Aperture Radar (SAR), Light Detection And Ranging (LiDAR) and Satellite Altimetry (SA) systems for geodetic applications.

The reader is referred to the Geodesist's Handbook 2020 for further details on the objectives of Commission 4 and the descriptions of its entities. As shown above, Commission 4 consists of 4 Sub-Commissions (SC), with SC 4.3 by far the largest, composed of 5 SCs, 1 Joint Study Group not led by Comm. 4, 5 Working Groups (led by Comm. 4, SC 4.3) and Joint Working Groups: 2 (led by Comm. 4, SC 4.3), 5 (not led by Comm. 4). Most of these entities have been closely interacting with other IAG components including Commissions, Services, ICG, ICCM, ICCT, ICCC and GGOS, where positioning and the associated applications are of major concern. This report presents the activities performed during the period 2019-2021 by the various entities of Commission 4, most of which were very productive and made significant progress in their stated objectives and program of activities despite the severe impacts of the Covid-19 pandemic.

Activities during the reporting period 2019-2021

In addition to the work performed by the sub-components of Commission 4, the following list summarizes major activities in 2019-2021 that were pursued on behalf of the entire Commission:

- A new web site for Commission 4 was established at http://iag-comm4.survey.ntua.gr and is hosted by the School of Rural and Surveying Engineering, National Technical University of Athens
- The terms of reference and structure of Commission 4, as well as the membership and the descriptions of its sub-components were detailed in our contribution to the Geodesist's Handbook 2020.
- A new Steering Committee was formed, which is composed of the President and Vice-President, the Chairs of the 4 Sub-Commissions, one representative from IGS (Sharyl Byram), one representative from IVS (Robert Heinkelmann) and two IAG members-at large (Ana Paula C. Larocca (Brazil), Jiyun Lee (Korea))
- During the 2019-2021 period, the Commission 4 Steering Committee did not meet physically due to travel restrictions imposed by the Covid-19 pandemic. Commission-related business were mostly conducted through email discussions and electronic exchange of information. One remote meeting was held in May 2021 and the next business meeting of the Steering Committee is planned to take place during the IAG Scientific Assembly, Beijing, China in late June 2021.
- Commission 4 was represented at all IAG Executive Committee Meetings, at which brief progress reports were presented:
  1. San Francisco, USA (December 2019);
  2. Online Zoom meeting (October 2020);
  3. Online Zoom meeting (March 2021).
- Commission 4 is represented in the Steering Committees of various IAG components, including the Inter-Commission Committee on Theory (ICCT), the Inter-Commission Committee on Climate Change (ICCC), the Inter-Commission Committee on Marine Geodesy (ICCM) and the IAG Project "Novel Sensors and Quantum Technology for Geodesy". Commission 4 is also represented in the ICG and the GGOS Committees.
- *IAG Scientific Assembly 2021, Beijing, China*. Commission 4 was strongly involved in the preparation of the scientific program of the virtual IAG Scientific Assembly 2021. The organization of Symposium 4 "Positioning and Applications" was coordinated by the

President and it is divided into 9 different sessions, with a total number of about 63 presentations.

- *Other events.* During the reporting period 2019-2021, Commission 1 was involved in the organization of several scientific conferences and workshops, including ION, FIG, MGA, EGU, AGU and COSPAR meetings, which are presented in detail in the following activity reports. Naturally, however, all these activities were severely limited due to the Covid-19 situation.
- *Commission Symposium.* Commission 4 is planning its next major scientific event in September 2022 at Potsdam, Germany. Depending on the progress of the Covid-19 pandemic, it is foreseen that this will be a normal physical meeting in continuation of the traditional series of previous commission symposia.

Activities of Working and Study groups

The following pages provide individual reports for all IAG components that are primarily affiliated with Commission 4 and its Sub-Commissions.

Sub-commission 4.1: Emerging Positioning Technologies and GNSS Augmentations

Chair: Laura Ruotsalainen (Finland)
Vice Chair: Ruizhi Chen (China)

Overview

IAG Sub-Commission 4.1 comprises five Working Groups in total (i.e., WG4.1.1, WG4.1.2, WG4.1.3, WG4.1.4 and WG4.1.5), and one Special Study Group (SSG4.1.1) During the current term 2019-21, SC4.1 activities were coordinated remotely via electronic means due to the Covid-19 pandemic.

Working Groups of Sub-commission

4.1: WG 4.1.1: Multi-Sensor Systems

Chair: Allison Kealy(Australia)

Vice Chair: GüntherRetscher(Austria)

Activities and publications during the period 2019-2021

WG 4.1.1 has a joint project in EU Erasmus+ Programme Capacity Building in Higher Education, coordinators Gunther Retscher (Austria), Vassilis Gikas (Greece). The kick-off was held on March 2021.

lbs2its.net
LBS2ITS
Curricula Enrichment
delivered through the Application of
Location-based Services to
Intelligent Transport Systems
Co-funded by the
Erasmus+ Programme
of the European Union

Meetings and Conferences

Participation in key roles in the

- ION GNSS+ conference (2020 virtual)
- ISPRS, Nice (Postponed)
- virtual ION ITM (2021)
- FIG eWW (2021)

Publications

Journal Publications

Retscher, Guenther; Kealy, Allison; Gabela, Jelena; Li, Yan; Goel, Salil; Toth, Charles K; Masiero, Andrea; Błaszczak-Bąk, Wioleta; Gikas, Vassilis; Perakis, Harris; A benchmarking measurement campaign in GNSS-denied/challenged indoor/outdoor and transitional environments, Journal of Applied Geodesy, 14 (2), 215-229, 2020

Retscher, Guenther; Kealy, Allison; Gikas, Vassilis; Gabela, Jelena; Goel, Salil; Li, Yan; Masiero, Andrea; Toth, Charles K; Perakis, Harris; Błaszczak-Bąk, Wioleta; A Benchmarking Measurement Campaign to Support Ubiquitous Localization in GNSS Denied and Indoor Environments, 2020

Masiero, A; Perakis, H; Gabela, J; Toth, C; Gikas, V; Retscher, G; Goel, S; Kealy, A; Koppányi, Z; Błaszczak-Bak, W; INDOOR NAVIGATION AND MAPPING: PERFORMANCE ANALYSIS OF UWB-BASED PLATFORM POSITIONING, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, 449-555, 2020

Retscher G. (2020): Fundamental Concepts and Evolution of Wi-Fi User Localization: An Overview Based on Different Case Studies. Sensors, 2020:20; 36 pgs.

Conference Publications

Bai, Yuntian Brian; Kealy, Allison; Retscher, Guenther; Hoden, Lucas; A Comparative Evaluation of Wi-Fi RTT and GPS Based Positioning, Proceedings of the International Global Navigation Satellite Systems IGNSS 2020 Conference, Sydney, Australia, 5-Jul, 2020

Gabela, Jelena; Majic, Ivan; Kealy, Allison; Hedley, Mark; Li, Shenghong; Robust Vehicle Localization and Integrity Monitoring Based on Spatial Feature Constrained PF, IEEE/ION Position, Location and Navigation Symposium (PLANS), 661-669, 2020

Goel S., J. Gabela, G. Retscher, C. K. Toth, A. Masiero, A. Kealy (2020): UWB Cooperative Localization of Pedestrians along a Constrained Building Hallway. in: Papers presented at the International Global Navigation Satellite Systems (IGNSS) 2020 Conference, February 5-7, 2020, Sydney, Australia.

Retscher G., Y. Li, A. Kealy, V. Gikas (2020): The Need and Challenges for Ubiquitous Positioning, Navigation and Timing (PNT) Using Wi-Fi. FIG Working Week 2020, Amsterdam, The Netherlands; 10.05.2020 - 14.05.2020; paper-No. 10335, 18 pgs.

Cheng W., Y. Dai, N. El-Sheimy, C. Wen, G. Retscher, Z. Kang, A. Lingua (2020): ISPRS Benchmark on Multisensory Indoor Mapping and Positioning. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Nice, France, pp. 117 - 123.

Retscher G., V. Gikas, R. Gerike (2021): Curricula Enrichment for Sri Lankan Universities Delivered through the Application of Location Based Services to Intelligent Transport Systems FIG eWorking Week 2021, paper-No. 10865, 16 pgs.

WG 4.1.2: Autonomous Navigation for Unmanned Systems

Chair: *Ling Pei (China)*
Vice Chair: *Giorgio Guglieri*
(Italy)

Activities and publications during the period 2019-2021

WG4.1.2 has been actively collecting data in various data campaigns, commit research visits and publishing joint papers. The plan is to establish a ResearchGate portal for disseminating and sharing the outputs widely for the whole WG, SC and wider public.

Publications

Journal Publications

Y. Li et al., "Toward Location-Enabled IoT (LE-IoT): IoT Positioning Techniques, Error Sources, and Error Mitigation," in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2020.3019199.

Research Projects and Data Sets

- SJTU and Politecnico di Torino applied together to a grant MAECI-MOST for navigation in smart city scenarios.
- SJTU and NetEase Ltd. released an open dataset "NEAR: The NetEase AR Oriented Visual Inertial Dataset"in 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). The full dataset with calibration parameters and ground truth is publicly available via https://github.com/EZXR-Research/ NEAR-VI-Dataset.
- SJTU added semantic saliency information to the Euroc dataset to generate an open-source saliency SLAM dataset. More details could be found from a preprint on aXiv"Attention-SLAM: A Visual Monocular SLAM Learning from Human Gaze.

Research Visits

- Giorgio Guglieri, Fabio Dovis, Politecnico di Torino, Italy hosted by Ling Pei, Shanghai Jiao Tong University, China
- Prof. Elisa Capello Politecnico di Torino, Italy came to SJTU to teach the 1 week course "Flight control system design for multirotor UAVs".
- Two master students from Politecnico di Torino, Italy came to complete their master thesis at SJTU Shanghai, hosted by assistant professor Daniele Sartori.
- Dr. Gabriele Ermacora graduated from Politecnico di Torino, Italy is working as post-doctor offered by Prof. Ling Pei
- SJTU and Politecnico di Torino officially signed a memorandum of understanding for cooperation between the department of mechanical and aerospace engineering of Politecnico and the lab.

Cooperation with other Organizations

- SJTU has utilized the dataset from WG 4.1.5 Positioning and Navigation in Asian Urban Canyons. A paper based on the dataset has been submit to IEEE Sensors Journal
- Planned: Cooperation with other IAG SC 4.1 WGs in Commission 4.1 Symposium via Internet.

WG 4.1.3: 3D Point Cloud based Spatio-temporal Monitoring

Chair: Jens-Andre Paffenholz (Germany) Vice Chair: Corinna Harmening (Austria)

Activities and publications during the period 2015-2017

The WG has set-up a project corresponding to the WG at the social networking site ResearchGate (www.researchgate.net) and is intensifying its use for exchange as well as preparing actively for FIG WW2020.

Meetings and Conferences

- Joint session of FIG Commission 6 and IAG WG 4.1.3., Working Week in Amsterdam in May 2020
    - five talks plus a talk dealing with the topics "point cloud-based monitoring in engineering surveying"
    - all papers are available via the FIG website.
- Preparing for FIG WW2020, planned to be held in 2021 in Utrecht

Publications

Journal Publications

- Joint journal paper under preparation
- Submitted a paper (2020) for a conference in Austria about "Spatio-temporal monitoring of soil erosion by means of 3D point clouds", joined work with a colleague form the Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover.

Conference Publications

- Paffenholz and Harmening (2021), paper submitted for the FIG

Cooperation with other Organizations

- ResearchGate portal used for collaboration among other WGs, SC, and wider IAG community
- Trying to find ways to get more in touch with the other WGs at least the chairs about general aspects of the WGs and the Commission.

WG 4.1.4: Computer Vision in Navigation

Chair: *Andrea Masiero (Italy)*

Vice Chair: *Kai-Wei Chiang (Taiwan)*

Activities and publications during the period 2019-2021

The Working Group 4.1.4 has actively been collecting data, sharing data with all WG members and using that for joint research resulting in publications. The WG has also been actively participating and collaborating in different meetings.

Meetings and Conferences

The WG presented the goals and actions of the group in the following events:

- ISPRS World Congress, Nice, France, in June 2021
- IAG Assembly, June-July 2021, online
- IPIN 2021, Barcelona, Spain, in October 2021
- MMT International Symposium in Padua, Italy, in May 2022
- IAG Commission 4 “Positioning and Applications Symposium” in Postdam, Germany, in September 2022

Cooperation with other Organizations

- JRC and other stakeholders in activities related to the SARA project (October 2020).

Research Visits

- Paolo Dabove, Polytechnic of Turin, Italy hosted by Andrea Masiero, University of Padua, Italy
- Vincenzo Di Pietra, Polytechnic of Turin, Italy hosted by Andrea Masiero, University of Padua, Italy

Publications

Conference Publications

- Masiero et al. "A CASE STUDY OF PEDESTRIAN POSITIONING WITH UWB AND UAV CAMERAS", ISPRS Archives, 2021
- "Towards collaborative positioning of pedestrian and UAS platforms by integrating vision, UWB, and IMU data", IAG Assembly, 2021
- Masiero, A., Perakis, H., Gabela, J., Toth, C., Gikas, V., Retscher, G., ... Li, Y. (2020). Indoor Navigation and Mapping: Performance Analysis of Uwb-Based Platform Positioning. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, 549-555.

WG 4.1.5: Localization at Asian urban canyons

Chair: *Li-Ta Hsu (Hong Kong)*

Vice Chair: *Kubo Nobuaki (Japan)*

Activities and publications during the period 2019-2021

The Working Group 4.1.5 has actively been collecting data, sharing data with all WG members and using that for joint research resulting in publications. WG builds an integrated dataset collected in diverse challenging urban scenarios in Hong Kong and Tokyo, that provides full-suit sensor data, which includes GNSS, INS, LiDAR and cameras. The open-source data, UrbanNav collection campaign is in two-stages. Stage one: Pilot Dataset collected by Tokyo and Hong Kong The pilot data collected by both teams are online available through the link https://www.polyu-ipn-lab.com/urbannav. The GitHub page is also maintained to allow the user to ask questions on the use of the open-source data. Several conference and journal papers are published using this pilot dataset. ION is working with the WG to invite papers that used the open-source data to submit to ION Pacific PNT 2021. Stage two: Pilot Dataset collected by Tokyo and Hong Kong. The Hong Kong team is preparing a complete sensor-kit (See the figure below.). The new setup will include, Smartphone, commercial Geodetic level GNSS receivers, two 16 channel LiDARs and one 32 channel LiDAR and one stereo camera with a baseline of 30 cm. 5 new routes are designed to include various urban environments in Hong Kong.

Members

Taro Suzuki, Chiba Institute of Technology, Japan
Junichi Meguro, Meijo University, Japan
Wu Chen, PolyU, Hong Kong
Zhizhao Liu, PolyU, Hong Kong

Grants

1. Internal Grant from Smart Cities Research Institute, PolyU:

Project Title: Urban Positioning Infrastructure for Autonomous Vehicles
Project Investigator: Prof Wu CHEN, PolyU
Co-Investigators: Dr Li-Ta HSU, PolyU, Dr Wei YAO, PolyU, Dr Bin XIAO, PolyU , Dr Yiping, JIANG, PolyU, Dr Wang Hei HO, PolyU, Prof. Xiaoli DING, PolyU, Prof. Ruizhi CHEN, Wuhan University
Funding nature: Research Grant (Competitive)
Period: 30 Apr 2021 - 29 Apr 2023
Amount: HK$ 1,000,000
Aims:
1) Establish a testbed for autonomous vehicle navigation system;
2) Develop an open architecture for multi-sensor vehicle navigation system;
3) Investigate algorithms for the integration of vehicle sensors and road infrastructures.

2. External Grant from Germany/Hong Kong Joint Research Scheme (RGC/DAAD)
Project Title: Collaborative Navigation for Smart Cities
Project Investigators: Dr Li-Ta Hsu, PolyU (Hong Kong Side), Prof. Schön Steffen, Leibniz, Universität Hannover (Germany Side)
Funding nature: Travelling Grant (Competitive)
Period: 1 Jan 2021 - 31 Dec 2022
Amount: HK$ 57,200 (Hong Kong Side) EU€ 10, 616 (Germany Side)
PhD Students participated: Mr Guohao, Zhang, PolyU (Hong Kong), Ms Lucy Icking, Leibniz Universität Hannover (Germany)
Aims:
In recent years, the possibility for communication from vehicle-to-participants (V2X) has enabled exchanging information between traffic participants as well as elements of the environment. In this context, collaborative positioning has become a widely noticed topic and shows great potential for improved accuracy and integrity for navigation in urban areas. Global Navigation Satellite Systems (GNSS) is the only navigation sensor that provides absolute positioning. However, urban areas form the most challenging environment for GNSS to achieve a reliable position. Because of the reduced satellite visibility and signal disturbances like diffraction and multipath, the resulting position has a reduced accuracy and availability. Multipath is the error arising by an incoming reflected signal, making it hard to determine the actual signal path length. The overall research objective of this project is to reduce these shortcomings through collaboration.
1) Develop strategies for improved GNSS based navigation using 3D building models.
2) Investigate collaboration between nodes to share GNSS observations information.
3) Evaluate similarities and differences in challenges and solutions for GNSS based positioning in the urban areas Hong Kong and Hannover.

Publications

Journal Publications

- Qian Meng, Li-Ta Hsu (2020) A New Kalman Filter based Solution Separation for Integrity Monitoring of Multi-Sensor Integrated Navigation System, *IEEE Sensors Journals*, (online available)
- Xiwei Bai, Wen Weisong, Li-Ta Hsu (2020) Robust Visual-Inertial Integrated Navigation System Aided by Online Sensor Model Adaption for Autonomous Ground Vehicles in Urban Areas, *Remote Sensing*, vol. 12, pp. 1686-1701.
- Wen Weisong, Xiwei Bai, Zhang, Guohao, Shengdong Chen, Feng Yuan, Li-Ta Hsu (2020) Multi-Agent Collaborative GNSS/Camera/INS Integration Aided by Inter-ranging for Vehicular Navigation in Urban Areas, *IEEE Access*, vol. 8, pp. 124323-124338
- Yue J., Wen W., Han J., Hsu L.T. (2021) 3D Point Clouds Data Super Resolution Aided LiDAR Odometry for Vehicular Positioning in Urban Canyons, IEEE Transactions on Vehicular Technology,(

Accepted)
- Luo H., Li Y. , Wang J., Weng D., Ye J., Hsu L-T, Chen W. (2021) Integration of GNSS and BLE Technology With Inertial Sensors for Real-Time Positioning in Urban Environments, IEEE Access, 9:15744.
- Wen W., Pfeifer T.#, Bai X., Hsu L.T.*, (2021) Factor Graph Optimization for GNSS/INS Integra-tion: A Comparison with the Extended Kalman Filter, Navigation, Journal of Institute of Navigation (Accepted).

Conference Publications

- Bing Xu, Li-Ta Hsu, Taro Suzuki Intermediate Frequency Level GPS Multipath/NLOS Simulator based on Vector Tracking and Ray Tracing, ION ITM 2020, San Diego, California, USA.
- Weisong Wen, Tim Pfeifer, Xiwei Bai and Li-Ta Hsu, GNSS/LiDAR Integration Aided by Self-adaptive Gaussian Mixture Model in Urban Scenarios: An Approach Robust to Non-Gaussian Noise, IEEE/ION PLANS 2020, Portland, Oregon, USA.
- Xiwei Bai, Weisong Wen, Li-Ta Hsu and Huiyun Li, Perception-aided Visual/Inertial Integrated Positioning in Highly Dynamic Urban Areas, IEEE/ION PLANS 2020, Portland, Oregon, USA
- Weisong Wen, Yiyang Zhou, Guohao Zhang, Saman Fahandezh-Saadi, Xiwei Bai, Wei Zhan, Masayoshi Tomizuka, and Li-Ta Hsu, UrbanLoco: A Full Sensor Suite Dataset for Mapping and Localization in Urban Scenes, ICRA 2020, Paris, France.
- Li-Ta Hsu, Nobuaki Kubo, Wu Chen, Zhizhao Liu, Taro Suzuki and Junichi Meguro, "UrbanNav: An Open-Sourced Multisensory Dataset for Benchmarking Positioning Algorithms Designed for Urban Areas," ION GNSS+ 2021 (Virtually) on Sept 2021.

Research Visits

- Taro Suzuki, Chiba Institute of Technology, Japan, hosted by Li-Ta Hsu, PolyU, Hong Kong (2020)
- Li-Ta Hsu, PolyU, Hong Kong, hosted by Nobuaki Kubo, Tokyo University of Marine Science &Technology, Japan (2020)
- Tim Pfeifer, Chemnitz University of Technology, Germany, hosted by Li-Ta Hsu, PolyU, Hong Kong (2020)

Meetings and Conferences

- ION Pacific PNT 2019, Oral Presentation, Honolulu, Hawaii
- ION GNSS+ 2019, Oral Presentation, Miami, Florida
- International Workshop on Autonomous Guidance 2020, Navigation and Control of Unmanned System, Nanjing, China (Virtual Talk)
- Dr Li-Ta Hsu gives talk on the topic "3D LiDAR Aided GNSS and Its Tightly Coupled Integration with INS Via Factor Graph Optimization," at Aerospace Information Research Institute, Chinese Academy of Sciences (virtually) on 9 April 2021
- Dr Li-Ta Hsu gives talk on the topic "3D LiDAR Aided GNSS and Its Tightly Coupled Integration with INS Via Factor Graph Optimization," at Research Theme Group on Integrity and Collaboration in Dynamic Sensor Networks (i.c.sens), Leibniz Universität Hannover (virtually) on 21 May 2021

Cooperation with other Organizations

The group has established links between the following stakeholder for improved dissemination of the action deliverables and input of different user needs for the work:

- ION in the Council meetings in 2019 and 2020.
- The session "Challenging Navigation Problems" on ION Pacific PNT is inviting papers that used the open-source dataset, UrbanNav, to develop their algorithm

SSG 4.1.1: Positioning using smartphones

Chair: *Guenther Retscher (Austria)*

Vice Chair: *Ruizhi Chen (China)*

Activities and publications during the period 2019-2021

The SSG4.1.1 has committed the following actions during the reporting period.

- Continuation of investigation of the application of Wi-Fi for indoor and urban positioning using smartphones
- Development of an library navigation and guidance system at TU Wien
- Analyses of urban positioning with smartphones along a public transport route in Vienna
- Analyses of the new Google Pixel 5 dual frequency GNSS smartphone in Vienna
- Investigation of Bluetooth RSSI measurements for covid-19 contact tracing with an international measurement campaign of TU Wien, Ghent University and KU Leuven: https://www.youtube.com/watch?v=x6y8W80qH8M

Meetings and Conferences

- Give a keynote speech in the 12th China Satellite Navigation Conference entitled “Precise Ubiquitous Positioning-Extending From Outdoor to Indoor“, in May 26th, Nanchang, China.
- Pariticipating the Google “Smartphone Decimeter Challenge“, and will present in ION GNSS+ 2021. https://www.ion.org/gnss/sessions.cfm?sessionID=1318

Publications

- Retscher G. (2020): Fundamental Concepts and Evolution of Wi-Fi User Localization: An Overview Based on Different Case Studies. Sensors, 2020:20; 36 pgs.
- Retscher G., A. Bekenova (2020): Urban Wi-Fi Fingerprinting Along a Public Transport Route. Journal of Applied Geodesy, 14:4, pp. 379 – 392.
- Retscher G., A. Leb (2021): Development of a Smartphone-based University Library Navigation and Information Service Employing Wi-Fi Location Fingerprinting. Sensors 2021: 21; 37 pgs.
- Retscher G., A. Leb (2021): Development of a Navigation and Information Service for a University Library. 2021 International Technical Meeting ION ITM, virtual; 25.01.2021 - 28.01.2021; paper-No. 19, 14 pgs.
- Y. Yu, R. Chen, L. Chena, W. Li, Y. Wu and H. Zhou, A Robust Seamless Localization Framework Based on Wi-Fi FTM / GNSS And Built-in Sensors, in IEEE Communications Letters, doi: 10.1109/LCOMM.2021.3071412.
- Y. Yu, R. Chen, L. Chen, W. Li, Y. Wu and H. Zhou, Autonomous 3D Indoor Localization Based on Crowdsourced Wi-Fi Fingerprinting And MEMS Sensors, in IEEE Sensors Journal, doi: 10.1109/JSEN.2021.3065951.
- Y. Yu et al., A Novel 3-D Indoor Localization Algorithm Based on BLE and Multiple Sensors, in IEEE Internet of Things Journal, vol. 8, no. 11, pp. 9359-9372, 1 June1, 2021, doi: 10.1109/JIOT.2021.3055794.
- Peng X, Chen R, Yu K, Ye F, Xue W. An Improved Weighted K-Nearest Neighbor Algorithm for Indoor Localization. Electronics. 2020; 9(12):2117. https://doi.org/10.3390/electronics9122117
- Z. Liu, R. Chen, F. Ye, G. Guo, Z. Li and L. Qian, Improved TOA Estimation Method for Acoustic Ranging in a Reverberant Environment, in IEEE Sensors Journal, doi: 10.1109/JSEN.2020.3036170.

- Z. Liu, R. Chen, F. Ye, G. Guo, Z. Li, L. Qian (2020). Time-of-arrival estimation for smartphones based on built-in microphone sensor, in Electronics Letters, Vol. 56, Issue 23, p. 1280-1283.
- Y. Yu et al., "Precise 3-D Indoor Localization Based on Wi-Fi FTM and Built-In Sensors," in IEEE Internet of Things Journal, vol. 7, no. 12, pp. 11753-11765, Dec. 2020, doi: 10.1109/JIOT.2020.2999626.
- Li, M.; Chen, R.; Liao, X.; Guo, B.; Zhang, W.; Guo, G. A Precise Indoor Visual Positioning Approach Using a Built Image Feature Database and Single User Image from Smartphone Cameras. Remote Sens. 2020, 12, 869. https://doi.org/10.3390/rs12050869
- G. Guo, R. Chen, F. Ye, X. Peng, Z. Liu and Y. Pan, "Indoor Smartphone Localization: A Hybrid WiFi RTT-RSS Ranging Approach," in IEEE Access, vol. 7, pp. 176767-176781, 2019, doi: 10.1109/ACCESS.2019.2957753.
- F. Ye, R. Chen, G. Guo, X. Peng, Z. Liu and L. Huang, "A Low-Cost Single-Anchor Solution for Indoor Positioning Using BLE and Inertial Sensor Data," in IEEE Access, vol. 7, pp. 162439-162453, 2019, doi: 10.1109/ACCESS.2019.2951281.
- S. Xu, R. Chen, Y. Yu, G. Guo and L. Huang, "Locating Smartphones Indoors Using Built-In Sensors and Wi-Fi Ranging With an Enhanced Particle Filter," in IEEE Access, vol. 7, pp. 95140-95153, 2019, doi: 10.1109/ACCESS.2019.292738

Sub-commission 4.2: Multi-Frequency Multi-Constellation GNSS

Chair: *Michael Schmidt (Germany)*
Vice Chair: *Ehsan Forootan (Denmark)*

Overview

SC 4.2 is composed of four Working Groups. Besides, several of SC 4.2 members participate in other IAG Joint Study Groups and Working Groups related to GNSS PNT methods, integrity and control, e.g., WG 4.4.3: Reliability of Low-cost & Android GNSS in navigation and geosciences and SG 4.1.1 Positioning Using Smartphones.

SC4.2 coordinates activities to promote and deliver practical and theoretical solutions for engineering and scientific applications and also will stimulate strong collaboration with the IAG Services (IGS) and relevant scientific and professional sister organizations such as FIG, ION and IEEE.

In joint effort with SC 4.4, the SC 4.4. organized dedicated session at The Scientific Assembly of the International Association of Geodesy from June 28th to July 2nd, 2021, specifically session 4.3: Techniques and Applications in High Precision GNSS (http://www.iag2021.com/en/web/index/1646_)

Working Groups of Sub-Commission 4.2

WG 4.2.1: Interoperability of GNSS Precise Positioning (Joint WG between IAG and IGS)

Chair: *Allison Kealy/Suelynn Choy TBA (Australia)*
Vice Chair: *Sharyl Byram (USA)*

The objective of this WG is to promote interoperability of GNSS precise positioning to support a wide range of science and engineering applications, which will benefit society. Activities include: (1) encourage sharing and dissemination of knowledge of satellite parameters and receiver properties, which are essential for high precision GNSS applications; and (2) investigate new techniques and algorithms to ensure interoperability of correction products for precise point positioning (PPP).

This WG will work in close scientific collaboration with IGS, FIG and ICG.

Activities and publications during the period 2019-2021

ICG WG-D

In 2019, the WG 4.2.1 was formed in collaboration with the IAG, IGS and FIG as results of the work of WG-D within the United Nations International Committee on GNSS (UN ICG). Meetings took place in June and December 2019 together with members of the ICG and GNSS/RNSS System Providers to discuss opportunities and challenges of interoperability of GNSS precise point positioning (PPP) services.

In June 2019, a special technical session on GNSS PPP services was organized at the UN ICG Workshop on the Applications of GNSS, Suva Fiji, 24-28 June 2019. The aim of the workshop was to share ideas and promote the use and interoperability of GNSS PPP services. The link to the presentations of the workshop on the applications of GNSS is here: https://www.unoosa.org/oosa/en/ourwork/psa/schedule/2019/2019-workshop-on-global-navigation-satellite-systems_-presentations.html

Subsequently in December 2019, WG 4.2.1 met at ICG-14 in Bangalore, India, to progress the discussion of interoperability of GNSS PPP services. Based on the outcome of the workshop, a recommendation to establish a Task Force on PPP interoperability was adopted by the ICG. The Task Force will be co-chaired by Australia, the EU and Japan, and will prepare a workshop in 2020 to continue the discussion and address the issues raised at the 2019 workshop. The IGS, FIG and IAG are members of the Task Force. For more information about ICG-14, refer to:
https://www.unoosa.org/oosa/en/ourwork/icg/meetings/ICG-2019.html

In February 2020, the International Global Navigation Satellite Systems (IGNSS) Conference hosted presentation sessions and specifically a panel discussion on the "Future of GNSS Precise Point Positioning", in which interoperability of the GNSS PPP services were discussed. The panel was represented by members from government, industry and academia.

Selected publications during the period 2019-2021:

R. Hirokawa and I. Fernandez-Hernandez, "Open Format Specifications for PPP/PPP-RTK Services: Overview and Interoperability Assessment," Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2020), pp. 1268-1290, 2020.

R. Hirokawa, "Recent Activity of International Standardization for High-Accuracy GNSS Correction Service," Coordinates, vol. 15, no. 11, pp. 10-17, November 2019.

WG 4.2.2: Ambiguity resolution for low-cost GNSS positioning

Chair: Prof. Xiaohong Zhang (China)

Vice-Chair: Dr Robert Odolinski (New Zealand)

Members

- *Yang Gao, Calgary University (Canada)- TBD*
- *Wu Cheng, the Hong Kong Polytechnic University (China)*
- *Amir Khodabandeh, Melbourne University (Australia)*
- *Dinesh Manandhar, The University of Tokyo (Japan)*
- *Nacer Naciri, York University(Canada)*
- *Baocheng Zhang, Institute of Geodesy and Geophysics, CAS(China)*

The research conducted by WG 4.2.2 will focus on algorithms and methods for integer ambiguity resolution on low-cost handheld devices, to facilitate optimal modelling of precise positions and atmospheric delays (ionosphere and troposphere), to investigate the quality control methods for low-cost GNSS precise positioning, to develop a robust algorithms of integration GNSS with MEMS and other low-cost sensors.

Activities and publications during the period 2019-2020 relevant to the above objectives

(1) Frequency Division Multiple Access (FDMA) ambiguity resolution applied to short and long baseline GLONASS data

Teunissen and Khodabandeh (2019) and Hou et al. (2020) studied and applied the new GLONASS FDMA ambiguity resolution model, as developed by Teunissen (2019), for short- and long-baseline data. This FDMA model is also applicable to low-cost GNSS receivers able to track FDMA GLONASS signals, such as the ublox ZED-F9P receivers, as explicitly demonstrated in Teunissen and Khodabandeh (2019). Zaminpardaz et al. (2021) performed a Code Division Multiple Access (CDMA) and FDMA combination of GLONASS-only satellites for real-time kinematic (RTK) positioning, and analyzed its performance using the future GLONASS constellation.

(2) Best Integer Equivariant (BIE) estimation applied to low-cost multi-GNSS data, with comparison to the commonly used Integer Least Squares (ILS) estimator

Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency (SF) multi-GNSS RTK positioning. Odolinski and Teunissen (2020b) analyzed subsequently also the corresponding BIE performance for low-cost dual-frequency (DF) long baseline multi-GNSS RTK positioning. It was shown that the BIE estimator outperforms ILS and the float solutions in terms of their positioning mean squared errors (MSEs).

(3) Single-station precise point positioning RTK (PPP-RTK) that can enable low-cost positioning infrastructures

Khodabandeh and Nadarajah (2020) studied a single-receiver constant-velocity setup with which a reference receiver can act like a PPP-RTK correction provider. Khodabandeh (2021) further demonstrated how the ambiguity resolution performance for single-station PPP-RTK is driven by the correction latency and therefore by the uncertainty involved in the time-prediction of single-station PPP-RTK corrections. Supported by numerical results, Khodabandeh (2021) showed that the number of satellites and number of frequencies work in tandem to enable one to increase the correction latency, yet ensuring successful single-receiver ambiguity resolution.

(4) Single-receiver stochastic modeling of multi-frequency GNSS observables

In alignment with the single-station concept above, Zhang et al. (2020) applied the least-squares variance component estimation (LS-VCE), as developed by Teunissen and Amiri-Simkooei (2008), to the geometry-free functional model. This so as to facilitate the stochastic properties of multi-frequency GNSS observables at the undifferenced level and a single-receiver.

(5) On the temperature sensitivity of multi-GNSS intra- and inter-system biases (ISBs).

Mi et al. (2020) analyzed the temporal variability of the intra- and inter-system biases (ISBs), including the receiver-dependent differential code and phase biases (DCBs and DPBs, respectively). RTK positioning evaluations were further conducted to assess the performance improvement one can gain by modeling this time-variability in comparison to the commonly used models of time-invariant receiver DCBs, DPBs and ISBs. This is particular important in the context of optimal RTK performance while using low-cost multi-GNSS receivers, where further studies can be conducted. The short-term variability of receiver code biases was further mitigated in Wang et al. (2019) to improve the ambiguity resolution performance for PPP.

(6) Low-cost GNSS receiver integration with MEMS Inertial Measurement Units (IMUs)

Vana et al. (2019) studied the MEMS IMU and low-cost GNSS receiver data integration for dual-frequency PPP. Such integration can be particular beneficial for unmanned aerial vehicles (UAVs), pedestrian navigation, and autonomous vehicles. Zhu et al (2019 fused dual-antenna GNSS and MEMS to acquire heading, pitch, and roll with high accuracy in GNSS challenged environments. Instead of a Euler angle representation, the misalignment is used to build the state model in the integrated Kalman filter. Attitudes derived from dual-antenna GNSS and smoothed acceleration are adopted as measurements. It can be found that this filtering architecture is actually a subset of loosely coupled GNSS/MEMS integration. Therefore, the proposed module can be easily embedded into loosely coupled integration. In addition, due to the disadvantage that GNSS is sensitive to signal interference and obstacles, the fault detection and exclusion strategy was proposed to avoid the filtering divergence and to improve the reliability of attitude determination. Zhu et al (2019) introduces a dedicated android smartphone application called Walker that integrates the GNSS navigation solution and MEMS (micro-electromechanical systems) sensors to enable continuous and precise pedestrian navigation. The kinematic experiment verifies that the proposed method is capable of obtaining accuracy within 1–3 m for smooth and continuous navigation.

(7) New progress of PPP/PPP-RTK

Zhang et al (2020) summarized a brief review of the current state of development of precise point positioning (PPP) in recent years, with a focus on summarizing the latest research progress of several hot spots such as real-time rapid estimation of high-rate satellite clocks, multi-GNSS PPP ambiguity resolution, multi-frequency GNSS PPP models and ambiguity resolution, rapid initialization of PPP and PPP-RTK. The evaluation of positioning performance of single/multi-GNSS PPP with latest observation of GPS, GLONASS, Galileo and BDS, especially the positioning accuracy, convergence time and time to first fix of BDS-2+3, is given.

(8) Integer-estimable FDMA model as an enabler of GLONASS PPP-RTK

Zhang et al (2021) studied the GLONASS PPP-RTK that takes advantage of the integer-estimable FDMA (IE-FDMA) model developed by Teunissen (2019) to guarantee rigorous integer ambiguity resolution and simultaneously takes care of the presence of the inter-frequency biases (IFBs) in homogeneous and heterogeneous network configurations. When conducting GLONASS PPP-RTK based on a network of homogeneous receivers, code and phase observation equations were used to construct the IE-FDMA model, in which the IFBs were implicitly eliminated through reparameterization. For a network consisting of heterogeneous receivers, the code observables were excluded and a phase-only IE-FDMA model was developed, thereby circumventing the adverse effects of IFBs. Supported by numerical results, Zhang et al (2021) succeeded in fixing both GPS and GLONASS ambiguities, shortening the convergence time to 0.5 (3) minutes, compared to 8 (9) minutes of ambiguity-float positioning in the case of a homogeneous (heterogeneous) network with a data sampling rate of 30 seconds. Compared with GPS-only positioning, the integration of GPS and GLONASS yielded an improvement of 8%-34% in accuracy and leaded to a reduction of 25%-50% in convergence.

Special issues

A Special Issue "*Multi-GNSS Precise Positioning and Applications"* in Sensors on the objectives of the WG 4.2.2 (ed. R. Odolinski and A. Khodabandeh).

Selected publications

Hou, P., Zhang, B., Liu, T. (2020) Integer-estimable GLONASS FDMA model as applied to Kalman-filter-based short-to long-baseline RTK positioning. GPS Solutions 24 (4), 1-14

Khodabandeh A. (2021). Single-station PPP-RTK: correction latency and ambiguity resolution performance. Journal of Geodesy, https://doi.org/10.1007/s00190-021-01490-z

Khodabandeh A. & Nadarajah N. (2020). State-space Positioning Corrections via Single-receiver GNSS Data. ION GNSS+ 2020, pp. 2676–2685

Mi, X., Zhang, B., Odolinski, R., & Yuan, Y. (2020). On the temperature sensitivity of multi-GNSS intra- and inter-system biases and the impact on RTK positioning. GPS Solutions, 24, 112. doi: 10.1007/s10291-020-01027-5

Odolinski, R., & Teunissen, P. J. G. (2020a). On the best integer equivariant estimator for low-cost single-frequency multi-GNSS RTK positioning. Proceedings of the International Technical Meeting of the Institute of Navigation (ION). (pp. 499-508). Institute of Navigation. doi: 10.33012/2020.17158

Odolinski, R., & Teunissen, P. J. G. (2020b). Best integer equivariant estimation: Performance analysis using real data collected by low-cost, single- and dual- frequency, multi-GNSS receivers for short- to long-baseline RTK positioning. Journal of Geodesy, 94, 91. http://dx.doi.org/10.1007/s00190-020-01423-2

Teunissen, P.J.G., Khodabandeh, A. (2019) GLONASS ambiguity resolution. GPS Solut 23, 101. https://doi.org/10.1007/s10291-019-0890-7

Vana, S., Naciri, N., Bisnath, S. (2019) Low-cost, Dual-frequency PPP GNSS and MEMS-IMU Integration Performance in Obstructed Environments. Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+), Miami, Florida, September 2019, pp. 3005-3018.

Wang, J, Huang, G, Yang, Y, Zhang, Q, Gao, Y, Zhou, P (2019). Mitigation of short-term temporal variations of receiver code bias to achieve increased success rate of ambiguity resolution in PPP, Remote Sensing, 12(5):796. doi:10.3390/rs12050796

Zaminpardaz S, Teunissen PJG, & Khodabandeh A (2021), "GLONASS-Only FDMA+CDMA RTK: Performance and Outlook", GPS Solutions, https://doi.org/10.1007/s10291-021-01132-z

Zhang, B., Hou, P., Liu, T., Yuan, Y. (2020) A single-receiver geometry-free approach to stochastic modeling of multi-frequency GNSS observables. Journal of Geodesy 94 (4), 1-21

Zhu, Feng, Tao, Xianlu, Liu, Wanke, Xiang Shi, Fuhong Wang, Xiaohong Zhang(2019). Walker: Continuous and Precise Navigation by Fusing GNSS and MEMS in Smartphone Chipsets for Pedestrians [J]. Remote Sensing, 11(2): 139

Zhu, Feng, Hu, Zengke, Liu, Wanke, Xiaohong Zhang(2019). Dual-antenna GNSS integrated with MEMS for reliable and continuous attitude determination in challenged environments [J]. IEEE Sensors Journal, 19(9): 3449-3461.

Wanke Liu, Xiang Shi, Feng Zhu, Xianlu Tao, Fuhong Wang(2019). Quality analysis of multi-GNSS raw observations and a velocity-aided positioning approach based on smartphones[J]. Advances in Space Research, 2019, 63:2358-2377.

Xiaohong Zhang, Xianlu Tao, Feng Zhu, Xiang Shi, Fuhong Wang (2018). Quality assessment of GNSS observations from an Android N smartphone and positioning performance analysis using time-differenced filtering approach[J]. GPS Solutions, 22:70

Xianlu Tao, Xiaohong Zhang, Feng Zhu, Fuhong Wang, Weizheng Teng(2018). Precise Displacement Estimation from Time-differenced Carrier Phase to Improve PDR Performance[J]. IEEE Sensors Journal, 20(18):8238-8246.

Zhang, Xiaohong, Hu, Jiahuan, Ren, Xiaodong(2020). New progress of PPP/PPP-RTK and positioning performance comparison of BDS/GNSS PPP[J]. Acta Geodaetica et Cartographica Sinica,49(9):1084-1100. DOI:10.11947/j. AGCS. 2020.20200328

Zhang, Baocheng, Hou, Pengyu, Zha, Jiuping, Liu, Teng (2021). Integer-estimable FDMA model as an enabler of GLONASS PPP-RTK [J]. Journal of Geodesy.

Wang, J, Huang, GW, Zhang, Q, Gao, Y, Gao, YT, Luo, YR (2020). “GPS/BDS-2/Galileo Precise Point Positioning Ambiguity Resolution Based on the Uncombined Model”, Remote Sensing , Volume 12; doi:10.3390/rs12111853. June 8 2020.

Wang, J, Huang, GW, Yang, YX, Zhang, Q, Gao, Y, Zhou, PY (2019). “Mitigation of short-term temporal variations of receiver code bias to achieve increased success rate of ambiguity resolution in PPP”, Remote Sensing, 12(5):796. DOI: 10.3390/rs12050796 March 2020.

Du, Y, Huang, GW, Zhang, Q, Gao, Y, Gao, YT (2020). “Asynchronous RTK method for detecting the stability of the reference station in GNSS deformation monitoring”, Sensors, 20(5):1320, DOI: 10.3390/s20051320 February 2020.

Wang, J, Huang, GW, Zhou, PY, Yang, YX, Zhang, Q, Gao, Y (2020). “Advantages of Uncombined Precise Point Positioning with Fixed Ambiguity Resolution for Slant Total Electron Content (STEC) and Differential Code Bias (DCB) Estimation”, Remote Sensing, 12, 304; doi:10.3390/rs12020304.

Zhou, P, Nie, Z, Xiang, Y, Du, L and Gao, Y (2020). “Differential code bias estimation based on uncombined PPP with LEO onboard GPS observations”, Advances in Space Research. Volume 65, Issue 1, 1 January 2020, Pages 541-551.

Meeting and communications during the period 2019-2020

Xiaohong Zhang gave a invited talk‘A New Ionospheric Product：High precision Ionospheric STEC from IGS Network’ at CSNC-ION joint Panel, Nanchang, China, 27, June, 2021

Xiaohong Zhang gave a invited talk ‘Opportunities and Challenges of PPP-RTK’ at CSNC, Nanchang, China, 27, June, 2021

Yang Gao gave a keynote talk ‘Precision GNSS to the masses’ at CSNC, Nanchang, China, May 26, 2021

Yang Gao gave a panel talk ‘Precision GNSS for AI-Enabled Autonomous Systems’ at ION GNSS+, September 23, 2020.

Other references:

Teunissen, P.J.G., Amiri-Simkooei, A.R. (2008) Least-squares variance component estimation. J Geodesy 82:65–82

Teunissen, P.J.G. (2019) A new GLONASS FDMA model. GPS Solut 23, 100. https://doi.org/10.1007/s10291-019-0889-0

WG 4.2.3: GNSS and LEO constellation

Chair: Prof. Xingxing Li (Germany)

Vice-Chair: Dr. Safoora Zaminpardaz (Australia)

Members

- *Bofeng Li (China)*
- *Maorong Ge (Germany)*
- *Oliver Montenbruck (Germany)*
- *Yansong Meng (China)*
- *Xiaohong Zhang (China)*
- *Lang Bian (China)*
- *Denise Dettmering (Germany)*
- *Jan Dousa (Czech Republic)*
- *Inigo del Portillo (USA)*
- *Xiaodong Ren (China)*
- *Tyler G. R. Reid (USA)*
- *Adrian Jäggi (Switzerland)*
- *Qile Zhao (China)*
- *Jose van den Ijssel (Netherlands)*
- *Da Kuang (USA)*
- *Daniel Koenig (Germany)*
- *Wenhai Jiao (China)*
- *Rothacher Markus (Switzerland)*
- *Baoguo Yu (China)*
- *Xinyuan Mao (Netherlands)*
- *Qianxin Wang (China)*
- *Zak Kassas (USA)*

Activities and publications during the period 2019-2020

1. Integrated Precise Orbit Determination of GNSS and LEO satellites

Onboard GNSS observations from multiple LEO satellites have been used to investigate the LEO-augmented GNSS precise orbit determination (POD). The introduction of LEO satellites can effectively improve the orbit accuracy of GNSS satellites, whose effects are closely related to the number and the distribution of ground network. Based on a global 40-station network, the differences between the estimated GPS satellite orbits and the official IGS products decrease from 19.4 to 16.7 mm (13.9% improvement) in 1D-mean RMS when adding eight LEOs. The benefit of incorporating LEO satellites is more prominent in case of the regional network. With a regional 12-station network, the orbit accuracy of GPS satellites gets improved from about 68.4 to 19.5 mm (71.5% improvement) in 1D-mean RMS after integrating the eight LEOs. Our results also demonstrate that the orbit diversity of introduced LEO satellites has a significant impact on the GPS satellite orbits. By including three LEOs in three different orbital planes, the GPS satellite orbits improve more than from adding seven well-selected additional stations to the network.

Thanks to the availability of BDS-2 observations collected by FY-3C and FY-3D satellites, we got a great opportunity to study the contribution of LEO to BDS-2 POD, which generally suffers from the limited observation geometry when only using a ground network. Our results indicate that the inclusion of FY-3D contributes to the orbit precision improvement about 72% for the BDS-only solution. The most pronounced benefit can be observed in BDS GEO orbits, which is improved by 44% for the regional solution and 41% for the global solution. The further inclusion of FY-3C improves the orbit precision by 3%, 3%, and 1% for BDS GEO, IGSO, and MEO satellites respectively.

Considering the limited number of available LEO satellites, the simulated GNSS observations from large LEO constellation have also been applied to fully explore the potential of LEO satellites in the integrated POD. The accuracy improvement percentage with respect to the ground-based POD results can reach over 70% for all the integrated POD schemes with 60-, 66-, 96-LEO satellites. The largest orbit accuracy improvement of over 98% can be recognized for BDS GEO satellites. Compared with the 60- and 66-LEO schemes, a slightly better orbit quality is observed in the 96 LEO scheme due to the introduction of more LEO satellites. The impact of the LEO orbit type on the integrated POD has also been evaluated. With the same number of LEO satellites, the sun-synchronous-orbiting constellation presents a stronger enhancement to GNSS orbits than the polar-orbiting constellation. The results with partial LEO constellation demonstrate that introducing part of a LEO constellation can be an effective way to balance the conflict between the orbit accuracy and computational efficiency.

2. LEO-augmented GNSS Precise Positioning

We investigated the precise point positioning (PPP) performance of the LEO constellation-augmented full operational capability multi-GNSS. With the augmentation of 60-, 96-, 192- and 288-satellite LEO constellation, the multi-GNSS PPP convergence time can be shortened from 9.6 to 7.0, 3.2, 2.1 and 1.3 min, respectively, in midlatitude region. For LEO-augmented GPS- and BDS-only PPP, the improvement is more significant with the convergence time dramatically shortened by 90% from about 25 to within 3 min with 192- or 288-satellite constellation. To achieve better performance of LEO-augmented multi-GNSS precise positioning, the designing of hybrid LEO constellation using a genetic algorithm has been studied. With 100 LEO satellites, the average numbers of visible satellites during a regression period are 5.49, 5.44 and 5.47, with standard deviations of 0.44, 0.18 and 0.28, for the optimized hybrid polar-orbit/Walker, orthogonal circular-orbit/Walker and Walker/Walker constellations, respectively. For coverages with four and five visible satellites with an elevation mask angle of 7°, the required numbers of satellites are 90 and 93, respectively.

Furthermore, we built the model of multi-frequency PPP AR with the augmentation of different LEO constellations. The estimated results of uncalibrated phase delay (UPD) products of GNSS and LEO show that the performance of estimated LEO UPD is comparable to that of GNSS UPD. Based on the UPD products, LEO-augmented multi-GNSS PPP AR can be achieved. The augmentation performance is more remarkable in the case of increasing LEO satellites. The time to first fix (TTFF) of the GREC fixed solution can be shortened from 7.1 to 4.8, 1.1, and 0.7 min, by introducing observations of 60-, 192-, and 288-LEO constellations, respectively. The positioning accuracy of multi-GNSS fixed solutions is also improved by about 60%, 80%, and 90% with the augmentation of 60-, 192-, and 288-LEO constellations, respectively. Compared to the dual-frequency solutions, the triple-frequency LEO-augmented PPP fixed solution presents a better performance. The TTFF of GREC fixed solutions is shortened to 33 s with the augmentation of 288-LEO constellation under the triple-frequency environment. The averaged TTFFs are 71.8 s and 55.2 s for the 288-satellite LEO-only PPP AR in dual-frequency and triple-frequency modes respectively.

Apart from LEO-augmented PPP AR, the GNSS real-time kinematic (RTK) positioning with the augmentation of LEO constellation has also been investigated. The results of 68.7 km baseline indicate that the RTK convergence time can be shortened from 4.94 to 2.73, 1.47, 0.92, and 0.73 min with the introduction of 60, 96, 192, and 288 polar-orbiting LEO satellites respectively. Results also confirm that LEO satellites do helpfully obtain faster convergence and fixing, especially in the case of long baselines, using large LEO constellations. The averaged TTFF for long baselines decreases from 12 to 2 min approximately by combining with the larger LEO constellation of 192 or 288 satellites.

3. LEO-GNSS meteorology and ionospheric sounding methodology

An approach to generating a global topside ionospheric map (GTIM) using dual-frequency GPS data from multiple LEO satellites at different orbital altitudes is presented. NeQuick2 is employed to normalize LEO data to the same observation range, and 13 LEO satellites from 2015/01/01 to 2015/09/27 are used to generate GTIM-500 (with an ionospheric range from 500 km to 20,200 km) and GTIM-800 (with an ionospheric range from 800 km to 20,200 km). The coinciding pierce point technique is used to study the error induced by altitude normalization. The results show that the relative bias error is approximately 1%. Then, the performance and accuracy of the GTIMs as well as the differential code bias (DCB) of GPS receivers onboard LEO and GPS satellites are compared and analyzed. The statistical results of the differences between the official LEO-DCB products and the LEO-DCBs estimated by different solutions show an RMS improvement of 23% and 41% for GTIM-500 and GTIM-800, respectively. The improvement in RMS of GPS-DCBs for the proposed method is approximately 20%. Moreover, the accuracy of GTIM is evaluated by the dSTEC assessment method. The results show that the RMS of GTIM-500 is 0.50 TECU (total electron content unit) for both methods. In terms of GTIM-800 estimated by the proposed method, the RMS has an improvement of 24%. In addition to the research on generating GTIM by LEO satellites, the ionospheric modelling with both GNSS and LEO satellites is also investigated. Two approaches are proposed to combine GNSS and LEO observation data for ionosphere modeling, which are single-layer normalization (SLN) method and dual-layer superposition (DLS) method, respectively. The results exhibit a significant improvement of ionospheric model accuracy by combining LEO and GNSS observation data based on proposed methods compared with that using GNSS data only, with a reduction in root mean square (rms) error of about 25% and 21% for SLN method and DLS method, respectively. The relations between the performance of ionospheric model estimated by the SLN method and LEO ionospheric observations with different observation accuracy and different satellite cut-off elevations are also highlighted. The results indicate that ionospheric model estimated by GNSS/LEO using SLN method improves at least 25% compared with that by GNSS only. The improvement of ionospheric model estimated with the cut-off elevation of 50° is the best, followed by 70°, and then 20°.

Selected publications during the period 2019-2021:

Huang W, Männel B, Sakic P, Ge M, Schuh H. (2020) Integrated processing of ground- and space-based gps observations: improving gps satellite orbits observed with sparse ground networks. Journal of Geodesy, 94(10).

Huang W, Männel B, Brack A, Schuh H. (2020) Two methods to determine scale-independent GPS PCOs and GNSS-based terrestrial scale: comparison and cross-check. GPS Solutions, 25:4

Li X, Zhang K, Ma F, Zhang W, Zhang Q, Qin Y, Zhang H, Meng Y, Bian L. (2019) Integrated Precise Orbit Determination of Multi-GNSS and Large LEO Constellations. Remote Sensing, 11(21):2514.

Li X, Zhang K, Meng X, Zhang Q, Zhang W, Li X, Yuan Y. (2020) LEO–BDS–GPS integrated precise orbit modeling using FengYun-3D, FengYun-3C onboard and ground observations. GPS Solutions, 24(2).

Su M, Su X, Zhao Q, Liu J. (2019) BeiDou Augmented Navigation from Low Earth Orbit Satellites. Sensors, 19(1).

Li B, Ge H, Ge M, Nie L, Shen Y, Schuh H. (2019) LEO enhanced Global Navigation Satellite System (LeGNSS) for real-time precise positioning services. Advances in Space Research, 63(1).

Li X, Li X, Ma F, Yuan Y, Zhang K, Zhou F, Zhang X. (2019) Improved PPP Ambiguity Resolution with the Assistance of Multiple LEO Constellations and Signals. Remote Sensing, 11(4):408.

Ma F, Zhang X, Li X, Cheng J, Guo F, Hu J, Pan L. (2020) Improved PPP Ambiguity Resolution with the Assistance of Multiple LEO Constellations and Signals. GPS Solutions, 24:62.

Li X, Lv H, Ma F, Li X, Liu J, Jiang Z. (2019) GNSS RTK Positioning Augmented with Large LEO Constellation. Remote Sensing, 11(3):228.

Li X, Ma F, Li X, Lv H, Bian L, Jiang Z, Zhang X. (2019) LEO constellation-augmented multi-GNSS for rapid PPP convergence. Journal of Geodesy, 93:749-764.

Ren X, Zhang J, Chen J, Zhang X. (2021) Global Ionospheric Modeling Using Multi-GNSS and Upcoming LEO Constellations: Two Methods and Comparison. IEEE Transactions on Geoscience and Remote Sensing, 99:1-15.

Ren X, Chen J, Zhang X, Schmidt M, Li X, Zhang J. (2020) Mapping topside ionospheric vertical electron content from multiple LEO satellites at different orbital altitudes. Journal of Geodesy, 94(9).

Ren X, Chen J, Zhang X, Yang P. (2020) Topside ionosphere of NeQuick2 and IRI-2016 validated by using on-board GPS observations from multiple LEO satellites. Journal of Geophysical Research: Space Physics.

Ren X, Zhang X, Schmidt M, Zhao Z, Chen J, Zhang J, Li X. (2020) Performance of GNSS Global Ionospheric Modeling Augmented by LEO Constellation. Earth and Space Science, 7, e2019EA000898.

Meetings and communications during the period 2019-2020

A Special Issue of *Remote Sensing* on "High-precision GNSS: Methods, Open Problems and Geoscience Applications".

WG 4.2.4: Multi-GNSS in Asia

Chair: Prof. Chalermchon Satirapod (Thailand)

Vice-Chair: Prof. Hung-Kyu Lee (Korea)

Members
- *Toshiaki Tsujii (Japan)*
- *Hyung Keun Lee (Korea)*
- *Ben K.H. Soon (Singapore)*
- *Horng-Yue Chen (Taiwan)*
- *Michael Moore (Australia)*
- *Dudy Darmawan Wijaya (Indonesia)*
- *Trong Gia Nguyen (Vietnam)*

Activities and publications during the period 2019-2021

As the Asia Oceania GNSS downstream market continues to grow rapidly, the role of the WG is to further promote GNSS scientific research, development and applications in the region. It will also focus on education and capacity building such as training, research, and networking activities to encourage the next generation of GNSS researchers. The working group will work in close cooperation with Multi-GNSS Asia (MGA) to promote applications of GNSS and SBAS such as in surveying, construction, agriculture, transportation and logistics, as well as emergency response and disaster management.

Dr. Horng-Yue Chen and Prof. Chalermchon Satirapod attended the IUGG2019 conference in Montreal, Canada in July 2019. Prof. Satirapod attended the Multi-GNSS Asia conference 2019 and gave one keynote presentation in Bangkok, Thailand. Several members (Prof. Chalermchon Satirapod, Prof. Hung-Kyu Lee, Prof. Hyung-Keun Lee, Prof. Toshiaki Tsujii, Dr. Horng-Yue Chen and Dr. Ben K.H. Soon) joined the International symposium on GPS/GNSS 2020 held in Bangkok during 17-19 January 2020. It was a great opportunity to exchange ideas and discuss some potential research collaborations.

Technical work on developing a new IGS multi-GNSS orbit combination is being developed at Geoscience Australia. The software is currently being tested to create IGS multi-GNS repro 3 products. Preliminary reprocessing results show that Galileo perform just as well as GPS from mid 2019, QZSS, Beidou have a way to go in terms of improving their orbit modelling. Geoscience Australia is also developing it's own inhouse GNSS processing engine called with the intention of being released for as open-source package. Furthermore, some related publications from the group members are as shown in the publication section.

Selected publications during the period 2019-2021:

Trakolkul, C., and Satirapod, C. (2020) Variations of Precipitable Water Vapor Using GNSS CORS in Thailand. Survey Review, https://doi.org/10.1080/00396265.2020.1713611.

Trakolkul, C., and Satirapod, C. (2020) Analysis of PWV derived from the GNSS CORS stations for determining the onset of the southwest monsoon in Thailand, International Journal of Geoinformatics, 16 (2), 71-78.

Charoenphon, C. and Satirapod. C. (2020) Improving Accuracy of a Real-Time Precipitable Water Vapor using the local meteorological models with Precise Point Positioning in Thailand, Journal of Spatial Science, https://doi.org/10.1080/14498596.2020.1758969.

Jongrujinan, T. and Satirapod. C. (2020) Stochastic modeling for VRS network-based GNSS RTK with residual interpolation uncertainty, Journal of Applied Geodesy, 14(3), 317-325.

Uaratanawong V., Satirapod C. and Tsujii T. (2020) OPTIMISATION TECHNIQUE FOR PSEUDORANGE MULTIPATH MITIGATION USING GNSS SINGLE POINT POSITIONING MODE, Artificial Satellites, 55 (2), 77-86.

Uaratanawong V., Satirapod C. and Tsujii T. (2021) Evaluation of multipath mitigation performance using signal-to-noise ratio (SNR) based signal selection methods, 15(1),75-85.

Yun, S., Lee, H., Nguyun, D.H. (2019) A study on status of multi-GNSS constellation and its positioning performance on SPP mode, Journal of the Korea Academia-Industrial Cooperation Society, 20(8), pp.622-673.

Yun, S., Lee, H. (2020) Influence of radome types on GNSS antenna phase center variation, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 38(1), pp.11-21.

Nguye, D.H, Lee, H., Yun, S. (2020) A study on simultaneous adjustment of GNSS baseline vectors and terrestrial measurements, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 38(5), pp.415-423.

Yun, S., Lee, H. (2021) Quality assessment of GPS L2C signals and measurements, Journal of Positioning, Navigation, and Timing, 10(1), pp.13-20.

Horng-Yue Chen, Hsin Tung, Ya-Ju Hsu and HungKyu Lee (2019) Evaluation of Single-frequency Receivers for Studying Crustal Deformation at the Longitudinal Valley Fault, Eastern Taiwan, Survey Review, 52, 374, Page 454-462. https://doi.org/10.1080/00396265.2019.1634340.

Hsin Tung, Horng-Yue Chen, Ya-Ju Hsu, Jyr-Ching Hu, Yo-Ho Chang, and Yu-Ting Kuo (2019) Triggered slip on multifaults after the 2018 Mw 6.4 Hualien earthquake by continuous GPS and InSAR measurements, Terr. Atmos. Ocean. Sci., 30, 285-300, doi: 10.3319/ TAO.2019.04.03.01.

Le Huy Minh, Vu Tuan Hung, Jyr- Ching Hu, Nguyen Le Minh, Bor- Shouh Huang, Horng-Yue Chen, Nguyen Chien Thang, Nguyen Ha Thanh, Le Truong Thanh, Nguyen Thi Mai, and Pham Thi Thu Hong (2020) Contemporary movement of the Earth's crust in the Northwestern Vietnam by continuous GPS data, September 2020, Vietnam Journal of Earth Sciences 42(4) DOI: 10.15625/0866-7187/42/4/15282.

Horng-Yue Chen, Ryoya Ikuta*, Ya-Ju Hsu, Toshiaki Tsujii, Masataka Ando, Yoko Tu, Takeru Kohmi, Kiyomichi Takemoto, Koto Mizuno, Hsin Tung, Chin-Shang Ku and Cheng-Horng Lin (2021) A Decade of Global Navigation Satellite System/Acoustic Measurements of Back-Arc Spreading in the Southwestern Okinawa Trough, Front. Earth Sci., 10 February 2021, https://doi.org/10.3389/feart.2021.601138.

W. J. Yoo, L. W. Kim, Y. D. Lee, and H. K. Lee, "A Coarse-Time Positioning Method for Improved Availability," GPS Solutions, GPS Solut 24, 2. https://doi.org/10.1007/s10291-019-0919-y, 2019

K. H. Choi, W. J. Yoo, L. W. Kim, Y. D. Lee, and H. K. Lee, "A Distributed Method to Estimate RDCB and SDCB Using a GPS Receiver Network," Measurement Science and Technology, Vol. 30, Article #105105, 2019.

Trong N. (2020) The method for connecting CORS station into VN-2000 reference coordinate system, University report, Hanoi University of Mining and Geology, Vietnam.

Sub-commission 4.3: Atmosphere Remote Sensing

Chair: *Michael Schmidt (Germany)*
Vice Chair: *Ehsan Forootan (Denmark)*

Overview

The SC 4.3 is composed of five Working Group (WG) and two Joint Working Groups (JWG). Besides, several SC 4.3 members participate in other IAG and GGOS Joint Study Groups (JSG) and JWGs related to atmosphere remote sensing, for instance, the GGOS Focus Area "Geodetic Space Weather Research" (FA-GSWR) which is chaired by Michael Schmidt and Ehsan Forootan, too.

Due to the Corona pandemic many of the planned activities at conferences and workshops did not work out during the reporting period and had to be postponed to the second half of 2021 or to an even later time moment. As one example we want to mention the EGU General Assembly 2020, where we have postponed all SC 4.3 activities by one year to the virtual EGU 2021 which was running in the second half of April 2021. For this online conference we installed the Session G5.1 "Ionosphere, thermosphere and space weather: monitoring and modelling" lead by the main convener Ehsan Forootan. Another example is the IAG Commission 4 Symposium, which was originally scheduled for September 2020 in Potsdam, Germany, but then was postponed to September 5 to 9, 2022.

As a positive aspect, many papers related to the scientific content of the SC 4.3's WGs and the JWGs have been written during working in home-offices. Significant progress has also been made in third-party funded national and international projects; the work within these projects is often strongly coupled with the objectives of individual WGs and JWGs of the SC 4.3.

On the next pages the different WGs and JWGs of the SC 4.3 give an overview about their work within the last two years, i.e. the reporting period 2019 to 2021.

Working Groups of Sub-commission 4.3: Atmosphere Remote Sensing

JWG 4.3.1: Real-time Ionosphere Monitoring and Modelling

(joint with IGS and GGOS)

Chair: *Zishen Li (China)*
Vice Chair: *Ningbo Wang (China)*

Members

Alberto Aarcia-Rigo (Spain), Alexis Blot (France), Andre Hauschild (Germany), Andreas Goss (Germany), Andrzej Krankowski (Poland), Attila Komjathy (USA), Cheng Wang (China), Eren Erdogan (Germany), German Olivares (Australia), Kenji Nakayama (Japan), Libo Liu (China), Manuel Hernández-Pajares (Spain), Nicolas Bergeot (Belgium), Qi Liu (China), Qile Zhao (China), Raul Orús (The Netherlands), Reza Ghoddousi-Fard (Canada), Wookyoung Lee (Korea), Xingliang Huo (China), Yunbin Yuan (China), Zhizhao Liu (China Hongkong)

Activities and publications during the period 2019-2021

Standardization on real-time ionospheric information dissemination

To mitigate the ionospheric delay errors in real-time GNSS applications, the spherical harmonic expansion up to degrees 15 is defined in RTCM v3 standard for the dissemination of real-time global ionospheric vertical total electron content (VTEC) messages. In 2019, the IGS-RT WG launched the “IGS-SSR Task Force” to design different types of IGS State Space Representation (SSR) messages in support of real-time scientific applications in current multi-frequency and multi-constellation GNSS environment. Within the IGS-SSR Task Force WG, colleagues from CAS, CNES, DLR, GEO++ and UPC-IonSAT discussed the “Ultrarapid”, “Rapid” and “Final” time scales for delivering IGS ionospheric SSR messages. In the “Ultrarapid” time scale, it is suggested to implement exactly the same type of existing RTCM ionospheric message, but increasing the maximum degree of the spherical harmonic expansion as much as possible. In the “Rapid” time scale, it is suggested to consider a second IGS-SSR ionospheric message directly implanting the IONEX format, i.e., based on a pixel- or voxel-basis function. This extends the well-known IONEX format from post-processed to real-time applications, allowing in particular high resolution VTEC information at given regions, and also allowing to broadcast in the same format other useful information, such as effective height or topside electron content fraction among other many possibilities. In the “Final” time scale, it is suggested to consider other paradigms to broadcast accurate ionospheric corrections as well as the associated accuracy information at long term. In IGS-SSR format v1.0 released in October 2020, the global ionospheric message is identical to the existing RTCM one (i.e., spherical harmonics) but with different message type. It is now under discussion the possibility of increasing the degree of spherical harmonic expansion and adding the ionospheric accuracy information in IGS-SSR message within the community. For defining IGS-SSR ionospheric message in “Rapid” and “Final” time scales, it is considered to share the information as well with colleagues of the IGS ionospheric WG and other IGS colleagues active in the field to properly drive such an importance process.

Real-time regional and global ionospheric modeling

During the period 2019-2021, the contributors for real-time global ionospheric maps (RT-GIMs) computation increase from 3 to 6. Aside from CAS, CNES and UPC-IonSAT who had been working on the routine generation of RT-GIMs, three additional contributors, i.e. DGFI-

TUM, NRCan and Wuhan University (WHU) also started RT-GIM computation and distribution. At CAS, an adjusted spherical harmonic expansion is used for its real-time regional ionospheric map (RT-RIM) computation based on the ionospheric two-layer assumption (Li et al. 2019). A predicting-plus-modelling approach is employed for its RT-GIM computation using multi-GNSS streams of the IGS-RTS (Li et al. 2020). At CNES, the spherical harmonic expansion up to degree 12 is directly used for global VTEC representation. At UPC-IonSAT, the Tomographic model with spherical harmonic interpolation was used to replace the original Kriging interpolation in September 2019. And then, a new interpolation technique, i.e. Atomic Decomposition Interpolation of GIMs (ADGIM, Yang et al. 2021) interpolation, has been implemented since January 2021 for its RT-GIM computation in the beta test phase. In the comparison of RT-GIM from different analysis centres (ACs) and JASON-3 VTECs (see Fig. 1), the quality improvement of UPC's RT-GIM can be clearly found with the transition from spherical harmonic interpolation to ADGIM interpolation.

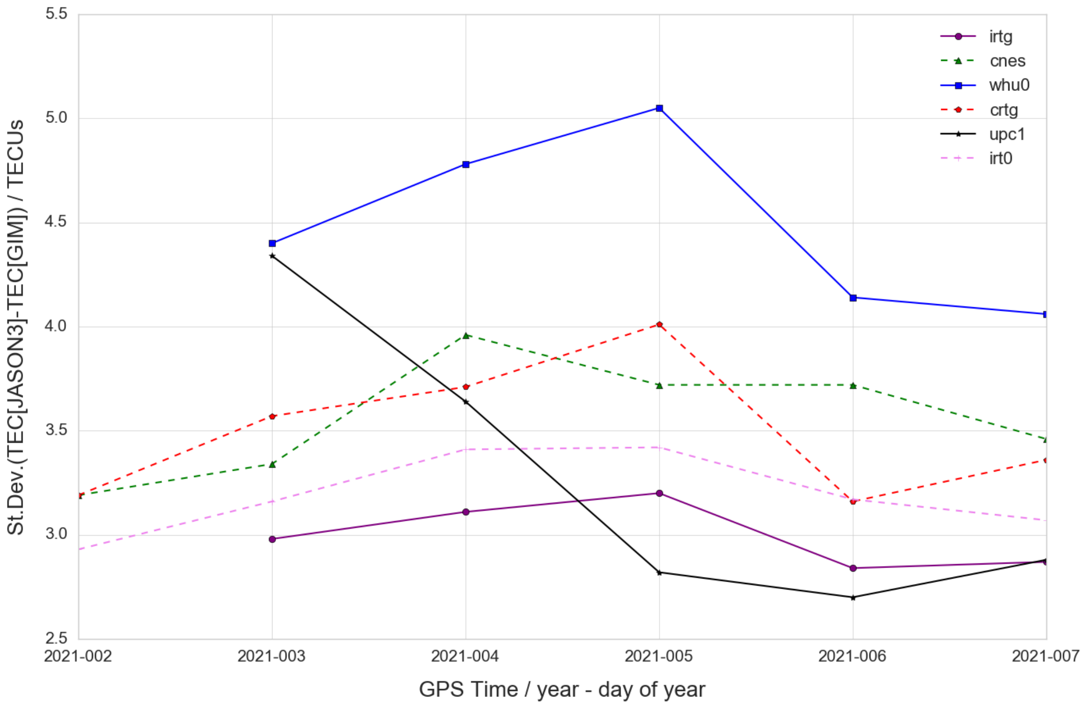


Figure 1: The comparison between RT-GIMs from CAS (crtg), CNES (cnes), UPC-IonSAT (upc1), WHU (whu0) and JASON-3 VTECs during 002/2021 and 007/2021.

The current implementation of the VTEC modelling approach of DGFI-TUM relies on both a global and a regional sequential estimator (Kalman filter) running in a parallel mode. The global VTEC estimator produces VTEC maps with B-splines using real-time data from global IGS network (Schmidt et al. 2015, Erdogan et al. 2020). The regional estimator makes use of the VTEC product of the real-time global estimator as background information and generates high-resolution VTEC maps using real-time data from the EUREF Permanent GNSS Network. The concept that was carried out for the regional ultra-rapid VTEC modelling approach of the DGFI-TUM (Goss et al. 2019, 2020a) are applied to the regional real-time modelling approach using real-time GNSS data. NRCan and WHU recently continues to encode their near-real-time TEC maps for real-time distribution in the RTCM format. NRCan distributes the proposed RTCM SSR message type 1264 at a 30 second rate, whereas WHU at 1 minute rate.

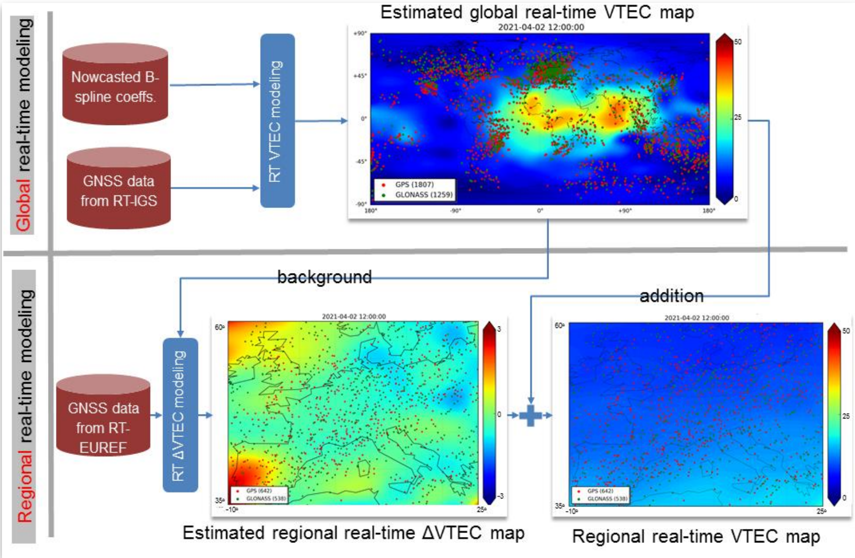


Figure 2: Process chain of DGFI-TUM to generate RT regional and global VTEC maps

The global real-time ionospheric corrections are now transmitted in both RTCM- and IGS-SSR formats by different contributors, among which CAS, CNES and UPC-IonSAT streams support IGS- and RTCM-SSR messages, whereas DGFI-TUM, NRCan and WHU only distribute the proposed RTCM-SSR message. The influences of different spectral, spatial and temporal resolutions on the performance of RT-GIMs were examined in detail by UPC-IonSAT (Liu et al. 2021a) and DGFI-TUM (Goss et al. 2020b) colleagues. A high accuracy 4-D regional ionospheric electron density model was reported by GA colleagues (Olivares-Pulido et al. 2019), and its usage in GNSS high precision positioning, i.e., PPP-RTK, was also analysed. An open-source tool to estimate precise ionospheric estimates, namely ESA UGI (Unified-GNSS-Ionosphere), was undocumented by ESA-ESTEC colleagues (Orus-Perez et al. 2020), which should largely benefit the research of real-time regional and global ionospheric modelling within GNSS ionosphere communities.

Real-time Global Ionospheric Map combination

The first experimental combination of IGS RT-GIM has been generated by applying the weights given by the real-time dSTEC assessment technique to RT-GIMs provided by CAS, CNES and UPC-IonSAT since October 2018 (Li et al. 2020). Note that such experimental IGS RT-GIM is transmitted in RTCM-SSR message type 1264 and available from the caster of UPC-IonSAT itself. With the transition of UPC's RT-GIM from spherical harmonic interpolation to the newly developed ADGIM interpolation, a new version of IGS combined RT-GIM (i.e., irtg) was developed at UPC-IonSAT, adapting to the updated RT-GIM of UPC-IonSAT and supporting the IGS-SSR ionospheric message (Liu et al. 2021b). The IGS RT-GIM is now generated using RT ionospheric streams from 4 centres, i.e. CAS, CNES, UPC-IonSAT and WHU, which is broadcasted in IGS-SSR message type and available from the IGS caster (products.igs-ip.net). In addition to RT data streams, the latest IGS RT-GIMs are also archived at the FTP site of UPC-IonSAT (http://chapman.upc.es/irtg/archive/). The computation and dissemination of the IGS RT-GIM is now maintained by UPC-IonSAT. CAS also started the experimental combination RT-GIM with additional data streams from NRCan since April 2021.

The performance of global VTEC representation in all of the RT-GIMs has been assessed by VTEC directly measured from JASON3 altimeter. During the recent testing period (see Fig. 3), the accuracy of most IGS RT-GIMs is close to post-processed GIMs. These results indicates that the IGS RT-GIMs turn out to be reliable sources of real-time global VTEC information.

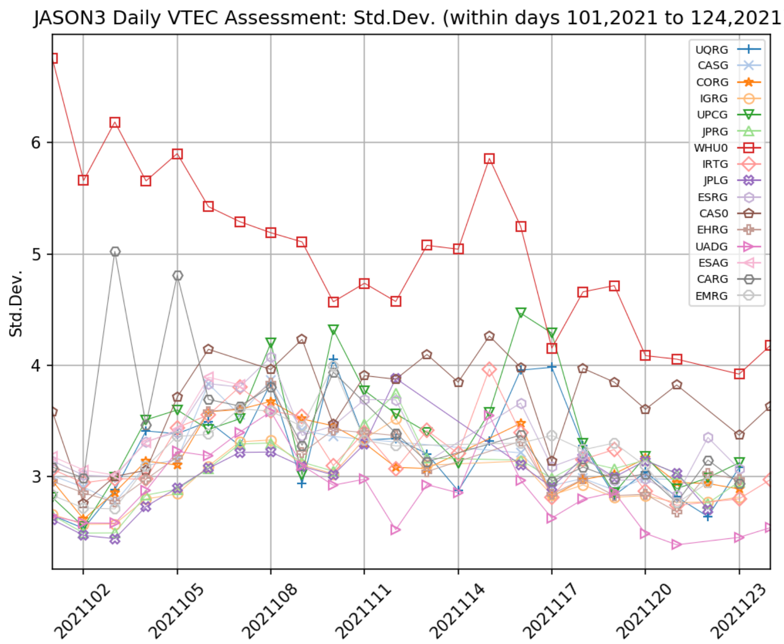


Figure 3: Daily standard deviation of GIM VTEC versus measured Jason3-VTEC (in TECU), from April 11 to May 04 in 2021, including the updated IGS RT-GIM, the rapid IGS GIM and the rapid IGS GIM.

Real-time ionospheric irregularity monitoring

The ionospheric irregularities have a strong impact on many applications of GNSS and other space-based radio systems. The rate of ionospheric total electron content (TEC) change index (ROTI, TECU/min), defined as the standard deviation of rate of TEC change (ROT) within a short time (e.g. 5 minutes), has been used to describe the ionospheric irregularities and associated scintillations. Since 2017, the ionospheric ROTI map covering the northern hemisphere has been routinely generated at UWM, Poland in post-processing mode, which is a helpful scientific data set for the climatology characteristics analysis of ionospheric irregularities (Kotulak et al. 2020). The availability of RT GNSS data streams from regional and global networks of GNSS stations also support the ionospheric irregularity monitoring in real-time. The global RT ROTI map has been generated at UPC-IonSAT and CAS using real-time GPS data from the IGS Network. At NRCan, ionospheric irregularities as sensed by 1Hz GPS and GLONASS phase rate measurements continued to be monitored in near-real-time and have been used to study geomagnetic storms (Ghoddousi-Fard et al. 2020, Prikryl et al. 2019, 2020). Additionally, an ionospheric climate index based on GNSS was proposed by BUAA colleagues (Wang et al. 2020). We will continue the work with the IGS ionospheric WG on developing ionospheric TEC gradient indicators as well as the associated real-time monitoring products, which are of the great interest of the GNSS community.

Generation and dissemination of real-time ionospheric accuracy information

The possibility of generating and broadcasting the accuracy information of RT-GIM has been discussed within the WG. Such information is of importance in designing the stochastic model of the PPP algorithm in the case RT global ionospheric corrections were used as constraints. In the current RTCM-SSR or IGS-SSR messages, only one quality flag is defined along with the spherical harmonic expansion. At CAS, it has been tried to fit the RT ionospheric residuals to express VTEC error estimates using spherical harmonics and, broadcasting those spherical harmonic coefficients by adding one additional message type temporally (message body similar to VTEC). An example of CAS RT-GIM and associated quality indicator is presented in the left plot of Fig. 4. A method based on the high-quality dual-frequency GNSS phase measurements is developed to indirectly analyse the reliability of RMS maps of post-processed GIMs (Zhao et al. 2021). The method is then extended to check the reliability of global ionospheric QIs provided in CAS RT-GIM (see right plot of Fig. 4). The discussion on the generation and dissemination of RT ionospheric QI message will be continued with close collaboration with IGS-RT WG.

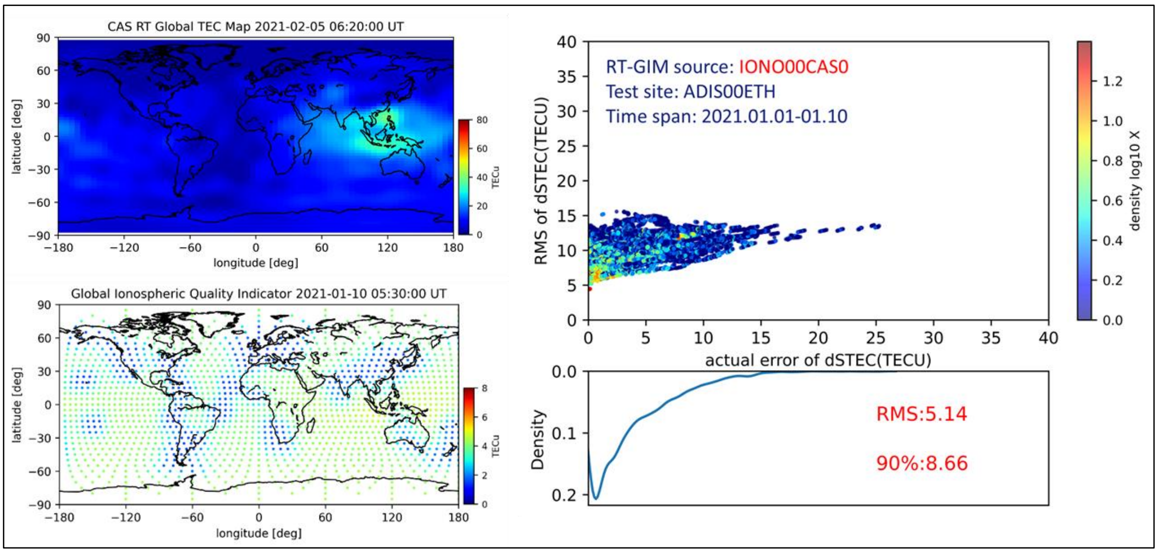


Figure 4: An example of CAS RT-GIM as its quality indicator (QI) map (left plot) and assessment of RT-GIM QI at one equatorial site ADIS00ETH.

Publications

Erdogan E, Schmidt M, Goss A, Görres B, Seitz F (2020). Adaptive Modeling of the Global Ionosphere Vertical Total Electron Content. Remote Sensing, 12(11), 1822. doi: 10.3390/rs12111822

Ghoddousi-Fard R, Prikryl P, Weygand J (2020). Considerations on mapping the GNSS ionospheric phase irregularities over Canada using kriging. AGU Fall meeting 2020, December, Virtual

Goss A, Schmidt M, Erdogan E, Görres B, Seitz F (2019). High-resolution vertical total electron content maps based on multi-scale B-spline representations. Annales Geophysicae, 37(4), 699–717. doi: 10.5194/angeo-37-699-2019

Goss A, Schmidt M, Erdogan E, Seitz F (2020a). Global and Regional High-Resolution VTEC Modelling Using a Two-Step B-Spline Approach. Remote Sensing, 12(7), 1198. doi: 10.3390/rs12071198

Goss A, Hernández-Pajares M, Schmidt M, Roma-Dollase D, Erdogan E, Seitz F (2020b). High-Resolution Ionosphere Corrections for Single-Frequency Positioning. Remote Sensing 13 (1): 12. doi: 10.3390/rs13010012

Kotulak K, Zakharenkova I, Krankowski A, Cherniak I, Wang N, Fron A (2020) Climatology Characteristics of Ionospheric Irregularities Described with GNSS ROTI. Remote Sensing 12 (16): 2634. doi: 10.3390/rs12162634

Li Z, Wang N, Wang L, Liu A, Yuan H, Zhang K (2019). Regional ionospheric TEC modeling based on a two-layer spherical harmonic approximation for real-time single-frequency PPP. J Geod 93 (9): 1659–1671. doi: 10.1007/s00190-019-01275-5

Li Z, Wang N, Hernández-Pajares M, Yuan Y, Krankowski A, Liu A, Zha J, García-Rigo A, Roma-Dollase D, Yang H, Laurichesse D, Blot A (2020). IGS real-time service for global ionospheric total electron content modeling. J Geod 94 (3). doi: 10.1007/s00190-020-01360-0

Liu Q, Hernández-Pajares M, Lyu H, Goss A (2021a) Influence of temporal resolution on the performance of global ionospheric maps. J Geod 95 (3). doi: 10.1007/s00190-021-01483-y

Liu Q, Hernández-Pajares M, Yang H, Monte-Moreno E, Roma-Dollase D, García-Rigo A, Li Z, Wang N, Laurichesse D, Blot A (2021b). The cooperative IGS RT-GIMs: a global and accurate estimation of the ionospheric electron content distribution in real-time. Earth System Science Data Discussions 1–24

Olivares-Pulido G, Terkildsen M, Arsov K, Teunissen PJG, Khodabandeh A, Janssen V (2019). A 4D tomographic ionospheric model to support PPP-RTK. J Geod 93 (9): 1673-1683. doi: 10.1007/s00190-019-01276-4

Orus-Perez R, Nava B, Parro J, Kashcheyev A (2020). ESA UGI (Unified-GNSS-Ionosphere): An open-source software to compute precise ionosphere estimates. Adv Space Res. doi: 10.1016/j.asr.2020.09.011

Prikryl P, Weygand J, Ghoddousi-Fard R, Jayachandran PT, Themens DR, McCaffrey AM (2019). GPS TEC and Phase Variations during Substorms and Auroral Breakups. AGU fall meeting, San Francisco, CA, USA, 9–13 December 2019

Prikryl P, Weygand JM, Ghoddousi-Fard R, Jayachandran PT, Themens D R, McCaffrey AM, Kunduri BS, Nikitina L (2020). Temporal and spatial variations of GPS TEC and phase during auroral substorms and breakups. Polar Science. doi: 10.1016/j.polar.2020.100602

Schmidt M, Dettmering D, Seitz F (2015). Using B-Spline Expansions for Ionosphere Modeling, in: Handbook of Geomathematics, edited by: Freeden, W., Nashed, M. Z., and Sonar, T., 939–983, doi:10.1007/978-3-642-54551-1_80, Springer Berlin Heidelberg, Berlin, Heidelberg, 2015.

Wang C, Li Y, Wu J, Fan L, Wang Z, Zhou C, Shi C (2021). An Ionospheric Climate Index Based on GNSS. Space Weather 19 (1). doi: 10.1029/2020sw002596

Yang H, Monte-Moreno E, Hernández-Pajares M, David RD. Real-Time Interpolation of Global Ionospheric Maps by means of Sparse Representation, Journal of Geodesy, to be published, 2021.

Zhao J, Hernández-Pajares M, Li Z, Wang N, Yuan H (2021). Integrity investigation of global ionospheric TEC maps for high-precision positioning. J Geod 95 (3). doi: 10.1007/s00190-021-01487-8

WG 4.3.2: Prediction of Ionospheric State and Dynamics

Chair: *Mainul Hoque (Germany)*
Vice Chair: *Eren Erdogan (Germany)*

Members

Mahdi Alizadeh (Iran), Enric Monte (Spain), Fabricio Prol (Germany), Liangliang Yuan (China), Adria Rovira Garcia (Spain), Murat Durmaz (Turkey), Ningbo Wang (China), Cheng Wang (China)

Activities and publications during the period 2019-2021

To realize WG 4.3.2 objectives and goals, group members accomplished individual activities as well as worked in cooperation with other group members. The progress during the period 2019-2021 is briefly described below.

Real-time Ionosphere Modelling, Nowcasting and Forecasting using B-splines

At DGFI-TUM, two approaches for VTEC forecasting/nowcasting have been studied: 1) sum of a linear model, a series expansion in terms of trigonometric basis functions and an ARIMA model, as well as 2) a machine learning technique trained with historical VTEC maps. The first approach was recently updated, and is operationally in use.

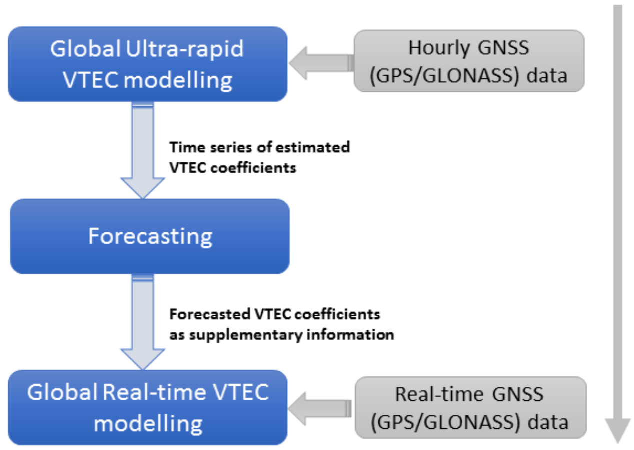


Figure 1: Processing chain for global real-time VTEC modelling in support of forecasted VTEC products

The first approach makes use of the VTEC maps represented by a series expansion in tensor products of polynomial B-splines in latitude and trigonometric B-splines in longitude (Schmidt et al. 2015). The VTEC products, feeding the forecast/nowcast model, are ultra-rapid products of the DGFI-TUM and generated with a delay of 2–3 hours (Goss et al. 2019, 2020, Erdogan et al. 2020). The unknown parameters of the forecast model are recomputed at the end of every hour using a time series in a moving window consisting of estimated ultra-rapid B-spline coefficients from the last 30 days. Later forecasted VTEC maps are computed for the next days. Besides, the approach was recently used to provide nowcasted supplementary information to global real-time ionosphere modelling. The concept is illustrated in Figure 1 and operationally runs in the context of the OPTIMAP project.

The second approach is based on Machine Learning (ML) tools. In a study applied at the DGFI-TUM, an artificial recurrent neural network (NN), based on a Long Short-Term Memory (LSTM) approach has been applied to a time series of historical VTEC (global mean value) data to forecast values for different future horizons (1h, 24h, 120h). Figure 2 provides the real global mean VTEC values (red) and the corresponding forecasted values, based on the NN for different horizons. The forecast of 1h hour provides with a RMS value of 0.32 TECU w.r.t the real data a high forecast accuracy. With increasing horizons, i.e., 24h and 120h the forecast accuracy decreases and provides RMS values of 0.86 TECU and 1.23 TECU, respectively.

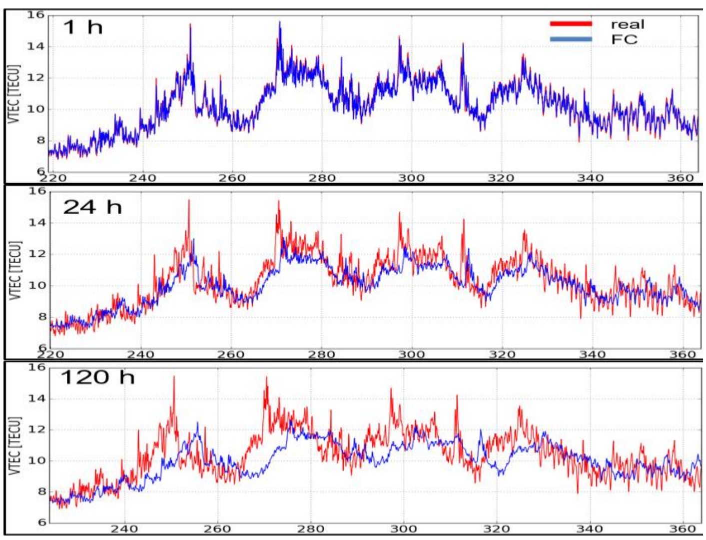


Figure 2: Mean VTEC Forecasting using machine learning tools; the real global mean VTEC values (red) and the corresponding forecasted values based on the method of neural network.

Ionospheric prediction algorithm for Galileo single frequency users

Hoque et al. (2019, 2020) proposed an alternative ionospheric correction approach for single frequency Galileo users. In the proposed approach the broadcasted coefficients are used to drive the Neustrelitz Total Electron Content (TEC) Model (NTCM) instead of the standard Galileo ionosphere model NeQuick-G. The NTCM-based correction approach uses 12 model coefficients, the solar radio flux index F10 and a few empirically fixed parameters. The required TEC values can be computed at any location and time without using any spatial or temporal interpolation of parameters. This makes NTCM very fast running in operational applications. The presented approach performs well when fed with the same Az parameter as NeQuick-G. The global performance analysis with reference Vertical Total Electron Content (VTEC) data from the International GNSS Service (IGS) shows that the performance of the NTCM was better than that of NeQuick-G. A comparison with reference Slant TEC (STEC) data shows that there is no significant difference between both models performance in terms of residual statistics such as Root Mean Square (RMS), mean and Standard Deviation (STD). An improved mapping function could even reduce corresponding errors when transforming NTCM derived VTEC to STEC values used for comparison. When comparing the computational time, it is found that the NTCM use is in average 65 times faster than the NeQuick-G operation.

The model residuals ($VTEC_{model} – VTEC_{igsg}$) are determined and corresponding mean, Standard Deviation (STD), and Root Mean Squares (RMS) are computed and enlisted in the Table 1 for the years 2014 and 2015. Additionally, we compared the model performance for the low latitude region 30° N – 30° S covering all longitude and the hours of 06:00-18:00 local time. Ionospheric effects are most dominant in the low latitude region during day time hours. The model residual statistics are given in Table 1.

Table 1: Statistics of model residuals with respect to the reference igsg data showing their performances for global day and nighttime and low latitude daytime analysis.

Residual error statistics in TECU	NeQuick-G		NTCM	
	2014	2015	2014	2015

global RMS	9.6	7.8	7.8	6.4
global mean	-3.3	-2.7	-1.5	-0.6
global STD	9.0	7.4	7.7	6.4
regional RMS	17.0	10.7	13.8	9.6
regional mean	-9.1	1.2	-6.8	0.8
regional STD	14.4	10.6	12	9.5

By comparing values in Table 1, we find that NTCM residual statistics are less than the corresponding NeQuick-G values for both global and regional (low latitude day time) cases during 2014 and 2015.

In the Figures 3 and 4 the RMS residuals over the globe are shown for different local time (LT) periods in 2014 and 2015. Figure 3 shows the error distribution when all local times (0-24 LT) are considered, whereas Figure 4 shows the error distribution for the daytime hours 12-15 LT. In each case the RMS residuals are determined separately at each grid location (2.5° and 5° latitude and longitude grid) considering a full year of data and shown in the global map.

Figure 3 shows that at the equatorial regions on both sides of the geomagnetic equator NeQuick-G shows larger RMS errors when compared to the NTCM model. By comparing NeQuick-G errors in Fig. 4 and Fig. 3, we see that RMS errors are much higher for the local noon case (12-15 LT) compared to the all local time case. On the contrary, the NTCM errors are slightly increased for the local noon case.

Global equivalent slab thickness model of the Earth's ionosphere

Jakowski and Hoque (2021) presented a prediction model for the equivalent slab thickness (Neustrelitz equivalent Slab Thickness Model – NSTM). The model approach is similar to a family of former model approaches successfully applied for Total Electron Content (TEC), peak electron density NmF2 and corresponding height hmF2 at DLR. The model description focuses on an overall view of the behaviour of the equivalent slab thickness as a function of local time, season, geographic/geomagnetic location and solar activity on a global scale. The equivalent slab thickness of the ionosphere that characterizes the width of vertical electron density profiles is an important parameter for a better understanding of ionospheric processes under regular as well as under perturbed conditions. The equivalent slab thickness is defined by the ratio of the vertical total electron content over the peak electron density and is therefore easy to compute by utilizing powerful data sources nowadays available thanks to ground and space based GNSS techniques. They used peak electron density data from three low earth orbiting (LEO) satellite missions, namely CHAMP, GRACE and FORMOSAT-3/COSMIC, as well as total electron content data obtained from numerous GNSS ground stations.

In conclusion, the model agrees quite well with the overall observation data within a RMS range of 70 km. There is generally a good correlation with solar heat input that varies with local time, season and level of solar activity. However, under non-equilibrium conditions, plasma transport processes dominate the behaviour of the equivalent slab thickness. It is assumed that night-time plasmasphere-ionosphere coupling causes enhanced equivalent slab thickness values like the pre-sunrise enhancement. The overall fit provides consistent results with the mid-latitude bulge (MLB) of the equivalent slab thickness, described for the first time in this paper. Furthermore, the model recreates quite well ionospheric anomalies such as the Night-time Winter Anomaly (NWA) which is closely related to the Mid-latitude Summer Nighttime Anomaly (MSNA) like the Weddell Sea Anomaly (WSA) and Okhotsk Sea Anomaly (OSA). Further model improvements can be achieved by using an extended model approach and considering the particular geomagnetic field structure.

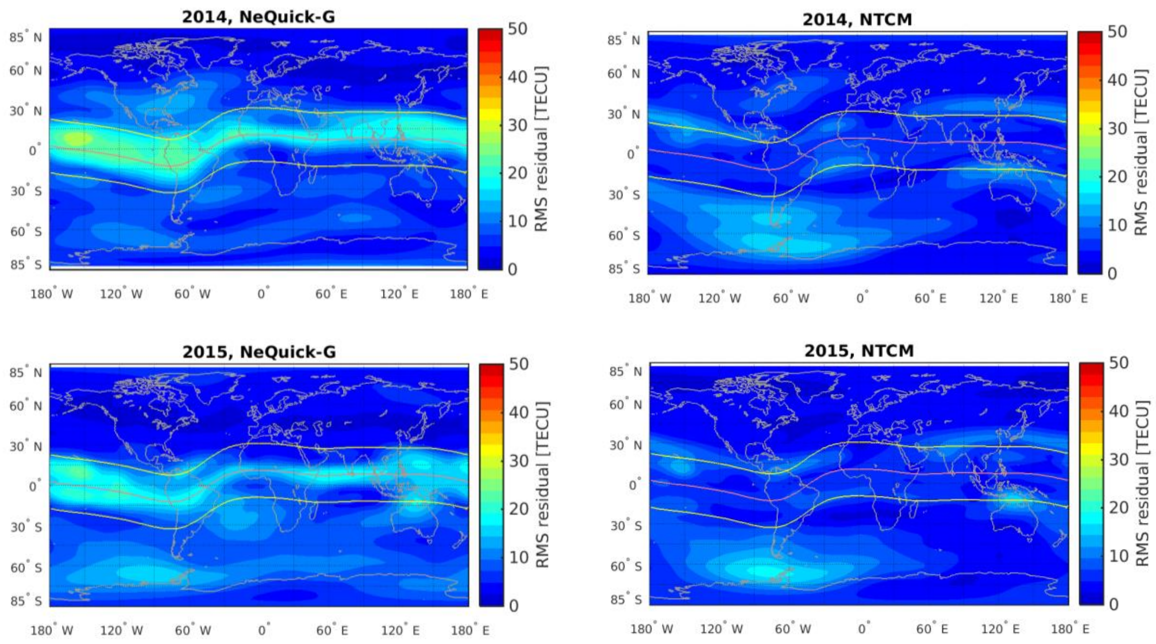


Figure 3: VTEC RMS residual error distribution in 2014 (top panel) and 2015 (bottom panel) for NeQuick-G (left panel) and NTCM (right panel) considering all local time.

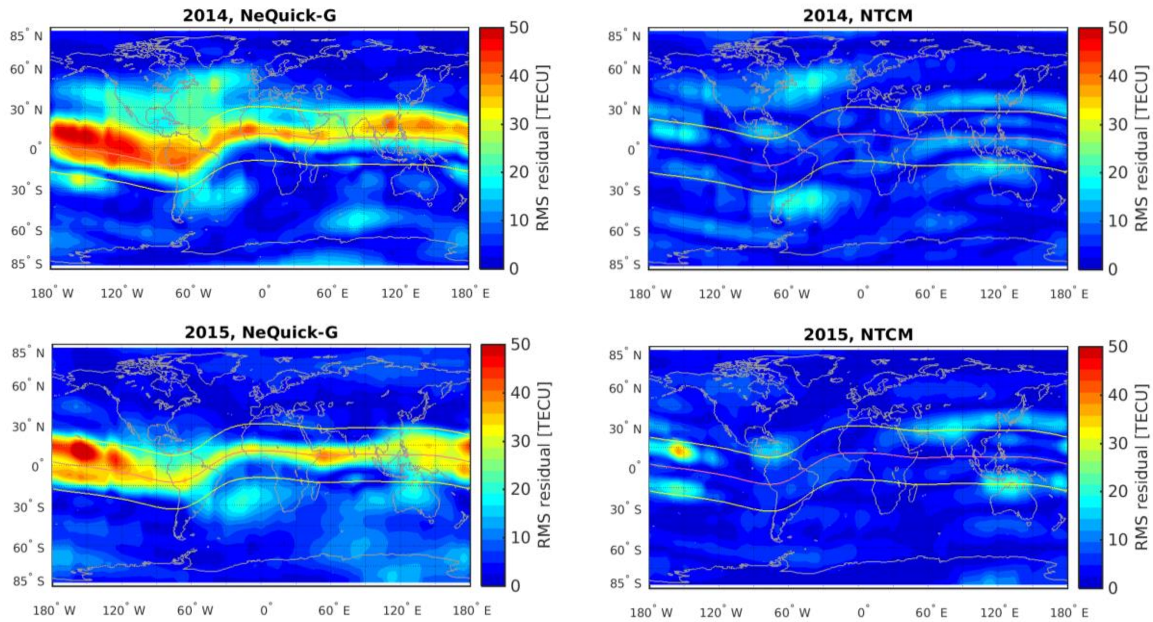


Figure 4: VTEC RMS residual error distribution in 2014 and 2015 for daytime hours 12-15 LT for NeQuick-G (left panel) and NTCM (right panel).

Use of CAS rapid GIM for global total electron content prediction

CAS rapid GIM is computed by spherical harmonic expansion using a global network of GNSS stations. A maximum posterior estimation-based method is proposed to predict the variation of global ionospheric total electron contents using CAS rapid ionospheric products. CAS 1-, 2- and 5-day predicted GIMs are routinely generated by predicting each spherical harmonic coefficient using the proposed algorithm. In case individual spherical harmonic coefficients are derived, the predicted GIM is then reconstructed by spherical harmonic expansions. The quality of CAS predicted GIMs as well as those from CODE, ESA and UPC-IonSAT was evaluated during 2008-2020. Results show that the performance of CAS predicted GIM is on the same level with CODE product, which is notably better than ESA and UPC predicted ones. While

CAS predicted GIMs have not yet been provided to the IGS, the products are downloadable from CAS repository itself (ftp://ftp.gipp.org.cn/product/ionex/). Note that predicted models are commonly computed by either extrapolation technique or physical model using historical ionospheric observation data, the pronounced performance degradation can be foreseen in the occurrence of ionospheric disturbances or perturbances.

Use of CAS predicted GIM for RT-GIM generation

To enable GNSS applications with low or no latency, the real-time service (RTS) of the IGS was launched in 2013. IGS RTS provides real-time data streams with typical latencies of up to few seconds, containing multi-frequency and multi-constellation GNSS measurements from a global network of high-quality GNSS receivers. The availability of RT-GNSS data streams is being explored to generate the experimental global ionospheric maps in real-time. Considering the discontinuous real-time data streams in some cases, CAS 2-day predicted GIM is introduced to provide priori ionospheric information to support the reconstruction of real time ionospheric maps. A predicting-plus-modeling approach is employed at CAS for the routine computation of its RT-GIM, which is provided in RTCM-SSR and IGS-SSR streams via CAS caster (cas-ip.gipporg.cn:2101) in real time, and IONEX files (ftp://ftp.gipp.org.cn/product/ionex/) for post-processing applications. Details on the generation and validation of RT-GIM are reported in Li et al. (2020). It is planned at CAS to shorten the time span of the prediction model from 2 days to few hours to support the generation of more reliable real-time global ionospheric models.

Ionospheric forecasting activity at Beihang University

Since the beginning of 2018, the daily prediction of GIMs has been implemented in routine operation at Beihang University (Wang et al. 2018, 2020). The 1-d ahead and 2-d ahead predicted GIMs are provided with temporal resolution of 1 hour. The predicted GIMs products are available at http://pub.ionosphere.cn/prediction/daily/. Also, the TEC maps of the latest predictions can be found on the web page: http://ionosphere.cn/page/daily_gim_prediction. The performance of the predictions (B1PG, 1-d ahead) is investigated by comparison with our final GIMs (BUAG) from Jan. 22 in 2018 to Apr. 22 in 2021. The following Figure 5 shows the daily bias and RMS of the differences between the B1PG and BUAG.

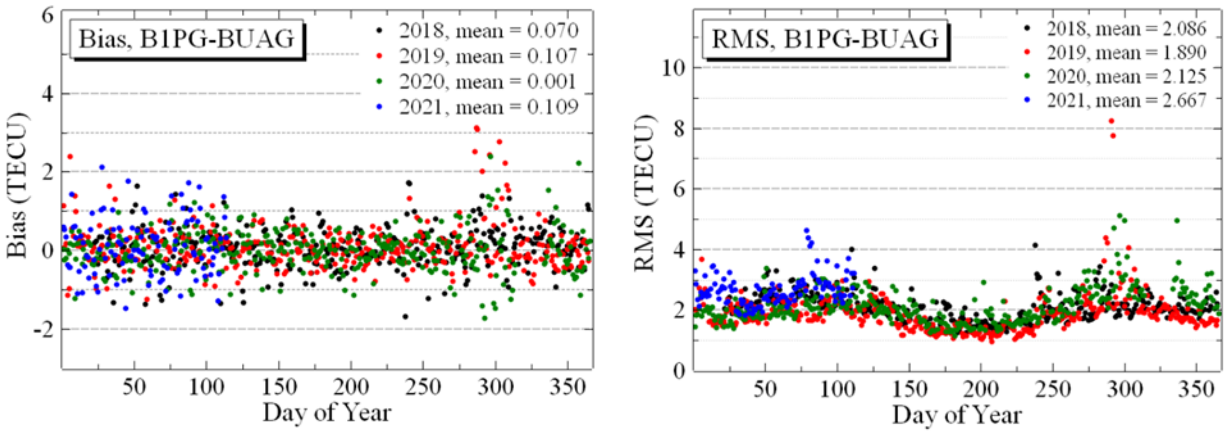


Figure 5: daily bias and RMS of the differences between the 1-d ahead predicted B1PG and final BUAG from Jan. 22 in 2018 to Apr. 22 in 2021.

Wang et al. (2021) performed the prediction of ionospheric climate index (ICI) indicating the general state of the ionosphere. And the ICI predictions are calculated from the predicted GIMs (B1PG and B2PG). The comparison between the final ICI and predictions is depicted as the following figure. The data source of ICI and predictions is public access at http://pub.ionosphere.cn/space_weather/

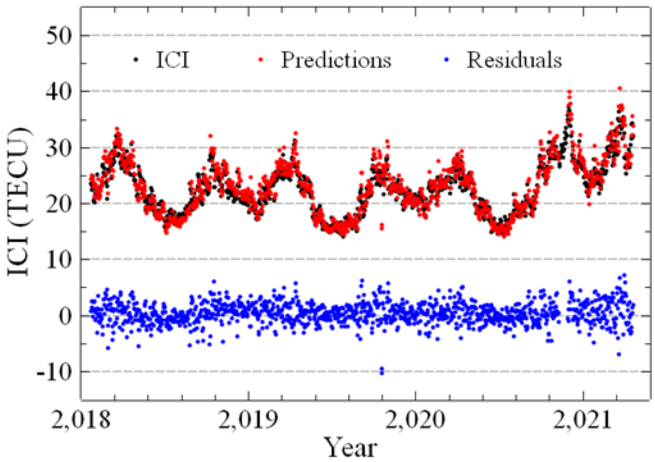


Figure 6: The final ICI, predictions and residuals from Jan. 22 in 2018 to Apr. 22 in 2021.

Ionospheric Scintillation Prediction on S4 and ROTI Parameters using Artificial Neutral Network and Genetic Algorithm

Atabati et al. (2021) studied ionospheric scintillation prediction on S4 and ROTI Parameters using Artificial Neutral Network and Genetic Algorithm. Irregularities in electron density usually correlate with ionospheric plasma perturbations. These variations making radio signals fluctuations, in response, generate ionospheric scintillations that frequently occur in the low latitude regions. In this research, the combination of Artificial Neural Network (ANN) with Genetic Algorithm (GA) is implemented to predict the ionospheric scintillations. The GA method is considered for obtaining the ANN model's initial weights. This procedure is applied to GNSS observations at GUAM (13.58°E, 144.86°N, 201.922H) station to the daily prediction of Ionospheric amplitude scintillations via predicting the signal to noise ratio (S4) or via prediction of Rate of TEC Index (ROTI). 30-day modelling was carried out for three months of January, March, and July, representing different seasons of the winter solstice, equinox, and summer solstices during three different years of 2015, 2017, and 2020 with different solar activities. The models, along with ionospheric physical data, were used for the daily prediction of ionospheric scintillations for the consequent day after the modelling. The prediction results are evaluated using S4 derived from GNSS observations at the GUAM station. The designed model has the ability to predict daily ionospheric scintillations with an accuracy of about 81% for S4 and about 80% for ROTI (Atabati et al. 2021).

Aragon-Angel et al. (2021) conducted an optimization study of NeQuick-G which is used as Galileo ionospheric correction algorithm. Aragon-Angel et al. (2019) integrated Galileo Ionospheric Correction Algorithm into the Open-Source GNSS Laboratory Tool Suite (gLAB). They released NeQuick-G into the open source gLAB software tool. Rovira-Garcia et al. (2020) assessed the quality of ionospheric (prediction) models through GNSS positioning error. Timoté et al. (2020) studied the impact of medium-scale traveling ionospheric disturbances on network real-time kinematic services.

Publications

Atabati Alireza, Mahdi Alizadeh, Harald Schuh and Lung-Chih Tsai (2021) Ionospheric Scintillation Prediction on S4 and ROTI Parameters using Artificial Neutral Network and Genetic Algorithm, Remote Sensing, (accepted)

Aragon-Angel A, Rovira-Garcia A, Arcediano-Garrido E, Ibáñez-Segura D (2021) “Galileo Ionospheric Correction Algorithm Integration into the Open-Source GNSS Laboratory Tool Suite (gLAB)”. Remote Sensing 13(2):191. DOI 10.3390/rs13020191

Aragon-Angel A, Zürn M, Rovira-Garcia A (2019) "Galileo Ionospheric Correction Algorithm: An Optimization Study of NeQuick-G". Radio Science 54:1156-1169. DOI 10.1029/2019RS006875

Erdogan, E., Schmidt, M., Goss, A., Görres, B., & Seitz, F. (2020). Adaptive Modeling of the Global Ionosphere Vertical Total Electron Content. Remote Sensing, 12(11), 1822. https://doi.org/10.3390/rs12111822

Goss, A., Schmidt, M., Erdogan, E., Görres, B., & Seitz, F. (2019). High-resolution vertical total electron content maps based on multi-scale B-spline representations. Annales Geophysicae, 37(4), 699–717. https://doi.org/10.5194/angeo-37-699-2019

Goss, A., Schmidt, M., Erdogan, E., & Seitz, F. (2020). Global and Regional High-Resolution VTEC Modelling Using a Two-Step B-Spline Approach. Remote Sensing, 12(7), 1198. https://doi.org/10.3390/rs12071198

Hoque, M. M., Jakowski, N., Orús Pérez, R., “Fast ionospheric correction using Galileo Az coefficients and the NTCM model,” *GPS Solutions*, doi: 10.1007/s10291-019-0833-3, 2019

Hoque MM, N. Jakowski, J A Cahuasquí (2020) Fast Ionospheric Correction Algorithm for Galileo Single Frequency Users, European Navigation Conference, 23-24 Nov, Dresden, DOI: 10.23919/ENC48637.2020.9317502

Jakowski, Norbert und Hoque, Mohammed Mainul (2021) Global equivalent slab thickness model of the Earth’s ionosphere. Journal of Space Weather and Space Climate, 11 (10), Seiten 1-18. EDP Sciences. doi: 10.1051/swsc/2020083. ISBN eISSN: 2115-7251. ISSN 2115-7251.

Li Z, Wang N, Hernández-Pajares M, Yuan Y, Krankowski A, Liu A, Zha J, García-Rigo A, Roma-Dollase D, Yang H, Laurichesse D, Blot A (2020) IGS real-time service for global ionospheric total electron content modeling. J Geod 94 (3). doi: 10.1007/s00190-020-01360-0

Rovira-Garcia A, Ibánez D, Orus Perez R, Juan JM, Sanz J, González-Casado G, (2020) "Assessing the quality of ionospheric models through GNSS positioning error: Methodology and Results". GPS Solutions, 24:4. DOI 10.1007/s10291-019-0918-z

Schmidt M, D Dettmering, and F Seitz, Using B-Spline Expansions for Ionosphere Modeling, in: Handbook of Geomathematics, edited by: Freeden, W., Nashed, M. Z., and Sonar, T., 939–983, doi:10.1007/978-3-642-54551-1_80, Springer Berlin Heidelberg, Berlin, Heidelberg, 2015.

Timoté CC, Juan JM, Sanz J, González-Casado G, Rovira-García A, Escudero M (2020) "Impact of medium-scale traveling ionospheric disturbances on network real-time kinematic services: CATNET study case". Journal of Space Weather Space Climate 10(29). DOI 10.1051/swsc/2020030

Wang, C., Xin, S., Liu, X. et al. Prediction of global ionospheric VTEC maps using an adaptive autoregressive model. Earth Planets Space 70, 18 (2018). https://doi.org/10.1186/s40623-017-0762-8

Wang, C., Xue, K., Wang, Z. et al. Global ionospheric maps forecasting based on an adaptive autoregressive modeling of grid point VTEC values. Astrophys Space Sci 365, 48 (2020). https://doi.org/10.1007/s10509-020-03760-2

Wang, C., Li, Y., Wu, J., Fan, L., Wang, Z., Zhou, C., & Shi, C. (2021). An ionospheric climate index based on GNSS. Space Weather, 19, e2020SW002596. https://doi.org/10.1029/2020SW002596

WG 4.3.3 Ionosphere scintillations

Chair: *Jens Berdermann Germany*)
Vice-Chair: *Lung-Chih Tsai (Taiwan*)

Members

Charles L. Rino (USA), Michael Schmidt (Germany), Rui Fernandes (Portugal), Chi-Kuang Chao (Taiwan), Alexei V. Dmitriev (Russia), Yoshihiro Kakinami (Japan), Suvorova Alla (Russia), Sudarsanam Tulasiram (India), Chinmaya Kumar Nayak (India), Shin-Yi Su (Taiwan),Felix Antreich (Brazil), Michael Felux (Swiss), Dmytro Vasylyev (Germany)

Activities and publications during the period 2019-2021

The activities of this WG are

1. understanding the climatology of ionospheric scintillations, namely, its variation with latitude, season, local time, magnetic activity and solar cycle,

- *Study the relationship between low latitude scintillation onset in respect to changes of the sunset terminator over Africa*
  A method for automatic detection of plasma depletions by using GNSS measurements have been developed and tested at several GNSS stations in the equatorial region [Mersha et al, 2020]. The method has been applied to study the relationship between low latitude scintillation onset in respect to changes of the sunset terminator over Africa [Mersha et al, 2021]. Due to its permanent change, the solar terminator is in line with the geomagnetic declination line twice a year, providing optimal conditions for the rapid changes in the electromagnetic coupling processes especially in the E-region ionosphere. In the vicinity of the solar terminator, essential parameter like S4 index measurements have been analyzed to monitor and analyze perturbations in the ionosphere. The results give an insight into the underlying physical processes and will improve the model and forecast capabilities.

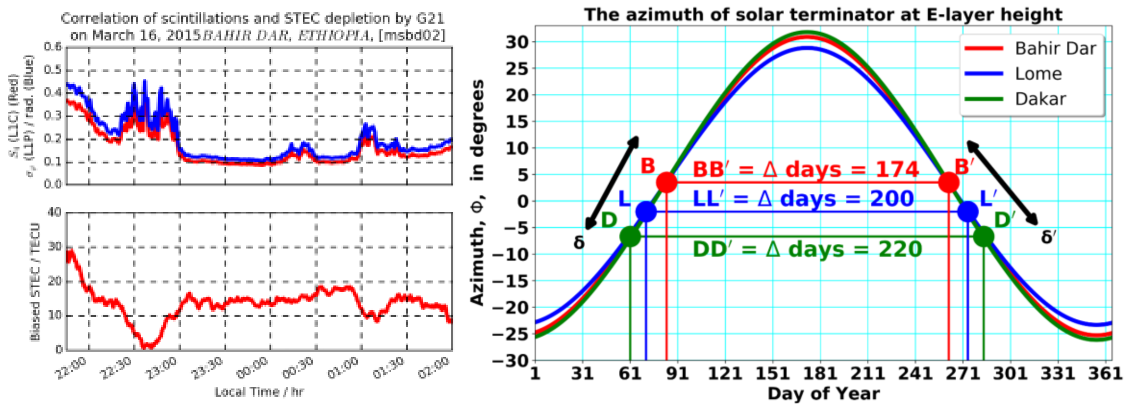


Figure 1 (left): scintillations indices (top panels) and STEC depletions (bottom panels) observed by GPS G21 and GLONASS R20 satellite at measurement station Bahir Dar 02 (msbd02)/Ethiopia, on 16 March 2015 [Mersha et al, 2020]; (right): seasonal variation of the azimuth of the day-night terminator at GNSS stations in Dakar, Lomé and Bahir Dar. The indicated dots are days of azimuth coincidence with geomagnetic declination (horizontal lines) at these three selected stations.

- *Storm-time scintillations associated with intense fluxes of energetic protons at low latitudes*

  Satellite experiments at low latitudes have shown that energetic (tens of keV) electrons and protons can penetrate from the Earth's radiation belt near the equator into the ionosphere. The effect of the fluxes of these particles on the upper atmosphere and ionosphere is investigated during a magnetic storm of July 22, 2009 [Golubkov et al., 2020]. Local variations in the concentration of ionospheric ions were investigated in the regions of injection of energetic electrons and protons with energies higher than 30 keV into the low-latitude ionosphere. Ion density and scintillations in the low-latitude ionospheric F-region were investigated using experimental data acquired from C/NOFS satellite [O. de la Beaujardiere et al., 2004]. The energetic particle fluxes were measured by NOAA/POES satellites at heights about 850 km [Evans and Greer, 2004]. It was shown a relationship between additional ionization by energetic electrons and an increase in the concentration in the F layer in the morning sector.

  The ionospheric inhomogeneities observed in the night sector in the form of strong concentration fluctuations are associated with the action of protons. The Figure 2 shows strong variations of the ion density observed by C/NOFS satellite in the nighttime low-latitude ionosphere in westward vicinity of the South Atlantic Anomaly (SAA) in the longitudinal sector around -120 deg. At the same time, NOAA/POES satellites observed in the same region intense fluxes of energetic protons with energies >30 keV. Those protons penetrated from the storm-time ring current to the ionospheric heights due to charge-exchange interactions. One can clearly see that the region of strong ion density fluctuations coincides in time and space with the region of intense energetic fluxes that might indicate their close relationship.

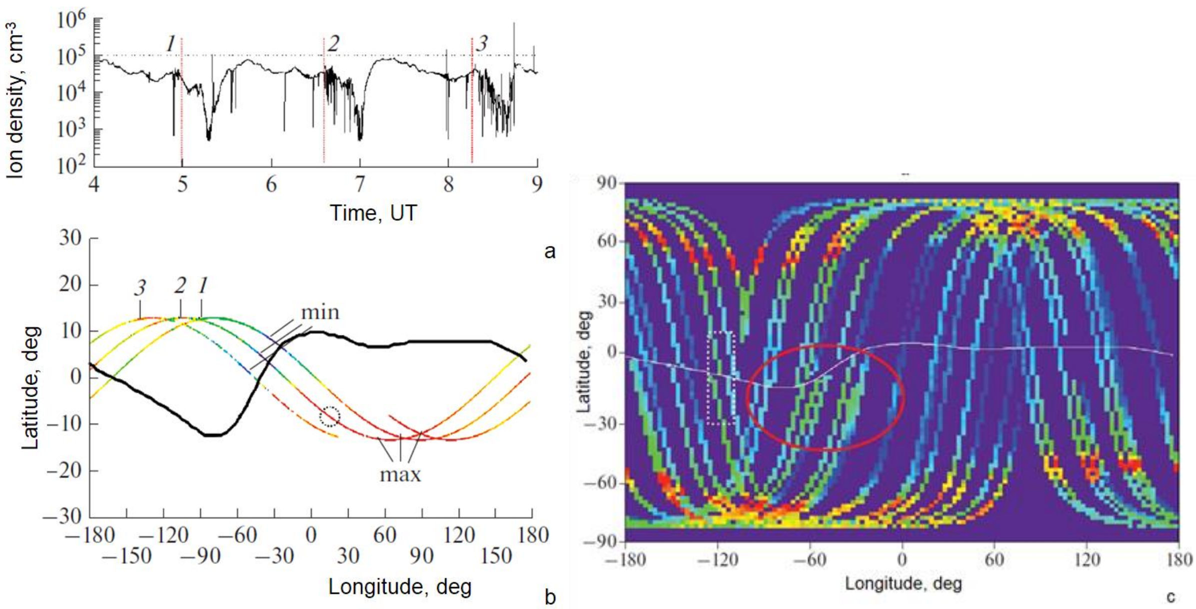


Figure 2: disturbances in the night-time low-latitude ionosphere during magnetic storm on July 22, 2009. Ionospheric ion density variations were measured by C/NOFS satellite: (a) time profile and (b) geographic map of three successive satellite orbits. Strong variations in

the ion density are indicated by numbers 1, 2 and 3 corresponding to the satellite orbits. Panel (c) shows geographic distributions of fluxes of energetic protons with energies > 30 keV observed by NOAA/POES satellites. The vicinity of South Atlantic Anomaly (SAA) with continuous proton precipitation at low latitudes is bounded by the red oval and the region of storm-time precipitation of protons is indicated by white dotted rectangle. It can be seen that both strong ion density fluctuations and intense energetic proton fluxes occur simultaneously at low latitudes in the longitudinal region around -120 deg.

- *Early development of shorter (3m) scale irregularities at the top of Equatorial Plasma Bubble*

  The Equatorial Plasma Bubbles (EPBs), once developed, grow nonlinearly into topside ionosphere and simultaneous secondary instabilities lead to the development of shorter scale irregularities. The altitudinal growth and generation of smaller scale irregularities determines the spatio-temporal occurrence and the intensity of ionospheric scintillations at wide spectrum of radio waves and have significant implications on the GNSS/Satellite Based Augmentation Systems. As the bubble grows into topside ionosphere, the significant reduction of ion-neutral collisions and increased ratio of F- to E-region field-line integrated conductivities give rise to more rapid development of intermediate-to-shorter scale irregularities at topside compared lower altitudes.

  The greater structuring of EPBs in the topside ionosphere is found to be one of the important factors explaining the much stronger L-band scintillations at low-latitudes compared to equatorial latitudes besides the higher background density and larger density gradients. Here, we present a unique EPB observation from Equatorial Atmosphere Radar (EAR) that provides hitherto undisclosed evidence for the smaller (3-meter) scale irregularities initially developing at higher altitudes and subsequently developing to lower altitudes which would have significant impact on the latitudinal development of L-band scintillations.

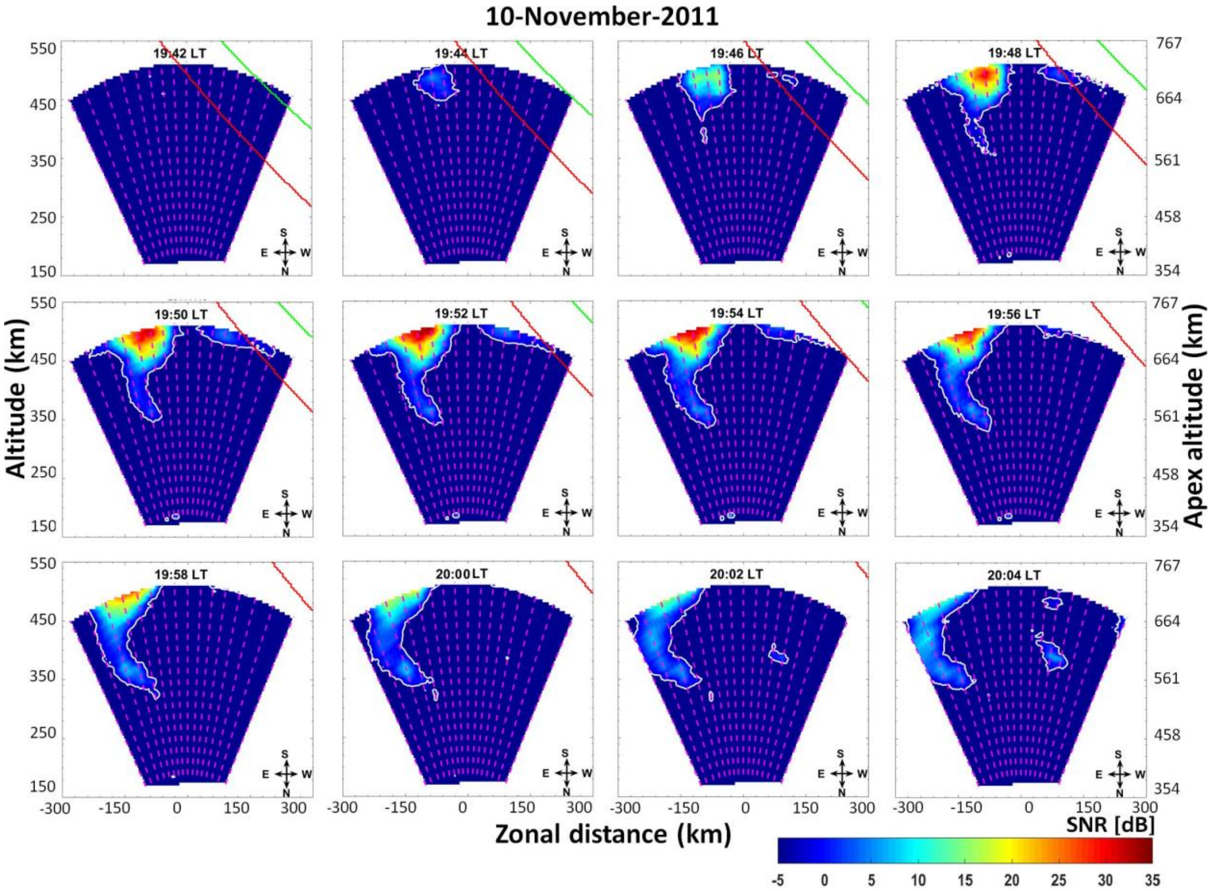


Figure 3: unique observational evidence for the early development of 3-m scale irregularities initially at the topside region of an Equatorial Plasma Bubble and subsequently at lower altitudes.

- *Periodic development of EPBs due to gravity waves originated from a Tropical Cyclone*

  The interesting cases of intense and periodic EPBs observed during 08 and 09 April 2013 by the 47 MHz Equatorial Atmosphere Radar at Kototabang, Indonesia have been thoroughly investigated in view of its possible connection with the tropical cyclone Victoria. The periodic EPBs are separated by about 200-250 km and were found to initiate before the sunset. The pre-sunset onset and development of these periodic EPBs were discussed in light of the gravity waves (GWs) excited in connection with the deep convection due to the tropical cyclone Victoria. The outgoing long-wave radiation measurement by very high-resolution radiometer (VHRR) onboard Indian meteorological satellite Kalpana-1 shows the occurrence of deep convective activity during these days. The presence of

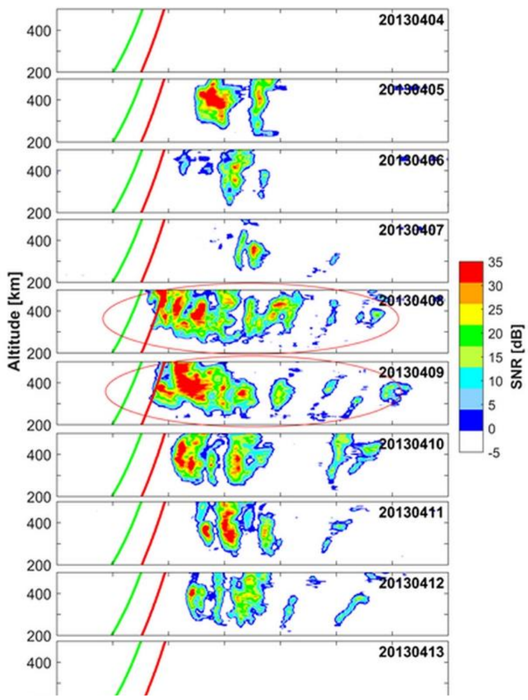


Figure 4: intense and periodic development of several equatorial plasma bubbles over Southeast Asian region in connection with the gravity waves originated from deep convective region associated with the tropical cyclone, Victoria

upward propagating gravity waves from the deep convective region associated with TC Victoria were confirmed using the GPS radio occultation observations. The GW signatures at ionospheric altitudes were also observed from the Ionosonde observations over magnetic equator and medium scale (~300 km) GWs were observed from the GPS-TEC data near to the magnetic equator and cyclone center. From the GW parameters observed from GPS-TEC and GPS-RO, we surmise that the secondary GWs generated by the dissipation of primary GWs associated with TC Victoria could have served as a seeding source on the generation of periodic EPBs during these two consecutive days.

2. investigation of the GNSS signal frequency and receiver impact on signal loss and phase cycle slips during scintillation events

- The impact of spatial and temporal ionospheric gradients as caused by small scale ionospheric irregularities or ionospheric storms is a threat for GNSS augmentation systems as well as for onboard GNSS receivers. Strong disturbances are able to produce severe scintillations or even can cause disruption of communication and data links, whereas strong ionospheric plasma gradients may lead to hazardous misleading information for the positioning domain, especially for differential GNSS applications [Berdermann et al, 2020].

  Scintillation occurrence and its impact on the tracking performance of GNSS receivers has ben analyzed, based on data from two high rate GNSS receiver stations at the northern crest region during the last solar maximum (2013-2015). The results show that scintillation occurrence time and statistics as well as the impact on GNSS signals are similar, which can be used for future development of improved nowcasts and forecasts for GNSS-related services. Furthermore, the impact on the different receiver types used is similar and a simple mathematical model has been derived able to estimate the Loss of Lock probability under disturbed ionospheric conditions at the equator. Such models might allow a better assessment of GNSS performance for aviation in the Equatorial region and can contribute to the definition of technical standards for GNSS aided inertial systems. In order to verify the robustness of different GNSS receiver under ionospheric scintillation conditions in detail the elaboration and validation of Bitgrabber data is needed. In the next step we plan to setup Bitgrabber-technique which enables us to investigate the effect of small scale ionospheric irregularities on different GNSS receivers.

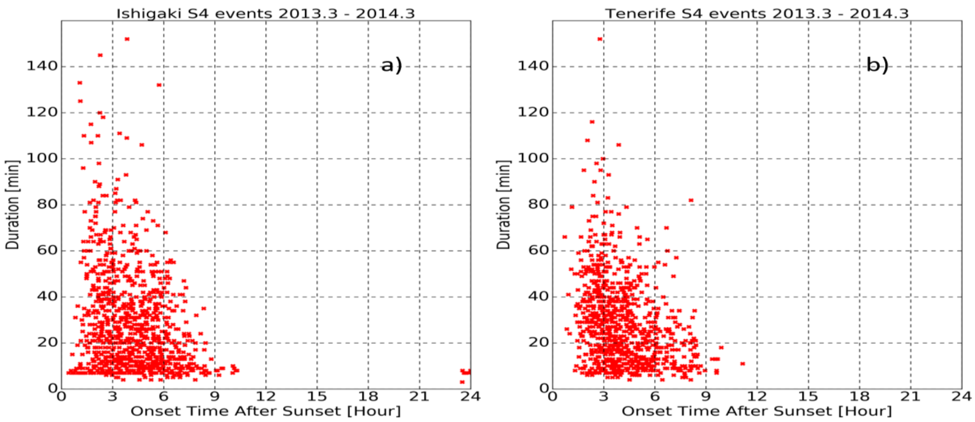


Figure 5: occurence and duration of amplitude scintillation events at Ishigaki (3a) and Tenerife (3b) from March 2013 till March 2014. Scintillation events are based on a S4 index > 0.2 using an 20° (Ishigaki) and 30° (Tenerife) elevation cut-off to remove multipath effects

[Berdermann et al, 2020]. Shown are the duration of the scintillation event versus local time after sunset (18:00 LT). In both regions' scintillation events start around 19:00 LT.

- In order to enhance robustness and monitoring capabilities of GNSS receiver with respect to ionospheric scintillation effects advanced mitigation and monitoring algorithms have to be developed. Also measures like S4 and the standard deviation of the phase tracking error are not sufficient to really characterize ionospheric effects and especially to study and evaluate GNSS receiver performance. It is desirable to separate the influence of the ionosphere on the amplitude and the phase of the received signal from other effects and from the dynamic of the satellite movement. Thus, it is possible provide estimates or observables of the scintillation phase and amplitude. An example for such advanced mitigation and monitoring algorithms was developed in [Fohlmeister et al., 2018] and was tested with bit-grabber data and GNSS receiver prompt-correlator data in [Fohlmeister et al. ,2018] and [Fohlmeister et al., 2019]. Hence, in the future receiver behavior can exactly be studied based on such observations or estimations and also especially correlation among different frequencies can be studied in detail and without any correlation introduced by the monitoring receiver.

3. Global modelling and forecasting of scintillations considering temporal and regional (Polar and Equatorial region) differences.
    - The Global Ionospheric Scintillation Model (GISM) is used to model phenomena relevant for the GNSS applications and provides the amplitude and phase scintillation indices. Due to the 3-dimensional nature of the GISM model it is capable to describe a variety of communication geometries such as satellite-ground station or satellite-satellite communication link. Moreover, it is able calculate scintillation maps at specific altitudes (see also Figure below for an example of the GISM output). At present first steps for further development, extension and validation of GISM has been started. We work on the extension of the 2D geometry, and will include drift velocity and the irregularity shape of Equatorial plasma bubbles.

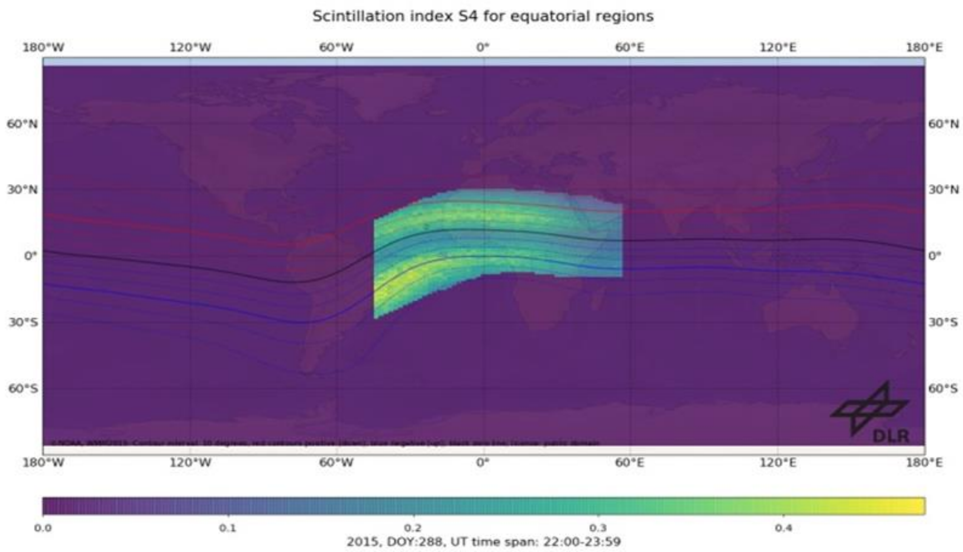


Figure 6: Excerpt of a scintillation map for the equatorial region obtained with the GISM model.

Publications (related to the activities)

Activity 1

Mogese Wassaie Mersha, Norbert Jakowski, Volker Wilken, Jens Berdermann, Martin Kriegel, Elias Lewi and Baylie Damtie, A method for automatic detection of plasma depletions by using GNSS measurements Radio Science, 55, e2019RS006978 (2020)

Chao Xiong, Lucilla Alfonsi, Jens Berdermann, Yaqi Jin, Jeffrey Klenzing vEGU (2021) Session ST3.3 Towards better understanding of the ionospheric plasma irregularities and scintillations

Mogese Wassaie Mersha *, Norbert Jakowski, Volker Wilken, Jens Berdermann, Martin Kriegel, Elias Lewi, On the relationship between low latitude scintillation onset and sunset terminator over A frica (2021) Atmosphere Remote Sensing (accepted)

Ankur Kepkar, Christina Arras, Jens Wickert, Harald Schuh, Mahdi Alizadeh, and Lung-Chih Tsai (2020), Occurrence climatology of equatorial plasma bubbles derived using FormoSat-3 COSMIC GPS radio occultation data, Ann. Geophys., 38, 611–623, https://doi.org/10.5194/angeo-38-611-2020.

Evans, D. S., and M. S. Greer (2004), Tech. Memo, Vol. 1.4 (NOAA Space Environm. Labor., Colorado, 2004).

Golubkov, G.V., A.V. Suvorova, A.V. Dmitriev, and M.G. Golubkov (2020), Effect of High-Intensity Electron and Proton Fluxes on a Low-Latitude Ionosphere, ISSN 1990-7931, Russian Journal of Physical Chemistry B, 2020, Vol. 14, No. 5, pp. 873-882, DOI: 10.1134/S1990793120050206

O. de la Beaujardiere, L. Jeong, B. Basu, et al. (2004), J. Atmos. Sol.-Terr. Phys. 66, 1573.

Tulasi Ram, S., K. K. Ajith, T. Yokoyama, M. Yamamoto, K. Hozumi, K. Shiokawa, Y. Otsuka, and G. Li, Dilatory and downward development of 3-meter scale irregularities in the Funnel-like region of a rapidly rising Equatorial Plasma Bubble, Geophysical Research Letters, https://doi.org/10.1029/2020GL087256, 2020.

Ajith, K. K., Li, G., Tulasi Ram, S., Yamamoto, M., Hozumi, K., Abadi, P., & Xie, H., On the seeding of periodic equatorial plasma bubbles by gravity waves associated with tropical cyclone: A case study., J. Geophys. Res. Space Physics, 125, e2020JA028003, https://doi.org/10.1029/2020JA028003, 2020.

Activity 2

J. Berdermann, H. Sato, M. Kriegel, T. Fujiwara and T. Tsujii, "Effects Of Equatorial Ionospheric Scintillation For GNSS Based Positioning In Aviation," 2020 European Navigation Conference (ENC), Dresden, Germany, 2020, pp. 1-8, doi: 10.23919/ENC48637.2020.9317407.

F. Fohlmeister, F. Antreich, V. Wilken, M. Kriegel, J. C. M. Mota, A. L. F. de Almeida, F. G. M. Pinheiro, and J. A. Nossek, "Evaluation of Low Latitude Scintillation Data with a Dual Kalman Smoother," in Proceedings of ITM GNSS 2019, Raston, VA, U.S.A., January 2019.

F. Fohlmeister, F. Antreich, and J. A. Nossek, "Dual Kalman filtering based analysis of GNSS data from low latitudes," in 2018 52nd Asilomar Conference on Signals, Systems, and Computers, October 2018.

F. Fohlmeister, F. Antreich, and J. A. Nossek, "Dual kalman filtering based gnss phase tracking for scintillation mitigation," in 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS), April 2018.

Activity 3

D. Vasylyev, Y. Beniguel, V. Wilken, M. Kriegel, and J. Berdermann EGU21-9441 solicited talk

D. Vasylyev, Y. Bèniguel, V. Wilken, M. Kriegel, and J. Berdermann, Further development of the Global Ionospheric Scintillation Model (GISM) : Perspectives and prospective URSI GASS 2021

Other related Papers

Rahmani, Y., Mahdi Alizadeh, M., Schuh, H., Wickert, J., Tsai, L.-C. (2020), Probing vertical coupling effects of thunderstorms on lower ionosphere using GNSS data, Advances in Space Research, doi: https//doi.org/10.1016/j.asr.2020.07.018

Mohamad Mahdi Alizadeh, Harald Schuh, Saeed Zare, Sahar Sobhkhiz-Miandehi, Lung-Chih Tsai (2020), Remote sensing ionospheric variations due to total solar eclipse, using GNSS observations, Geodesy and Geodynamics, doi: https://doi.org/10.1016/j.geog.2019.09.001.

JWG 4.3.4 Validation of VTEC models for high-precision and high resolution applications

(Joint with IGS)

Chair: Anna Krypiak-Gregorczyk (Poland)
Vice-Chair: Attila Komjathy (USA)

Members

Andreas Goss (Germany), Bruno Nava (Italy), Dieter Bilitza (USA), Eren Erdogan (Germany), Gu Shengfeng (China), Heather Nicholson (Canada), Mainul Hoque (Germany), Reza Ghoddousi-Fard (Canada), Shuanggen Jin (China), Wojciech Jarmołowski (Poland), Yunbin Yuan (China), Manuel Hernández-Pajares (Spain), Haixia Lyu (Spain), Qi Liu (Spain), Raul Orus-Perez (The Netherlands), Tam Dao (Australia), Beata Milanowska (Poland)

Activities during the period 2019-2021

Group members realized the goals of JWG 4.3.4 in their individual activities as well as in cooperation with other group members.

VTEC validation with external data (JASON) and GNSS

Global ionosphere maps (GIM) computed from dual-frequency GNSS measurements have been widely used for monitoring ionosphere as well as providing ionospheric corrections in Space Geodesy since 1998. Due to the inhomogeneous global distribution of GNSS real-time stations and especially due to the large data gaps over oceanic areas, the global VTEC models are usually limited in their spatial and spectral resolution. Most of the GIMs are mathematically based on globally defined radial basis functions, i.e., spherical harmonics (SH), with a maximum degree of 15 and provided with a spatial resolution of 2.5∘×5∘ in latitude and longitude, respectively. Regional GNSS networks, however, offer dense clusters of observations, which can be used to generate regional VTEC solutions with a higher spectral resolution.

In Goss et al. (2020), a two-step model (TSM) comprising a global model as the first step and a regional model as the second step was introduced. The authors apply polynomial and trigonometric B-spline functions to represent the global VTEC. Polynomial B-splines are used for modelling the finer structures of VTEC within selected regions, i.e., the densification areas. The TSM provides both, a global and a regional VTEC map at the same time. In order to study the performance, the authors apply the developed approach to hourly data of the global IGS network as well as the EUREF network of the European region for St. Patrick storm in March 2015. For the assessment of the generated maps, it was used the dSTEC analysis and compare both maps with different global and regional products from the IGS Ionosphere Associated Analysis Centers, e.g., the global product from CODE (Berne, Switzerland) and from UPC (Barcelona, Spain), as well as the regional maps from ROB (Brussels, Belgium) **(**Figure 1**)**. The assessment shows a significant improvement of the regional VTEC representation in the form of the generated TSM maps. Among all other products used for comparison, the developed regional one is of the highest accuracy within the selected time span.

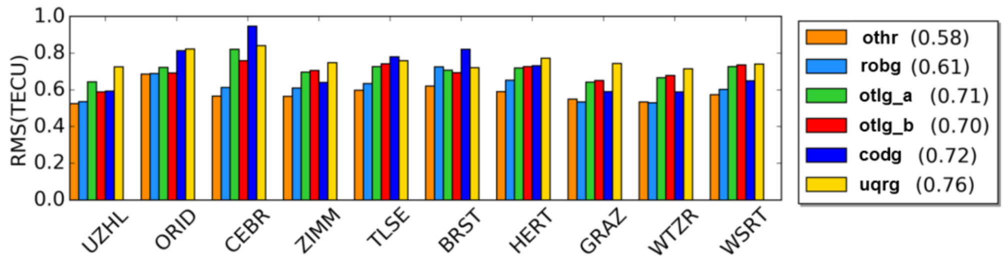


Figure 1: RMS values computed at the 10 stations for the products listed in the legend; the two global products 'otlg_a' and 'otlg_b' as well as the regional product 'othr', the external regional product 'robg' and the external global products 'codg' and 'uqrg' of the IAACs CODE and UPC are used for comparison. The values in the parantheses are the average RMS values over all 10 receiver stations for the entire test period between 8 March and 23 March 2015. *(Goss et al., 2020)*

UWM team analyzed the GIMs accuracy in relation to their temporal resolution and solar activity level. The accuracy evaluation was based on GIM-TEC comparisons to differential STEC derived from GNSS data and VTEC derived from altimetry measurements. The results show that temporal interval has no significant impact on the overall, annual map RMS during both high and low solar activity periods. However, during geomagnetic storms, when reducing map interval, the map accuracy improves by almost 25% (Milanowska et al. 2020). dSTEC analysis showed that during high solar activity period, when increasing GIM interval from 15 minutes to 60 and 120 minutes, STEC accuracy decreases by 3% and 21%, respectively. During low solar activity period 60-minute interval presents a good accuracy, and when increasing map interval to 120 minutes, the accuracy degrades by ~2% to 13%. Under disturbed conditions, GIMs with 60-min. interval are less accurate by ~3-5%, and 120-min. maps are less accurate by even~30% (comparing to 15-minute interval). In case of CASG GIM there is a little influence of map interval on STEC accuracy, this may suggest that intrinsic interval of the underlaying model is longer than 30 minutes (Figure 2).

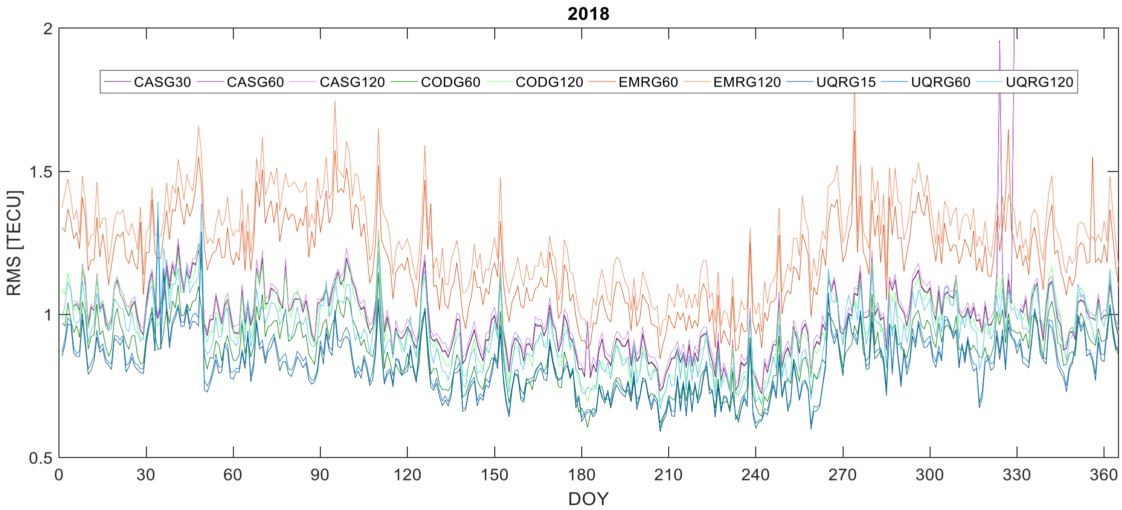


Figure 2: Daily RMS distribution for GIMs with different time resolution (year 2018) *(Milanowska et al., 2020)*

Liu et al. (2021) presented the influence of temporal resolution on the performance of global ionospheric maps (UQRG). The performance of the GIMs has been assessed by directly comparing with external vertical total electron content (VTEC) measurements from Jason altimeters over oceanic regions. In order to perform a complete assessment and analysis of involved GIMs, the influence of geographical position and solar and geomagnetic activities was also taken into account during more than one solar cycle. The assessment shows that discrepancy among GIMs with different time resolutions becomes more apparent at low latitudes and also at the high solar-geomagnetic activity. The results also suggest that the accuracy for GIMs with time resolution smaller or equal to 60 min is consistent during the period from 2002 to 2019 and is more accurate than other GIMs with lower temporal resolution **(**Figure 3**)**. Accordingly, high time resolution (including 15, 30, 45 and 60 min) is recommended for the application of GIMs with the highest accuracy.

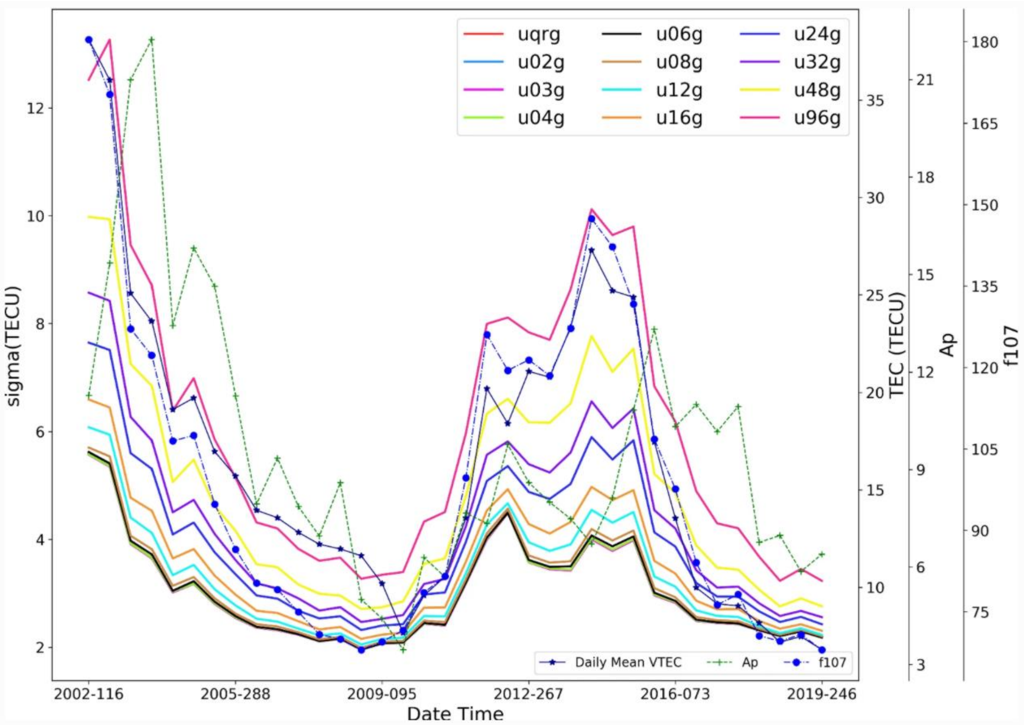


Figure 4: The evolution of standard deviation of the discrepancy of GIM VTEC versus measured altimeter VTEC, in TECUs, from day 26 of 2002 to day 335 of 2019, represented

simultaneously to Ap geomagnetic activity and F10.7 solar flux indices (green crosses and blue bullets, respectively) *(Liu et al., 2021)*

The scope of another study is on the evaluation the accuracy and consistency of the IAAC GIMs during high (2014) and low (2018) solar activity periods of the 24th solar cycle (Wielgosz et al. 2021). In this study, two different evaluation methods were applied. First, the authors carried out a comparison of the GIM-derived slant TEC (STEC) with carrier phase geometry-free combination of GNSS signals obtained from 25 globally distributed stations. Second, vertical TEC (VTEC) from GIMs was compared to altimetry-derived VTEC obtained from the Jason-2 and Jason-3 satellites and complemented for plasmaspheric TEC. The analyzed GIMs obtained STEC RMS values reaching from 1.98 to 3.00 TECU and from 0.96 to 1.29 TECU during 2014 and 2018, respectively. The comparison to altimetry data resulted in VTEC STD values that varied from 3.61 to 5.97 TECU and from 1.92 to 2.78 TECU during 2014 (Figure 5) and 2018, respectively. The results show that among the IAACs, the Center for Orbit Determination in Europe (CODE) global maps performed best in low and high solar activity periods. However, the highest accuracy was obtained by a non-IGS product - UQRG GIMs provided by the Universitat Politècnica de Catalunya (UPC) (Figure 6). It was also shown that the best results were obtained using a modified single layer model mapping function and that the map time interval has a relatively small influence on the resulting map accuracy.

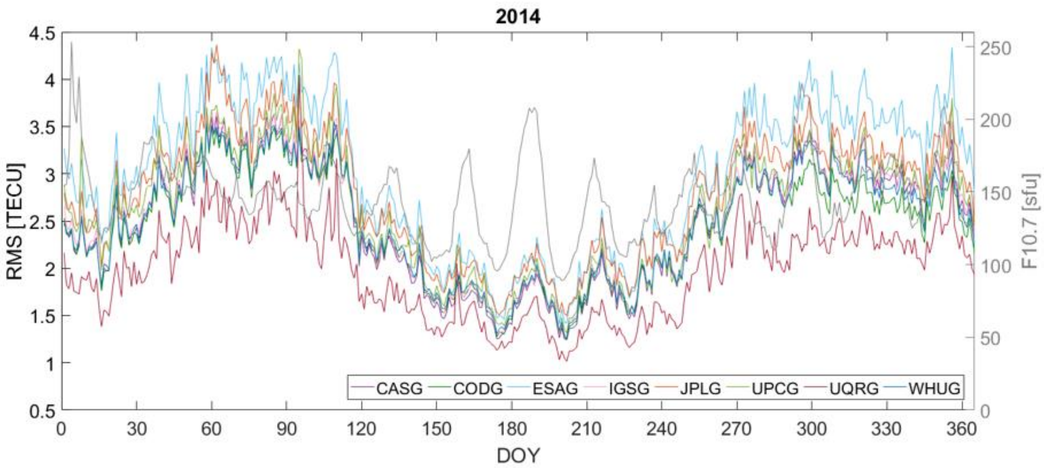


Figure 5: F10.7 index and daily GIM-derived STEC RMS distribution based on a comparison with ground GNSS observations from 25 stations in 2014 *(Wielgosz et al., 2021)*

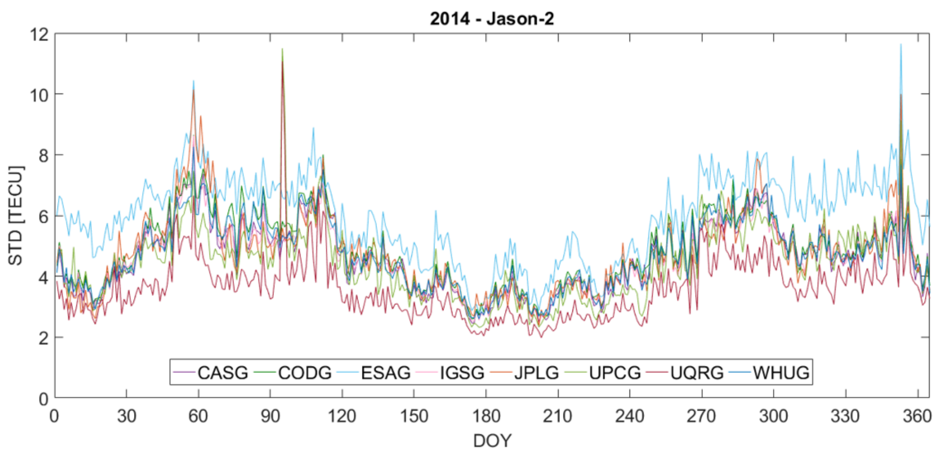


Figure 6: Daily GIM-derived VTEC STD distribution based on a comparison with the Jason-2 data in 2014 *(Wielgosz et al., 2021)*

VTEC validation in precise GNSS positioning

The ionosphere delay is the major issue in the undifferenced and uncombined observable model (Zhao et al. 2019). Though several ionosphere delay parameterization approaches have been promoted, the team from Wuhan argues that the functional model with only deterministic characteristic may not follow the irregular spatial and temporal variations. Thus, the deterministic plus stochastic ionosphere model (DESIGN) was developed, in which the deterministic part was expressed as a second-order polynomial and the stochastic part was estimated as random. Based on two-year data collected by about 150 stations, the second-order polynomial coefficients of the deterministic part was modeled with Fourier series, while, the constrains of the stochastic part was evaluated with variogram. From the statistic studies, it was concluded that the main frequency components are identical for different coefficients, different stations, as well as different ionosphere activity status, but with varying amplitude. Thus, in the Fourier series expression of the deterministic part, the frequency was fixed and the amplitude was estimated as daily constant unknowns.

Concerning the stochastic component, the variation of variogram was both, geomagnetic latitude and ionosphere activity status dependent. Thus, the Gaussian function was used and Epstein function to model the variation of geomagnetic latitude and ionosphere activity status, respectively. Based on the multi-GNSS zero-baseline observation, the ionospheric delay derived from PPP constrained with DESIGN was then compared to the result of the smoothed geometry-free observation model **(**Figure 7**)**. Moreover, the undifferenced ionospheric delay was also evaluated in the wide area PPP-RTK over Europe (Figure 8).

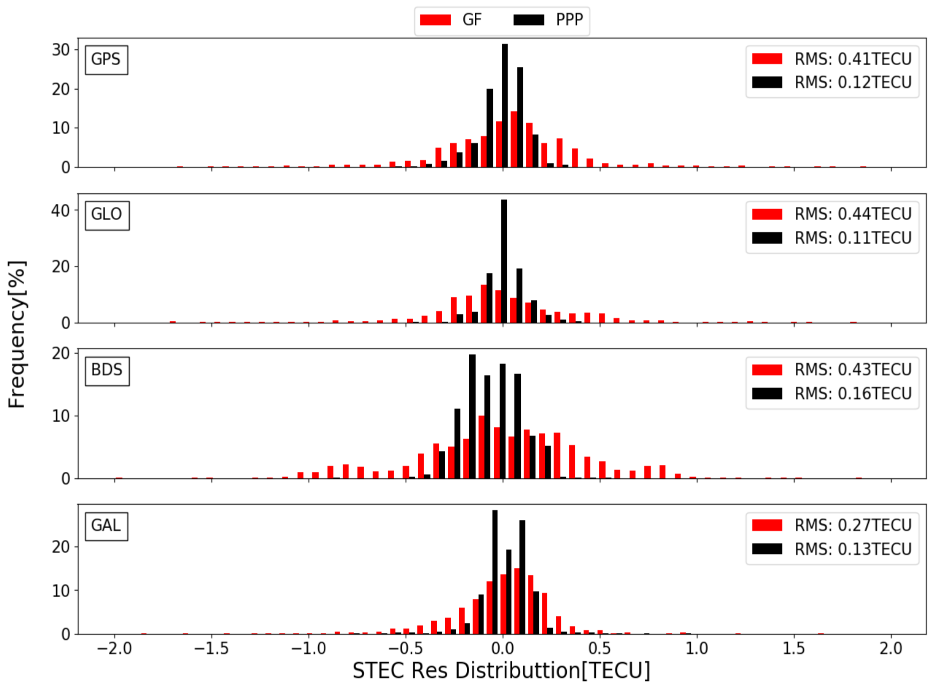


Figure 7: Comparison of the ionospheric delay estimation based on smoothed geometry-free observation model and the undifferenced and uncombined PPP model with zero-baseline

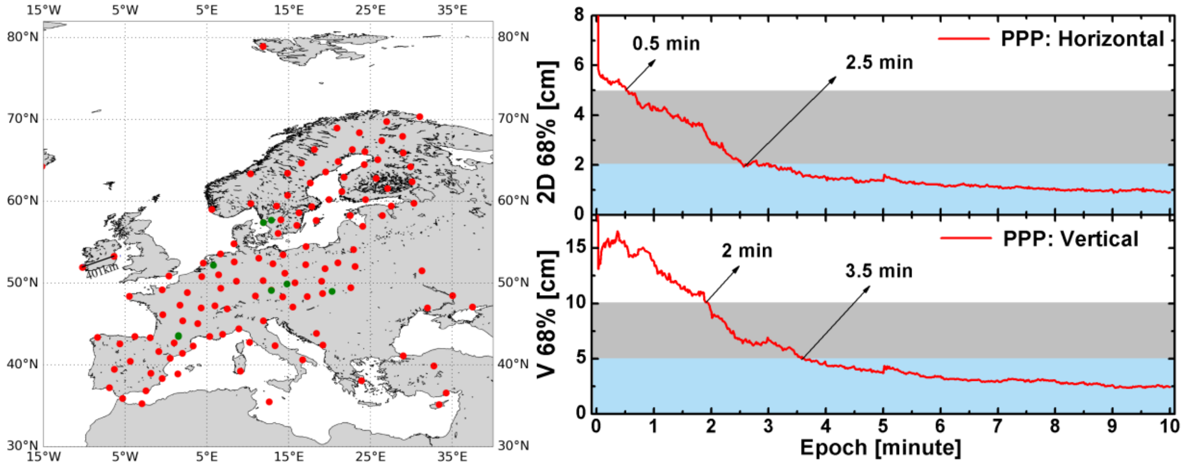


Figure 8: Application of undifferenced ionospheric delay modeling in wide area PPP-RTK over Europe

In another study, Goss et al. (2020) applied a single-frequency PPP using the RTKLIB software. They compared their high-resolution global B-spline ultra-rapid product (latency of approx 3 hours) with the final GIM `codg' (CODE) and the rapid GIM `uqrg' (UPC). What they see is an improvement in position when they use the high-resolution VTEC maps to correct for the ionospheric delay on the PPP.

Comparison of GNSS-derived VTEC maps and empirical models

Commonly used two-dimensional ionospheric models for GNSS positioning applications, including Total Electron Content (TEC) maps, require a mapping function (obliquity factor) which is used for conversion between vertical and slant TEC at ionospheric pierce points. In Ghoddousi-Fard (2020), NeQuick -a three-dimensional semi-empirical model, was used to simulate the level of uncertainties that one may expect from more simplified approaches. In order to evaluate the performance of mapping functions on GNSS vertical TEC estimation, coinciding pierce points from mixed stations and receivers from stations over North America are analyzed. A fit to the NeQuick derived mapping function values resulted in an empirical mapping function which performed slightly better than commonly used mapping functions during the studied periods and locations.

In another study, Hoque et al. (2020) compared NTCM-GlAzpar (Hoque et at. 2019) and NeQuick-G models with IGS global VTEC maps. The comparison shows that NTCM-GlAzpar performs better than NeQuick-G during 2014 and 2015. Comparison with Jason altimeter data shows similar results. Additionally, Hoque et al. (2020) validated the performance of the NTCM-GlAzpar model for GNSS single frequency positioning (SPP) applications taking test stations at high, middle and low latitude regions.

A new 3D electron density prediction model called Neustrelitz Electron Density Model (NEDM) is under development at DLR. Investigation shows promising results when compared with satellite in-situ and space- and ground-based TEC data (e.g., DMSP in-situ, COSMIC RO profile, Topex/Poseidon TEC, Swarm-A, B, C).

Publications

Ghoddousi-Fard R. (2020) An investigation on the GNSS ionospheric mapping-functions uncertainties using NeQuick model. Geomatics Canada, Open File 59, 11 pages, https://doi.org/10.4095/326084.

Gao C., Jin S.G., and L.L. Yuan (2020). Ionospheric responses to the June 2015 geomagnetic storm from ground and LEO GNSS observations. Remote Sensing, 12(14), 2200, doi: 10.3390/rs12142200

Goss A, Schmidt M, Erdogan E, Seitz F. (2020) Global and Regional High-Resolution VTEC Modelling Using a Two-Step B-Spline Approach. Remote Sensing, 12(7):1198. https://doi.org/10.3390/rs12071198

Goss A, Hernández-Pajares M, Schmidt M, Roma-Dollase D, Erdogan E, Seitz F. (2021) High-Resolution Ionosphere Corrections for Single-Frequency Positioning. Remote Sensing, 13(1):12. https://doi.org/10.3390/rs13010012

Hernández-Pajares M., Lyu H., Garcia-Fernandez M., & Orus-Perez R. (2020) A new way of improving global ionospheric maps by ionospheric tomography: consistent combination of multi-GNSS and multi-space geodetic dual-frequency measurements gathered from vessel-, LEO-and ground-based receivers. Journal of Geodesy, 94(8), 1-16

Hernández-Pajares M., Lyu H., Aragón-Àngel À., Monte-Moreno E., Liu J., An J., & Jiang H. (2020) Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology. Journal of Geophysical Research: Space Physics, 125(6), e2019JA027677

Hoque M.M., Jakowski N., Orús-Pérez R. (2019) Fast ionospheric correction using Galileo Az coefficients and the NTCM model. GPS Solutions, 23:41. https://doi.org/10.1007/s10291-019-0833-3

Hoque M.M., Jakowski N., Cahuasquí J.A. (2020) Fast Ionospheric Correction Algorithm for Galileo Single Frequency Users. European Navigation Conference, Dresden, https://ieeexplore.ieee.org/document/9317502

Milanowska B., Wielgosz P., Krypiak-Gregorczyk A., Jarmołowski W. (2020) Accuracy analysis of global ionospheric maps in relation to their temporal resolution and solar activity level. EGU General Assembly 2020, Virtual meeting 04-08 May 2020

Li, Z., Wang, N., Hernández-Pajares, M., Yuan, Y., Krankowski, A., Liu, A., ... & Laurichesse, D. (2020) IGS real-time service for global ionospheric total electron content modeling. Journal of Geodesy, 94(3), 1-16

Liu Q., Hernández-Pajares M., Lyu H., Goss A. (2021) Influence of temporal resolution on the performance of global ionospheric maps. Journal of Geodesy, 95, 34. https://doi.org/10.1007/s00190-021-01483-y

Wielgosz P., Milanowska B., Krypiak-Gregorczyk A., Jarmołowski W. (2021) Validation of GNSS-derived global ionosphere maps for different solar activity levels: case studies for years 2014 and 2018. GPS Solut 25, 103 (2021). https://doi.org/10.1007/s10291-021-01142-x

Zhao, Q., Wang, Y. T., Gu, S., Zheng, F., Shi, C., Ge, M., & Schuh, H. (2019). Refining ionospheric delay modeling for undifferenced and uncombined GNSS data processing. Journal of Geodesy, 93(4), 545–560. http://doi.org/10.1007/s00190-018-1180-9

WG 4.3.5 Real-time Troposphere Monitoring

Chair: *Cuixian Lu (China)*
Vice-Chair: *Galina Dick (Germany)*

Members

John Braun (USA), Junping Chen (China), Jan Douša (Czech Republic), Guergana Guerova (Bulgaria), Jonathan Jones (United Kingdom), Siebren de Haan (The Netherlands), Tomasz Hadaś (Poland), Xingxing Li (China), Thalia Nikolaidou (Canada), Benjamin Männel (Germany), Rosa Pacione (Italy), Eric Pottiaux (Belgium), Yoshinory Shoji (Japan), Andrea Stürze (Germany), Felix Norman Teferle (Luxembourg), Pavel Václavovic (Czech Republic), Henrik Vedel (Denmark), Karina Wilgan (Germany), Kefei Zhang (Australia), Florian Zus (Germany)

Activities during the period 2019-2021

To develop, optimize and assess new real-time or ultra-fast GNSS tropospheric products, and to exploit the full potential of multi-GNSS observations in weather forecasting has become one of the focuses in the field of GNSS meteorology (Dousa et al., 2015). Tropospheric zenith total delays, tropospheric linear horizontal gradients, slant delays, integrated water vapor (IWV) maps or other derived products in sub-hourly cycles are foreseen for future exploitation in numerical and non-numerical weather nowcasting or severe weather event monitoring (Lu et al., 2016; Guerova et al., 2016). The use of the Precise Point Positioning (PPP) processing strategy plays a key role in developing new products as it is an efficient and autonomous method, it is sensitive to absolute tropospheric path delays, it can effectively support real-time or ultra-fast production, it may optimally exploit data from all GNSS multi-constellations, it can easily produce a full variety of parameters such as zenith total delays, horizontal gradients or slant path delays and it may also support as reasonable as high temporal resolution of all the parameters. In particular, PPP is supported with global orbit and clock products provided by the real-time service of the International GNSS Service (IGS, Dow et al., 2009; Caissy et al., 2012).

The main objectives of the IAG WG 4.3.5 'Real-Time troposphere monitoring' are: (1) Develop real-time multi-GNSS processing algorithms and strategies for high-resolution, rapid-update NWP and nowcasting applications, (2) Develop new/enhanced GNSS tropospheric products and exploit the full potential of multi-GNSS (GPS, GLONASS, Galileo and BeiDou) observations for use in the forecasting of severe weather, (3) Evaluate the benefit of new/enhanced GNSS products (real-time, gradients, slants…) for numerical and non-numerical nowcasting, (4) Stimulate the development of application software for supporting routine production, (5) Demonstrate real-time/ultra-fast production, assess applied methods, software and precise orbit and clock products, and (6) Setup a link to the potential users, review product format and requirements.

Under the framework of the working group objectives, the main achievements during the period 2019-2021 focused on the establishment of GNSS real-time processing software (objective 1), the evaluation of new/enhanced GNSS tropospheric products for applying in numerical and non-numerical weather now-casting (objective 3), e.g., the atmospheric parameters retrieved from the Galileo and BDS-3 constellations, so as the assessment on the applied real-time methods, precise orbit and clock products offered by different ACs in terms of their effects on performance of the derived tropospheric products (objective 5).

Developing real-time/ultra-fast application software

Different software has been developed continuously by the working group members to produce real-time/ultra-fast tropospheric products with high accuracy, spatial-tempo resolution and reliability. Among these are the EPOS-RT Software (Li et al., 2014) developed by GFZ, the G-Nut/Tefnut software provided by Geodetic Observatory Pecny (GOP) (Douša and Václavovic et al., 2013), GNSS-WARP from Wroclaw University of Environmental and Life Science (WUELS, Hadaś, 2015), the real-time troposphere monitoring software of GREAT-Trop established by Wuhan University (Li et al., 2021) and the BKG Ntrip Client (Weber et al., 2016). Besides the provision of real-time ZTDs, gradients and STDs estimates can also be expected from this software. As examples, real-time STDs are able to be obtained from G-Nut/Tefnut of GOP (Dousa et al., 2016), and high-resolution tropospheric gradients as well as an ambiguity-fixed resolution for tropospheric parameters derivation are also offered by the GREAT-Trop software.

The Real-Time Demonstration campaign

Geodetic Observatory Pecný

The Geodetic Observatory Pecný of the Research Institute of Geodesy, Topography and Cartography has been developing the G-Nut/Tefnut software since 2013, and since 2018 continued in a collaboration with the G-Nut Software s.r.o. The latest G-Nut/Tefnut-RT is capable of estimating of all tropospheric parameters (ZTD, linear horizontal gradients and slant tropospheric delays) in real-time, near real-time, and post-processing mode using PPP method when supporting all the GNSS constellations. During 2015-2019, the GOP coordinated the Real-Time GNSS Troposphere Demonstration Campaign (Douša and Dick, 2017), it was a first contributor which has continued to the present time. In 2018, the real-time processing has been enhanced to a new all-in-one strategy enabling a simultaneous real-time and near real-time processing (Douša et al. 2018), the latter exploiting a backward smoother in addition to the Kalman Filter (Václavovic and Douša, 2016). In 2019, the un-combined and undifferenced processing strategy has been implemented and evaluated. In 2020, the real-time demonstration has been extended to about 200 stations, majority in Europe and some others in the world. The ZTD and horizontal tropospheric gradients are estimated in a 5-min sampling continuously with a RMS better than 10 mm and 0.5 mm, respectively. A quality of the real-time solution reached almost the quality of the traditional near real-time product. The monitoring web is available at https:/www.pecny.cz/RT-TROPO/ where the time-series of estimated parameters can be visualized and compared. In particular, a comparison of independent results from collocated stations provides a good indicator of the quality in real-time, see GOPE and GOP6 in Figure 1.

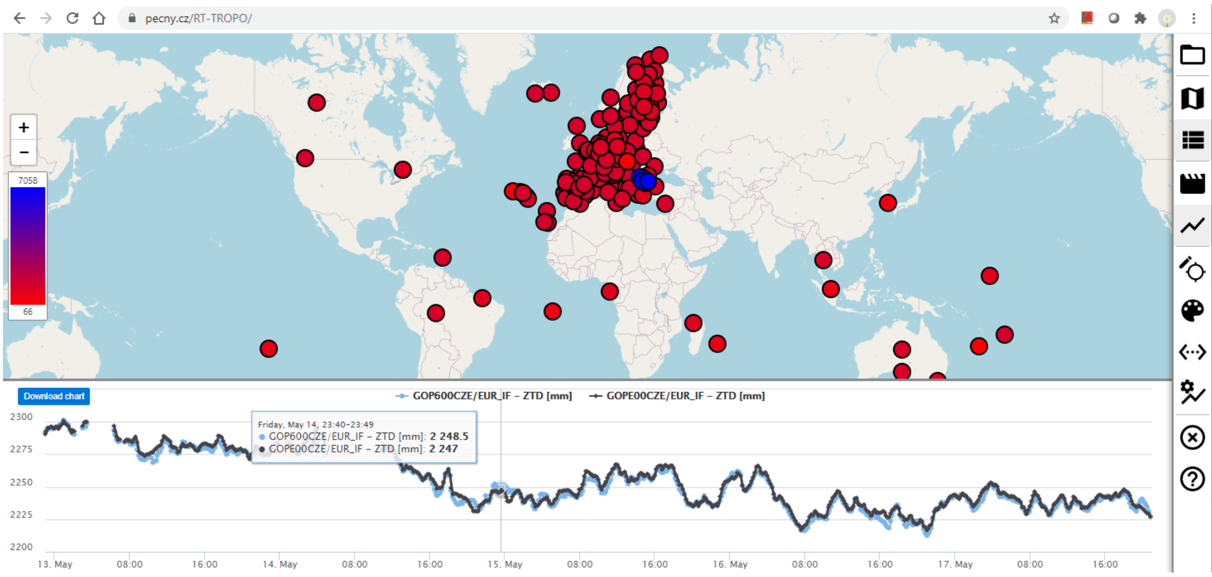


Figure 1: Web visualizing ZTD and gradients estimated in real-time at GOP. Example time-series of GOPE and GOP6 collocated stations, May 13-18, 2021.

A validation from the GOP real-time products against the EUREF combined tropospheric product is displayed in Figure 2. The RMS of ZTD is plotted on a monthly basis for 9 selected stations. Note offsets of +10 mm for each individual stations. The mean bias, standard deviation and RMS over all the stations and months is below 5 mm, 8 mm, and 10 mm, respectively.

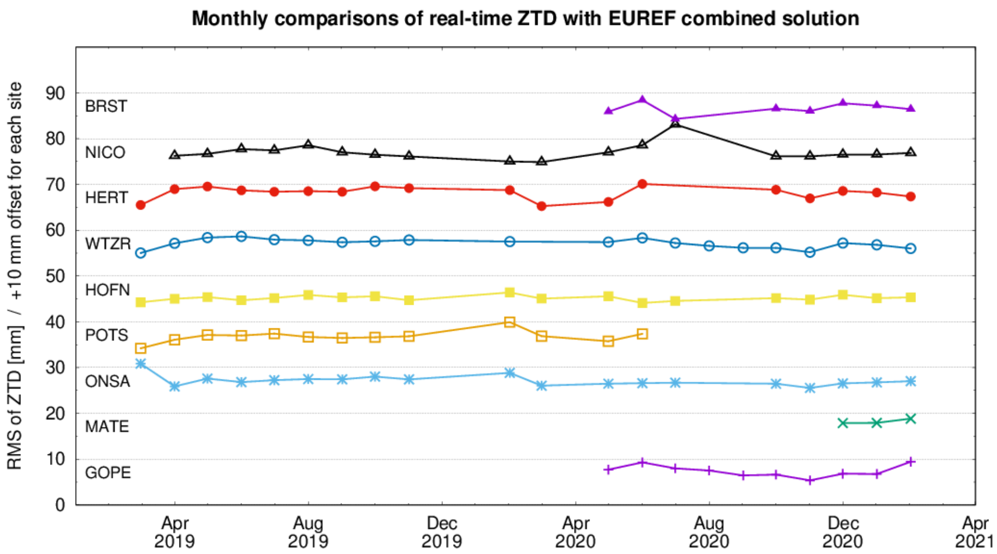


Figure 2: Monthly RMS of real-time ZTDs produced at GOP with respect to combined EUREF product.

UK Met Office

Sub-hourly GNSS data collection

The **B**KG (*Bundesamt für Kartographie und Geodäsie* – i.e. the German Federal Agency for Cartography and Geodesy) **N**trip (Networked Transport of RTCM via Internet Protocol) **C**lient (BNC, https://igs.bkg.bund.de/ntrip/bnc), is installed on the Met Office DMZ server GPSRT, for the collection of real-time (NTRIP) GNSS raw data streams, and for the subsequent writing of 15-minute RINEX files. The 15-minute RINEX are then pulled in through the Met Office firewall by the Met Office sub-hourly GNSS processing servers (see below).

BNC connects to specific ntrip broadcasters (i.e. casters) by way of ip address (or DNS name), username, password and port number. Once connected to the individual NTRIP caster, the individual GNSS sites (i.e. mountpoints) are selected for download.

Currently the Met Office has 5 separate instances of BNC running 24/7, collecting data from 5 NTRIP casters. Having separate instances of BNC running concurrently eliminates the risk of all data input failing if a problem arose with one caster's stream.

The BNC streams:

Bnc.os	Retrieving data from Ordnance Survey GB
Bnc.osi	Retrieving data from Ordnance Survey of Ireland
Bnc.osni	Retrieving data from Ordnance Survey of Northern Ireland
Bnc.eu	Retrieving data from EUREF
Bnc.igs	Retrieving data from the IGS

RINEX header information (e.g. antenna make/model etc) is critical to GNSS processing. When RINEX files are created using BNC, header information is not always available via the stream. As such, RINEX header information is added to the incoming streamed RINEX by way of skeleton (.skl) files. Skeleton files are (mostly automatically) collected from 3rd party data providers and uploaded to GPSRT. Once RINEX (with correct header) is created, it is then Hatanaka compressed, Unix compressed and moved to an archive, ready for download by the processing servers.

Met Office sub-hourly GNSS Data Processing

The Met Office currently operates five 24/7 GNSS processing services (each with a stack of Production, Test and Development servers, i.e. 15 servers in total), two services derive space weather products (i.e. TEC data), with the remaining three deriving tropospheric delays (i.e. ZTD and IWV). Of the GNSS tropospheric servers, one stack (METR) is dedicated to the processing of 15 minute RINEX data for delivery of ZTD and IWV products in real-time.

On the METR server, two 15 minute GNSS processing systems are running, METR (Bernese v5.0 solution) and MTRS (Metoffice Tropospheric Regional Subhourly) which is a Bernese v5.2 processing solution. 15 minute RINEX is downloaded from GPSRT every 15 minutes and Bernese estimates the ZTD at the start and end of the 15 minute file (e.g. for a 00-15min file, estimates of ZTD at 00:00 and 14:59). Data download and processing campaign setup takes 10 minutes and processing time of ~2 minutes, thus the most real-time ZTD/IWV estimate is around 12 minutes old by the time they are made available to customers. Bernese output files are converted to COST716 format (ASCII) which are uploaded to the E-GVAP server and also into binary BUFR format which are then ingested into the Met Office database (MetDB) and disseminated on the Global Telecommunication System (GTS) for use by other National Meteorological and Hydrological Services (NMHSs).

At the current time, data from the 15 minutes processing systems (METR and MTRS) is not operationally assimilated in any Met Office numerical weather prediction models as latency from other Met office GNSS processing systems is adequate. However, as NWP model assimilation progresses (e.g. to 4DVar) and with ever higher temporal and spatial resolution models, the 15 minute processed data will be operationally assimilated in the near future, with trials already underway.

Additionally, a separate script collects surface meteorological (SYNOP) data (temperature, pressure and dew point temperature) from the MetDB for conversion of ZTD to Integrated (Precipitable) Water Vapour. The IWV data is then plotted onto maps and animations for operational forecaster use in the Met Office operations centre. Additionally, the forecasters in the operations centre also use the IWV data with a nomogram to estimate maximum potential rainfall from a given air mass.

Real-time tropospheric products and validation

The rapid development of the European Galileo system and the Chinese BeiDou Navigation Satellite System (BDS) brings a great opportunity for the real-time retrieval of atmospheric parameters, including time-critical meteorological applications. Studies were carried out by employing Galileo observations to retrieve real-time water vapor based on the PPP technique, where the benefit of ambiguity resolution on water vapor sensing was also investigated (Lu et al., 2020). The ZTDs retrieved from Galileo are compared with post-processing GPS ZTDs, and Galileo PWV values are validated with ECMWF PWV products. Statistics reveal that the derived Galileo PWVs display good agreement with the ECMWF PWVs in general. The averaged RMS value of PWV from the Galileo float solution for all stations is 1.9 mm, and that of the fixed solution is 1.7 mm, revealing an improvement of 10.5%. In addition, the initialization time is shortened from 27.4 min to 20.8 min by applying the ambiguity fixed solution in comparison to the float solution.

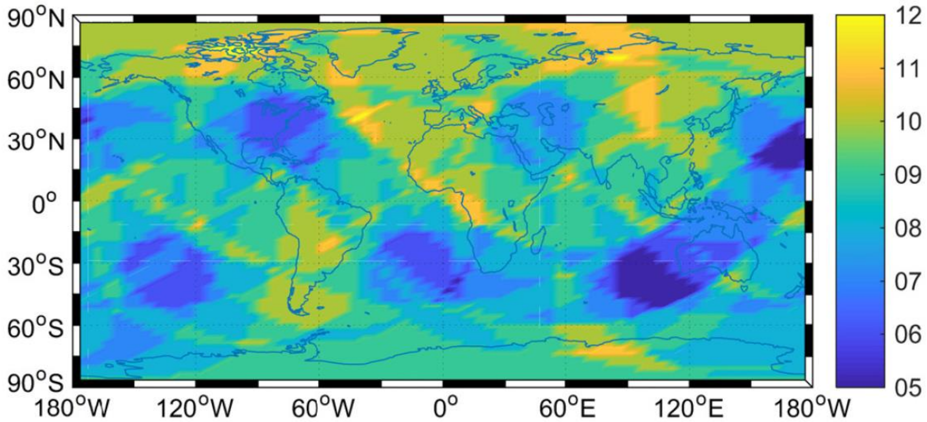


Figure 3: Averaged number of visible Galileo satellites with an elevation cutoff of 5 degrees on DOY 120, 2019.

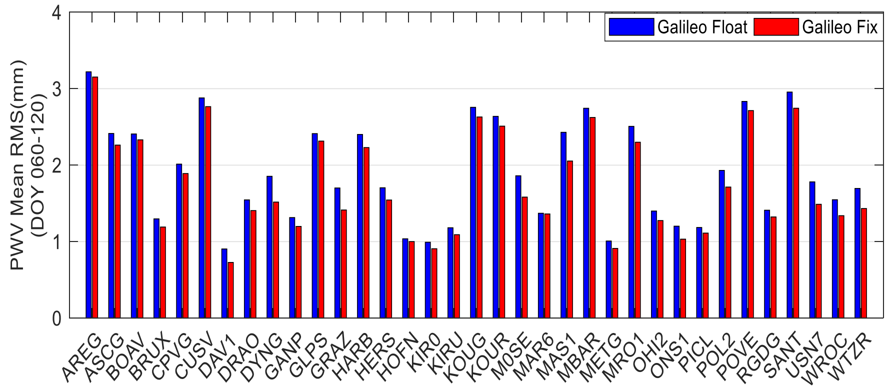


Figure 4: Averaged initialization time of the real-time Galileo ZTDs derived from float (blue) and fixed (red) solutions during DOY 060–120, 2019.

In another study, observations from 17 stations of the Hong Kong Continuously Operating Reference Stations and 15 stations of the Crustal Movement Observation Network of China (CMONOC) were used to retrieve BDS PWV based on the real-time precise point positioning ambiguity resolution approach (Li et al., 2018). The results show that the real-time BDS PWV series agree well with the GPS PWV series. RMS values for the Hong Kong Continuously Operating Reference Stations and CMONOC stations are 2.0-3.5 and 2.5-4.0 mm, respectively. In addition, short initialization time, strong reliability, and good distribution could be achieved by applying the fixed solution instead of the float solution.

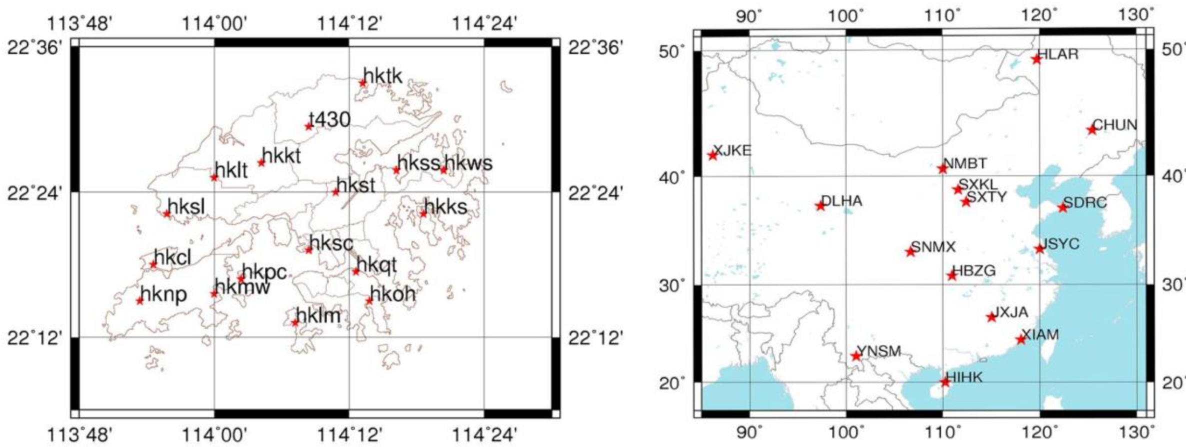


Figure 5: Distribution of selected stations in Hong Kong CORS (left) and CMONOC (right).

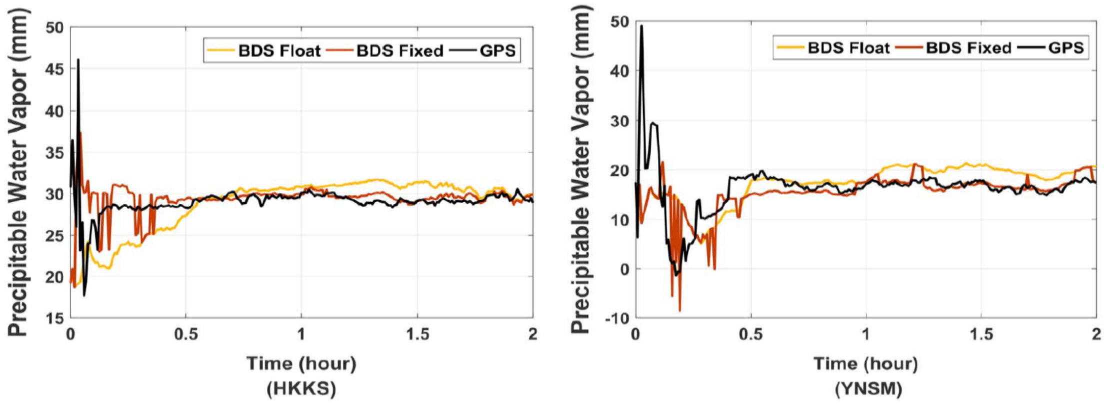


Figure 6: Real-time BDS PWV derived from float and fixed solutions at stations HKKS and YNSM

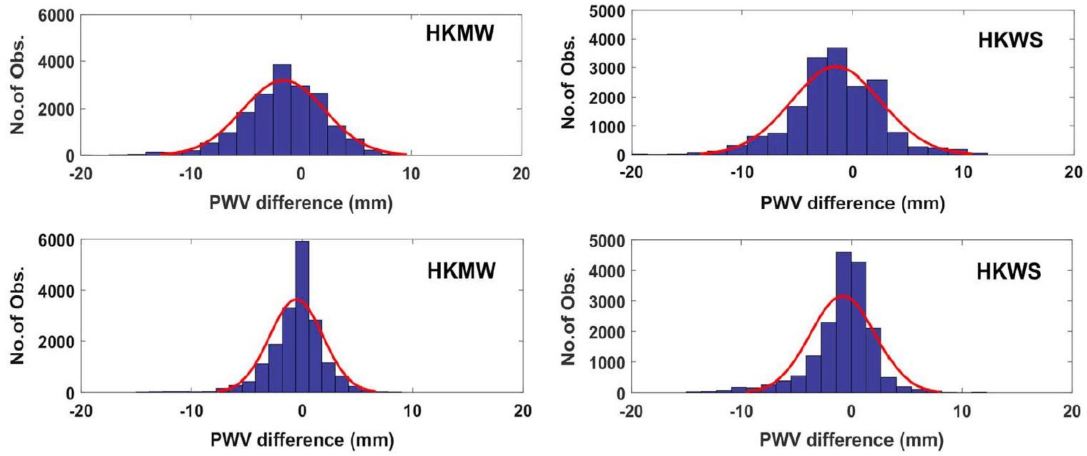


Figure 7: Distribution of PWV differences between real-time BDS solutions and post-processed GPS solutions at stations HKMW and HKWS.

GNSS ZTDs assimilation in the NWP models

In addition, the performance of assimilating GNSS ZTDs with different temporal resolutions on severe convective weather now-casting based on the weather research and forecasting (WRF) model was investigated. The GNSS ZTDs were processed with PPP method under the real-time mode based on the CORS network in Hubei Province, China and assimilated into a rapid update cycle (RUC) system. Figure 8 shows the comparison of four experiments with the observed precipitation in the inner domain at 03:00 UTC on 22 Aril 2018. In the control experiment (referred to CTR), the SYNOP and AIREP observations from NCEP Research Data Archive (RDA) were assimilated into the WRF model per every 3 hours, and the radiosonde observations were assimilated at 00:00 UTC. In the other three ZTD assimilation experiments, the additional GNSS ZTD data were assimilated into the WRF model with 12 h, 6 h and 3 h cycles, respectively, hereafter referred to as ZTD-12h, ZTD-6h, and ZTD-3h. It can be seen that assimilating the GNSS ZTDs helps to remove the incorrect model precipitation, especially over the eastern part of Hubei province. When more ZTD data are assimilated into the model, the incorrect precipitation decreases even more dramatically. The improvement is pretty remarkable for the ZTD-3h experiment, which may be attributed to more mesoscale information provided by the additional ZTD data.

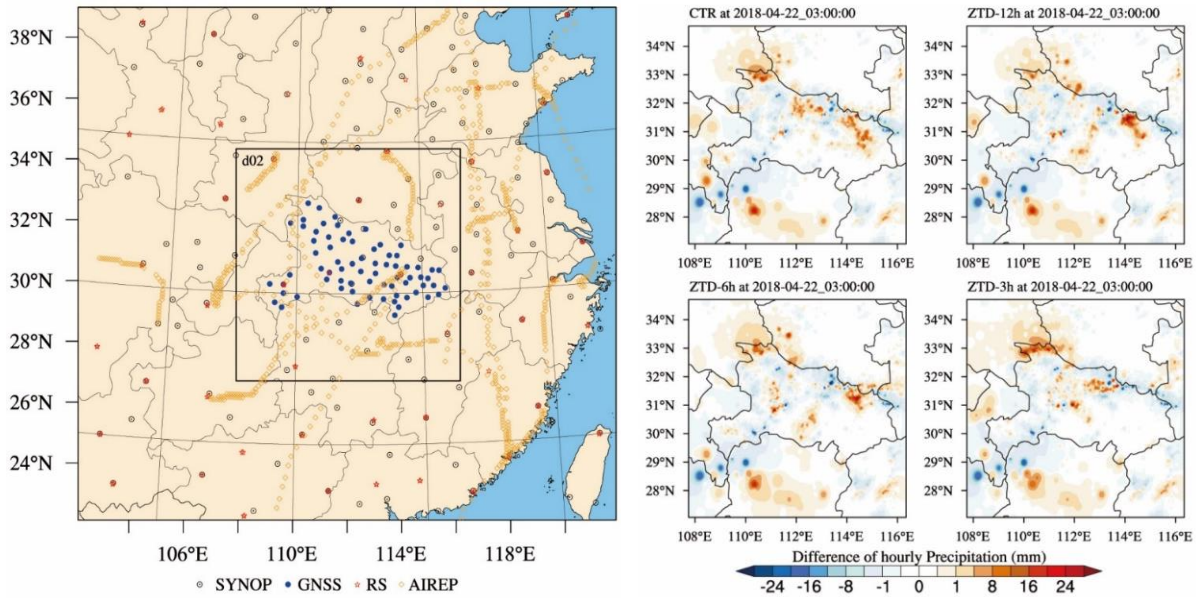


Figure 8, left: WRF domain configuration and stations distribution; right: Comparison of four experiments with the hourly precipitation observed by automatic stations at 03:00 UTC on 22 April 2018. The CTR is experiment without assimilation of GNSS ZTD, and the other three experiments describe the assimilation of ZTD-12h, ZTD-6h, and ZTD-3h, respectively.

Other related activities

In addition to the main objectives of this working group mentioned previously, some members have also worked on several related aspects. These include regional or global atmospheric modelling, applications of GNSS tropospheric products in numerical weather prediction or weather now-casting, the establishment of local real-time water vapor monitoring systems, the emerging implementation of machine-learning methods in GNSS meteorology, and GNSS water vapor retrieval from ocean regions based on ship-born platforms.

In this context, authors from Wuhan University formed a multi-source real-time local tropospheric delay model that uses polynomial fitting of ground-based GNSS observations, meteorological data and empirical GPT2w models (Yao et al., 2019), where the ZTDs were verified with a RMS of 1.48 cm in active troposphere conditions and 1.45 cm in stable troposphere conditions, which is superior to the conventional tropospheric GPT2w and Saastamoinen models. A pilot transnational severe weather service exploiting GNSS tropospheric products to enhance the safety, the quality of life and environmental protection in the Balkan-Mediterranean region was developed by a project "BalkanMed real time severe weather service" (2017-2019, Guerova et al., 2020). Since March 2021, Sofia University "St Kliment Ohridski" is leading a project to exploit the added value of GNSS tropospheric product for nowcasting of convective storm by building Storm Demonstrator (Storm Demo) in support of public weather and hail suppression services in Bulgaria. As a part of the Storm Demo real-time PPP processing will be conducted with G-Nut software for the first time in Southeast Europe for the hail suppression season May-September 2021.Authors from the Chinese Academy of Sciences Institute of Geodesy & Geophysics proposed a method to establish a real-time GNSS-PWV monitoring system using the national GNSS network of China (Zhang et al., 2019). The agreement between the real-time GPS-PWV and NCEP-II-PWV is approximately 2.0 mm in terms of RMS and has a mean bias of -0.8 mm. Authors from the Chinese Academy of Sciences Shanghai Astronomical Observatory proposed a regional zenith tropospheric delay (ZTD) empirical model SHAtropE, which is developed and provides tropospheric propagation delay corrections for users in China and the surrounding areas with improved accuracy (Chen et al., 2020). The model combines the exponential and periodical functions and is provided as regional grids with a resolution of 2.5◦ × 2.0◦ in longitude and latitude. Moreover, SHAtropE also provides the predicted ZTD uncertainty, which is valuable in Precise Point Positioning (PPP) with ZTD being constrained for faster convergence. And, the modeling quality control method for such models is proposed to establish the basis for the establishment of global ZTD models based on GNSS data (Ding et al., 2020). The accuracy and accuracy spatial-temporal properties of the latest model of the GPT series, GPT3, were analyzed, containing ZTD, eastward gradient and northward gradient (Ding and Chen, 2020).

In addition, exploration on GNSS water vapor sensing over the ocean regions were attempted. As an example, experimental observations of precipitable water vapor derived using GNSS receivers mounted on autonomous surface vehicles for real-time monitoring applications were reported by Fujita et al. (2020). PWV retrieval using kinematic PPP method with shipborne GNSS observations was also carried out during a 20-day experiment in 2016 in Fram Strait, the region of the Arctic Ocean between Greenland and Svalbard (Wang et al., 2019). Results showed that the shipborne GNSS PWV shows an agreement of similar to 1.1 mm with numerical weather model data and radiosonde observations.

Within the transpolar drifting expedition MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate), GNSS was used among other techniques to monitor variations in atmospheric water vapor (Männel et al., 2021). The derived ZTD values agree to 1.1 ± 0.2 mm (RMS of the differences 10.2 mm) with the numerical weather data of ECMWF's latest reanalysis, ERA5, computed for the derived ship's locations. The overall difference for integrated water vapor of 0.08 ± 0.04 kg m^{-2} (RMS of the differences 1.47 kg m^{-2}) demonstrates the good agreement between the GNSS and radiosonde data (Figure 9).

Moreover, the machine-learning method was introduced to solve the current related issues in the GNSS/Met attributing to its dramatic developments. Exemplarily, a generalized regression neural network (GRNN) was applied (Zhang et al., 2021) to fuse PWVs from GNSS, the Moderate-Resolution Imaging Spectroradiometer (MODIS) and the European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5).

"Advanced MUlti-GNSS Array for Monitoring Severe Weather Events" (AMUSE) is a current research project performed in cooperation of TUB (Technische Universität Berlin), GFZ (German Research Centre for Geosciences) and DWD (Deutscher Wetterdienst). The main objectives of the project are: 1) developments to provide multi-GNSS instead of GPS-only data, including GLONASS, Galileo and BeiDou; 2) developments to provide high quality advanced tropospheric products, i.e. slant tropospheric delays (STD); 3) developments to shorten the delay between measurements and the provision of the products to the meteorological services.

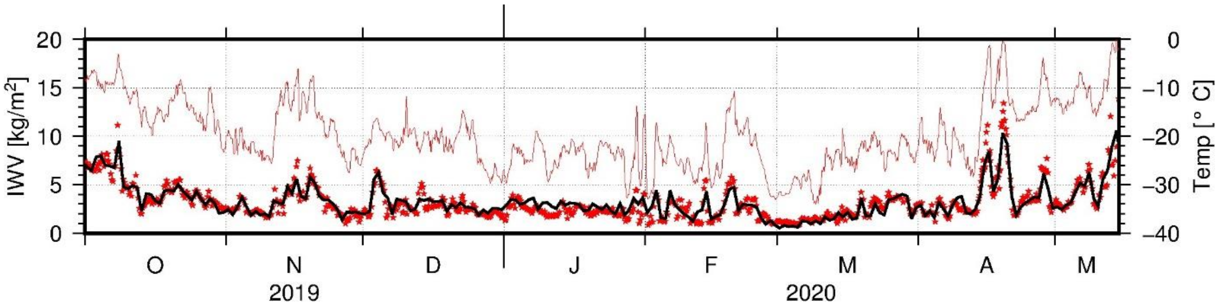


Figure 9. Integrated water vapor observed by GNSS (black) and radiosondes (red asterisks) during the MOSAiC campaign (October 2019 to May 2021), air temperature curve (thin red line, secondary axis).

At the moment, three multi-GNSS solutions are being calculated: GPS-only, GPS/GLONASS and GPS/GLONASS/Galileo based on a dense German network SAPOS and a global network

(GFZ/IGS). The slant total delays (STDs) are calculated every 2.5 minutes. The obtained parameters were compared with two global Numerical Weather Models (NWM): ERA5 reanalysis and a forecast model ICON. Figure 10 shows that all three solutions exhibited a similar level of agreement with the NWMs although, the GRE solution had slightly higher agreement with ERA5. When only the Galileo observations are considered, the biases were reduced by ~25% compared to the GPS-only solution.

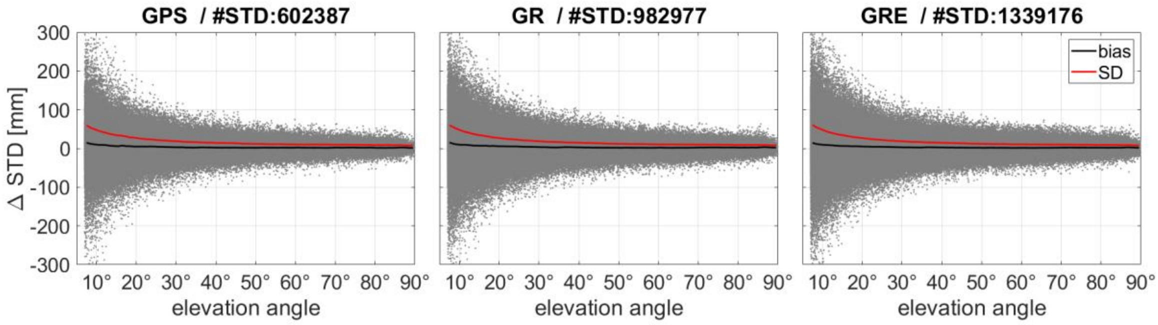


Figure 10. Differences between STDs from ERA5 and three GNSS solutions: GPS only (left), GPS/GLONASS (middle) and GPS/GLONASS/Galileo (right). Data period is October 2020.

Working group meeting and outreach

No in-situ IAG working group meetings were organized during the period of 2019-2021 affected by the COVID-19 pandemic. The last big gathering was the EGU General Assembly 2021 (19th-30th April 2021) that took place in online format, where the session "Atmospheric and Environmental Monitoring with Space-Geodetic Techniques" was held. Most of the members of IAG WG 4.3.5 submitted contributions to this session and it turned out to be a successful experiment of an online meeting. The next expecting and exciting event is the IAG Scientific Assembly 2021, which will be held in Beijing on June 28-July 2, 2021 and will be organized as a hybrid meeting. Recently, an online Joint splinter Meeting of IAG Sub-Commission 4.3 "Atmosphere Remote Sensing" was held on 26th April 2021. It discussed some general and urgent issues, including the IAG Scientific Assembly 2021, the IAG mid-term reports, GGOS website, etc. Furthermore, each working group reported their results achieved in the last two years, the current working topics, as well as the future research plan.

Publications

Caissy, M., Agrotis, L., Weber, G., Hernandez-Pajares, M., and Hugentobler, U.: INNOVATION-Coming Soon-The International GNSS Real-Time Service, GPS World, 23, 52–58, 2012.

Chen, J., Wang, J., Wang A., Ding, J., and Zhang, Y., (2020), SHAtropE—A Regional Gridded ZTD Model for China and the Surrounding Areas, Remote Sensing, 12,165.

Ding, J., and Chen, J., (2020), Assessment of Empirical Troposphere Model GPT3 Based on NGL's Global Troposphere Products, Sensors, 20, 3631.

Ding, J., Chen, J., and Wang, J., (2020), Quality Control Method for ZTD Modeling Based on GNSS Observation Data, Journal of Astronautics, 41(9), 1195-1203.

Dousa J, Vaclavovic P (2013), Real-time ZTD estimates based on Precise Point Positioning and IGS real-time orbit and clock products, In: Proceedings of the 4th International Colloquium Scientific and Fundamental Aspects of the Galileo Programme, 4-6 December 2013, Prague.

Douša J, Václavovic P (2016), Evaluation of ground-based GNSS tropospheric products at Geodetic Observatory Pecny, In: IAG 150 Years, Rizos Ch. and Willis P. (eds), IAG Symposia Series, Vol. 143, pp. 759-766, doi:10.1007/1345_2015_157.

Douša J, Václavovic P, Krč P, Eliaš M, Eben E, Resler J (2015), NWM forecast monitoring with near real-time GNSS products, In: Proceedings of the 5th Scientific Galileo Colloquium, Braunschweig, Germany, October 27-29, 2015.

Douša J, Eliaš M, Václavovic P, Eben K, Krč P, (2018) A two-stage tropospheric correction combining data from GNSS and numerical weather model, GPS Solut (2018) 22:77.

Douša J, Václavovic P, Zhao L, Kačmařík M (2018), New Adaptable All-in-One Strategy for Estimating Advanced Tropospheric Parameters and Using Real-Time Orbits and Clocks. Remote Sens. 2018, 10, 232. doi:10.3390/rs10020232

Dow, J. M., Neilan, R. E., and Rizos, C.: The International GNSS Service in a Changing Landscape of Global Navigation Satellite Systems, J. Geod., 83, 191–198, doi:10.1007/s00190-008-0300-3, 2009.

Fujita, M., Fukuda, T., Ueki, I., Moteki, Q., Ushiyama, T., Yoneyama, K. (2020): Experimental Observations of Precipitable Water Vapor over the Open Ocean Collected by Autonomous Surface Vehicles for Real-Time Monitoring Applications, SOLA, 16A, 19-24, doi: 10.2151/sola.16A-004.

Guerova G, Jones J, Douša, J, Dick G, de Haan S, Pottiaux E, Bock O, Pacione R, Elgered G, Vedel H, Bender M (2016): Review of the state of the art and future prospects of the ground-based GNSS meteorology in Europe, Atmos. Meas. Tech., 9, 5385-5406, doi: 10.5194/amt-9-5385-2016.

Guerova, G., Dimitrova, T., Vassileva, K., Slavchev, M., Stoev, K., Georgiev, S. (2020): real time severe weather service: Progress and prospects in Bulgaria, Advance in Space Research, 66(12), 2844-2853, doi: 10.1016/j.asr.2020.07.005.

Hadaś T. (2015) GNSS-Warp Software for Real-Time Precise Point Positioning. Artificial Satellites. Journal of Planetary Geodesy, Vol. 50 No. 2, Warsaw, Poland; Oldenburg, Germany 2015, pp. 59-76. doi: 10.1515/arsa-2015-0005.

Li, X., Dick, G., Ge, M., Heise, S., Wickert, J., and Bender, M. (2014): Real-time GPS sensing of atmospheric water vapor: precise point positioning with orbit, clock and phase delay corrections, Geophys. Res. Lett., 41(10), 3615-3621, doi: 10.1002/2013GL058721.

Li, X., Han, X., Li, X., Liu, G., Feng, G., Wang, B., and Zheng, H. (2021): GREAT-UPD: An open-source software for uncalibrated phase delay estimation based on multi-GNSS and multi-frequency observations, GPS Solut., 25-66, doi: 10.1007/s10291-020-01070-2.

Li, X., Tan, H., Li, X., Dick, G., Wickert, J., and Schuh, H. (2018): Real-time sensing of precipitable water vapor from BeiDou, observations: Hong Kong and CMONOC, networks. Journal of Geophysical, Research: Atmospheres, 123, 7897–7909, https://doi.org/10.1029/2018JD028320.

Lu, C., X. Li, M. Ge, R. Heinkelmann, T. Nilsson, B. Soja, G. Dick, and H. Schuh (2016): Estimation and evaluation of real-time precipitable water vapor from GLONASS and GPS, GPS Solut., 1-11, doi: 10.1007/s10291-015-0479-8.

Lu, C., G. Feng, Y. Zheng, K. Zhang, H. Tan, G. Dick and J. Wickert (2020): Real-Time Retrieval of Precipitable Water Vapor From Galileo Observations by Using the MGEX Network, IEEE Transactions on Geoscience and Remote Sensing, 58(7), doi: 10.1109/TGRS.2020.2966774.

Männel, B., Zus, F., Dick, G., Glaser, S., Semmling, M., Balidakis, K., Wickert, J., Maturilli, M., Dahlke, S., Schuh, H. (2021): GNSS-based water vapor estimation and validation during the MOSAiC expedition, ATM, 1-19, 10.5194/amt-2021-79

Wang, J., Wu, Z., Semmling, M., Zus, F., Gerland, S., Ramatschi, M., Ge, M., Wickert, J., Schuh, H. (2019): Retrieving Precipitable Water Vapor From Shipborne Multi-GNSS Observations, Geophys. Res. Lett., 46(9), 5000-5008, doi: 10.1029/2019GL082136.

Weber, G., L. Mervart, A. Stürze, A. Rülke and D. Stöcker (2016): BKG Ntrip Client, Version 2.12. Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Vol. 49, Frankfurt am Main, 2016.

Yao, Y., Xu, X., Xu, C., Peng, W., Wan, Y. (2019): Establishment of a Real-Time Local Tropospheric Fusion Model, Remote Sening, 11(11), doi: 10.3390/rs11111321.

Zhang, H., Yuan, Y., Li, W., Zhang, B. (2019): A Real-Time Precipitable Water Vapor Monitoring System Using the National GNSS Network of China: Method and Preliminary Results, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12 (5): 1587-1598, doi: 10.1109/JSTARS.2019.2906950.

Zhang, B. and Yao, Y. (2021): Precipitable water vapor fusion based on a generalized regression neural network, Journal of Geodesy, 95(3), doi: 10.1007/s00190-021-01482-z.

WG 4.3.6 Sensing small-scale structures in the lower atmosphere with tomographic principles

Chair: *Gregor Moeller (Switzerland)*
Vice-Chair: *Chi Ao (USA)*

Members

Zohreh Adavi (Austria), Natalia Hanna (Austria), Kefei Zhang (Australia), Hugues Brenot (Belgium), Eric Pottiaux (Belgium), Wenyuan Zhang (China), Chaiyaporn Kitpracha (Germany), Karina Wilgan (Germany), Riccardo Biondi (Italy),Estera Trzcina (Poland), Witold Rohm (Poland), Andre Garcia Sa (Portugal), Endrit Shehaj (Switzerland), George Hajj (USA), Kuo-Nung (Eric) Wang (USA)

Activities and publications during the period 2019-2021

The working group 4.3.6 was formed in December 2019 with the intention to bring together researchers and professionals working on tomography-based concepts for sensing the neutral atmosphere with space-geodetic and complementary observation techniques - sensitive to the water vapour distribution in the lower atmosphere. While geodetic GNSS networks are nowadays the backbone for troposphere tomography studies, further local densifications, more flexible tomography models as well as advanced processing strategies are necessary to achieve very fine spatial and temporal resolution.

In an initial survey, the collective interests of the 17 working group members have been inquired. In the virtual kick-off meeting, which took place on the 17th of January 2020, the results of the survey have been discussed and a priority list has been drafted, which serves as orientation and defines the objectives of the working group for the period 2019 - 2023.

Priority list (in decreasing order of interest):

1. Sensor fusion based on tomographic principles incl. a benchmark campaign for algorithm testing and validation;

2. Working on dynamical tomography models - adaptable to varying input data (continuous-time image reconstruction, trade-off between model resolution and variance size);
3. Advanced ray-tracing algorithms for the reconstruction of atmospheric signal paths for ground-based and space-based (e.g. radio occultation) observations;
4. Evaluating approaches for the densification of existing dual-frequency geodetic networks;
5. Standards and formats for data exchange.

Based on the survey, highest priority was given to the combination of techniques. In addition, a list of "missing objectives" was complied, which clearly indicates that more emphasis should be given to practical and science applications of tomography – including the assimilation of tomographic products into numerical weather prediction models. Within the period 2019 to 2021, the following achievements can be reported:

Tomographic fusion strategies

Tomographic fusion requires a strategy for observation selection and a weighting scheme for a reliable handling of the redundant information. By taking the individual sensor characteristics and possible combination (GNSS with radiosonde, GNSS with InSAR, etc.) into account, new strategies for inter- and intra-technique combination have been developed or are currently under investigation:

In terms of **intra-technique** combination, colleagues from Technische Universität Berlin (TUB), German Research Centre for Geosciences (GFZ) and Deutscher Wetterdienst (DWD) are currently working on a multi-GNSS solution for the estimation of high-quality GNSS slant wet delays, the basic input data for ground-based GNSS tomography. Therefore, three multi-GNSS solutions have been calculated: GPS-only, GPS/GLONASS and GPS/GLONASS/ Galileo based on the dense German network SAPOS (around 300 stations). The slant total delays (STDs) have been calculated every 2.5 minutes. The obtained parameters were compared with two global Numerical Weather Models (NWM): ERA5 reanalysis and a forecast model ICON. All three solutions exhibited a similar level of agreement with the NWMs although, the GRE solution had slightly higher agreement with ERA5. When only the Galileo observations are considered, the biases were reduced by ~25% compared to the GPS-only solution. In the next step, as part of the AMUSE project, we are planning to reconstruct the total and wet refractivity fields from the three GNSS solutions using the tomography methodologies developed at BIRA (Brenot et al., 2020).

Adavi and Weber (2021) from TU Wien investigated the effect of different GNSS constellations to solve the ill-posed inverse problem in GNSS tomography to retrieve a wet refractivity field by focusing on Galileo's impact on the accuracy of the estimated refractivity. Regarding this, the designed models have been loosely constrained to the a priori field to provide an optimum situation for assessing the influence of the Galileo constellation on the tomography derived wet refractivity fields. Therefore, three different schemes have been considered: 1) GPS+Glonass (GR), 2) GPS+Galileo (GE) and 3) GPS+Glonass+Galileo (GRE). To assess the impact of the individual solutions on the tomography derived wet refractivity field a validation campaign has been carried out in which the radiosonde RS11035 (Vienna, Hohe Warte) serves as reference. The major findings of the validation campaign are summarized in Table 1.

Table 1. The average of MAE [ppm] up to 2 km and for height 2 km to 6 km for different schemes at midnight

	GRE	GR	GE
Up to 2km	4.84	4.86	4.10
Height 2 km to 6 km	3.90	3.85	3.80

A combination of ground-based GNSS (geodetic and low-cost) with space-based GNSS (also known as radio occultation technique) is currently studied by colleagues from Wroclaw University of Environmental Life Sciences (UPWr), University of Wroclaw (UoW), ETH Zürich (ETH) and Spire Global. They addressing two major limitations of GNSS tomography: 1) inter-station distances that are usually 30-50 km rendering similar horizontal resolution of tomography model, 2) ill-posedness of the solution that is related to the lack of observations that traverse the troposphere in the horizontal direction. The high density of low-cost receivers (3-5km) and introduction of RO observations (limb sounding traversing troposphere in the horizontal direction) are expected to lift both limitations and thus, make this technology even more suitable for application in high-density weather predictions.

In terms of **inter-technique** combination, Adavi and Weber (2020) investigated the combination of GNSS with wet refractivity maps obtained from the 16 bands Advanced Baseline Imager onboard the Geostationary Operational Environmental Satellite (GOES). For this purpose, two different schemes have been defined to assess the impact of GOES data on the tomography solution: 1) GOES-16 as a constraint, and 2) ERA-5 as a constraint. For the tomography test case, a 3D tomographic model was defined over a regional area covered by the Continuously Operating Reference Station (CORS) Network in North America. Radiosonde measurements in the area of interest (RS72426) were used to validate the accuracy of the estimated 3D wet refractivity images, see Figure 3.

Another interesting combination of GNSS with infrared sensors has been studied by Zhang et al. (2021a) and Zhang et al. (2021b). In the study of Zhang et al. (2021a), high resolution precipitable water vapor (PWV) maps from MODIS were utilized. This data show great potential for the retrieval of positive cone-shaped slant water vapour (SWV) observations to complement the single GNSS acquisition geometry.

Tomographic experiments reveal that when introducing the infrared (IR) sensor observations into the tomography model, the acquisition geometry is significantly improved (see

Figure **4** for a schematic view). Moreover, the mean root-mean-square-error (RMSE) and bias of the water vapor profiles derived from the combined solution are dramatically decreased with respect to the GNSS-only results. Such improvements highlight that the combination of GNSS with IR products using tomographic principles has significant potential to retrieve a more accurate and reliable 4D atmospheric water vapor distribution. In the study of Zhang et al. (2021b), the developed approach was generalized for the incorporation of precipitable water vapor retrievals from infrared radiometers onboard remote sensing (RS) satellites. It is concluded that the rapid development of multi-source RS sensors provides great opportunities for the reconstruction of SWV for tropospheric tomography.

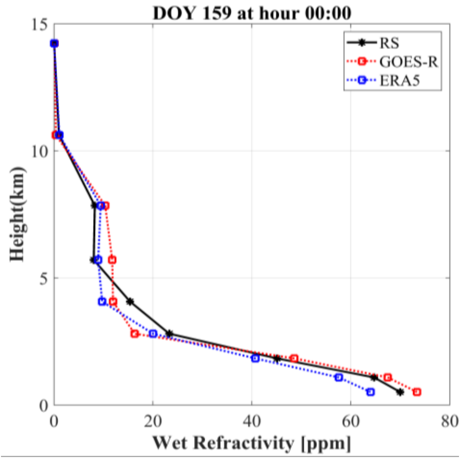
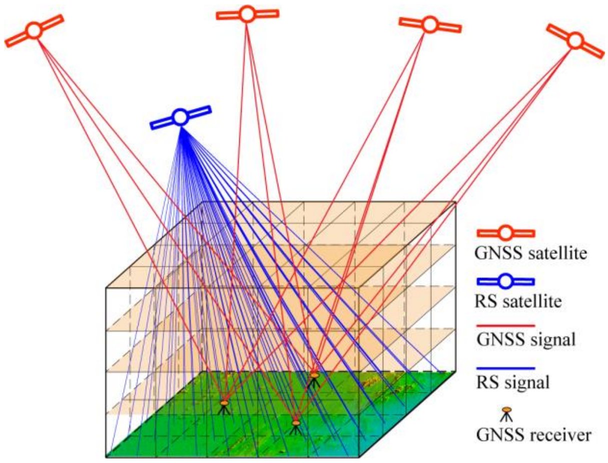


Figure 3. The comparison of reconstructed tomography profiles from GEOS-16 and ERA5 with RS72426 profiles at midnight for DoY 159

.

Figure 4: 3D observation geometry of GNSS and Remote Sensing (RS) measurements. Red and blue lines represent the transmission path of GNSS and RS signals, respectively. Source: Zhang et al. (2021b)



In Shehaj et al. (2020) an alternative approach for the combination of GNSS and InSAR data is described, in which GNSS and InSAR COSMO-SkyMed data were combined using the least-squares collocation software COMEDIE. A special model for the relative slant delays from InSAR was implemented. The results showed that the software can process large amounts of data as produced by InSAR, but still requires careful consideration of weighting of the data, as the combination was usually much closer to the InSAR data. This study also includes a simulation on the size of the SAR scene and the pixel resolution necessary to maintain a good agreement of the InSAR/GNSS product with the reference NWM data.

Dynamical tomography models:

In the study of Zhang et al. (2021a) a methodology based on a node tomography model was developed to solve the geometry defect in water vapor tomography. For validation, the node-based model was used for the combination of GNSS and MODIS data; a schematic view of the parametrization process is shown in Figure 5.

For assessment of the quality of the tomography derived refractivity fields, colleagues from TU Wien and Wroclaw University of Environmental Life Sciences proposed the concept of spread values as a mathematical tool to provide a quality measure without the need to use reference observations to calculate statistical measures like RMSE and Bias. Therefore, two different data sets of real and simulated observations have been used to investigate the information content of the proposed indicators: Bakus-Gilbert (BGH) and Michelini (Michi). Therefore, two different schemes were defined to estimate the a priori covariance matrix of unknown' parameters with low (LC) and high (TC) weighting.

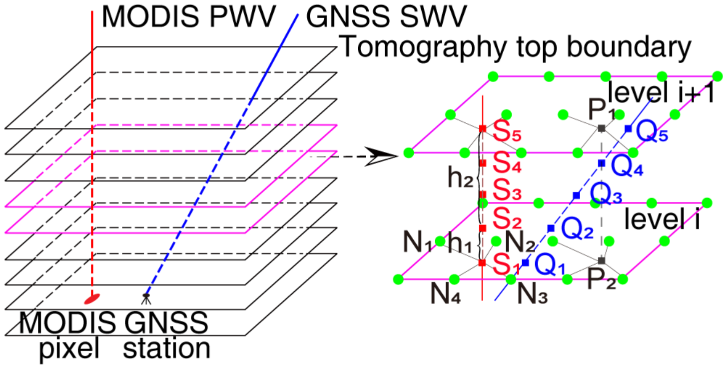


Figure 5: Schematic of the parameterization process for the GNSS and MODIS signals by using the node tomography model. The blue and red lines denote the GNSS and MODIS rays, respectively. Right: Partial enlarged drawing of the i-th layer. Source: Zhang et al. (2021a)

Error! Reference source not found. shows the results for 10 days, in which a significant correlation between quality indicator and standard deviation of the differences between tomography and radiosonde derived wet refractivity (0.69 for synthetic and 0.55 for real observations) is obtained. The correlation is also significant for bias, ranging from 0.71 for synthetic to -0.53 for real data.

Despite these achievements, the real-time or near-real-time GNSS tomography still remains a challenging task due to the accuracy of (near)-real-time GNSS tropospheric parameters and due to computational load. For this purpose, tomographic system SEGAL GNSS Water Vapor Reconstruction Image Software (SWART) was developed and tested, see Sá et al. (2021). The new method makes use of parallelized algebraic reconstruction techniques (ARTs) and supersedes other implementations in terms of speed by at least 50% for small networks, see **Error! Reference source not found.**.

Densification of existing geodetic networks:

Adavi and Weber (2019) analyzed the impact of different constraints on the accuracy of the reconstructed refractivity field. For this purpose, three different schemes have been defined to reduce the elements of the model null space to the trivial ones. In the first scheme, minimum horizontal and vertical constraints were added to the system of observation equations. Then, five real GNSS stations have been left out and replaced by data of two additional VRS sites to focus on the accuracy of the reconstructed field using the VRS stations concept in a sparse GNSS network. In the third schemes, constraints have been applied to the tomography model in the sparse GNSS network in order to evaluate the accuracy of estimated parameters by the previous schemes. According to the obtained results, the RMSE of the reconstructed refractivity field in the dense GNSS network with respect to the radiosonde profile was about 2.80 ppm for the selected period of interest. For the sparse GNSS network, the average RMSE for schemes with VRS stations and applied constraints was about 3.02 ppm and 3.27 ppm, respectively. Consequently, the quality of the reconstructed refractivity profiles in scheme 1 was generally better than in the other two schemes. Besides, according to these results applying VRS stations in the sparse GNSS network can lead to a better solution in comparison to just applying vertical and horizontal constraints. Thus, it can be concluded that the refractivity field can be reconstructed with acceptable accuracy from VRS stations if one of the following conditions is fulfilled: 1) the distance between GNSS stations are larger than the horizontal resolution, 2) topography is rough, 3) some GNSS station are not working for a short period of time. Nevertheless, applying VRS stations in dense GNSS networks is not recommended as it might increase the inconsistency between the reconstructed field and the reference solution.

Tomography applications:

In terms of tomography applications, the working group has initiated or is involved in a series of national and international research projects (excerpt).

- **3D integrated sensing of troposphere using ground and space-based GNSS observation:** This project, led by Wroclaw University of Environmental and Life Sciences (UPWr), aims on the use of the inverse Radon transform on dense space-based and ground-based GNSS observations for providing integrated 3D models of troposphere that will improve precipitation and humidity forecasts.
- **Water vapor fields by space-born geodetic sensing, tomographic fusion, and atmospheric modeling:** By using GNSS and InSAR based techniques in combination with high resolution regional atmospheric weather models and geostatistical data merging techniques, the research project, led by University of Augsburg, aims at developing and evaluating new approaches to derive improved spatio-temporal estimates of the atmospheric water vapor distribution. In particular, tomographic-based approaches for the evaluation of geodetic and remote sensing data will be further developed to improve the vertical and horizontal resolution of the investigated atmospheric state variables.
- **SINOPTICA** is a H2020 EU-project (collaboration of CIMA, DLR, AustroControl, GReD, UniBar and UniPd) which focuses on improving the prediction of extreme weather events (key objective to eliminate unexpected scenarios that compromise aviation safety). This project combines remote sensing derived, GNSS-derived and in situ weather stations variables, in an automated assimilation system of a numerical weather model.
- **ALARM** is a H2020 EU-project (collaboration of UC3M, DLR, SATAVIA, Unipd, and BIRA). The overall objective of ALARM (*multi-h**A**zard monitoring and ear**L**y w**AR**ning syste**M***) is to develop a prototype global multi-hazard monitoring and early warning system for all these hazards (https://alarm-project.eu). Within the framework of these 2 projects (SINOPTICA and ALARM), Hugues Brenot (BIRA) and Riccardo Biondi (UniPd) will conduct a test of tomography applications with the objective of implementing early warning of the initiation of deep convection. Vertical extension from tomography and precursor of 3D structures will be looked at using the algorithmic development of Brenot et al. (2020).

Tomography assimilation:

The first studies on assimilation of the GNSS tomography data into the numerical weather prediction model were performed by means of the AROME radiosonde observation operator (Moeller, 2016) and the GPSREF operator provided with the Weather Research and Forecasting (WRF) Data Assimilation (DA) system (Hanna et al., 2019; Trzcina and Rohm, 2019). The GPSREF operator requires total refractivity observations, which were calculated as a sum of tomographic wet refractivities and hydrostatic refractivities derived from ALADIN-CZ model. The validation against radiosondes shows an improvement in the weather forecasting of relative humidity (bias, standard deviation) and temperature (standard deviation) during heavy precipitation events.

A more recent study was focused on the direct assimilation of GNSS tomography-derived 3D fields of wet refractivity into the WRF model (Trzcina et al., 2020). To allow for a direct assimilation of wet refractivity fields, the TOMOREF observation operator was built. The new tool was tested based on wet refractivity fields derived during a very intense precipitation event. The results were validated using radiosonde observations, synoptic data, ERA5 reanalysis, and radar data. In the performed experiment, a small positive impact of the GNSS tomography data assimilation on the forecast of relative humidity (RH) was noticed (an improvement of root-mean-square error up to 0.5%). Moreover, within 1 hour after assimilation, the GNSS data reduced the bias of precipitation up to 0.1 mm. Additionally, the assimilation of GNSS tomography data had more influence on the WRF model than the Zenith Total Delay (ZTD) observations, which confirms the potential of the GNSS tomography data for weather forecasting.

References

Adavi, Z. and Weber, R.: Impact of the Galileo constellation on GNSS Tropospheric Tomography, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-41, *https://doi.org/10.5194/egusphere-egu21-41*, 2021.

Adavi, Z. and Weber, R.: Analysis of GOES-R as a Constraint in GNSS Tropospheric Tomography, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-14965, *https://doi.org/10.5194/egusphere-egu2020-14965*, 2020

Adavi, Z. and Weber, R.: Evaluation of Virtual Reference Station Constraints for GNSS Tropospheric Tomography in Austria Region, Adv. Geosci., 50, 39–48, *https://doi.org/10.5194/adgeo-50-39-2019*, 2019.

Brenot, H.; Rohm, W.; Kačmařík, M.; Möller, G.; Sá, A.; Tondaś, D.; Rapant, L.; Biondi, R.; Manning, T.; Champollion, C. Cross-Comparison and Methodological Improvement in GPS Tomography. *Remote Sens*, *12*, 30. *https://doi.org/10.3390/rs12010030*, 2020

Hanna, N., Trzcina, E., Möller, G., Rohm, W., and Weber, R.: Assimilation of GNSS tomography products into the Weather Research and Forecasting model using radio occultation data assimilation operator, Atmos. Meas. Tech., 12, 4829–4848, *https://doi.org/10.5194/amt-12-4829-2019*, 2019.

Moeller, G., Wittmann, C., Yan, X., Umnig, E., Joldzic, N., & Weber, R, 3D ground based GNSS atmospheric tomography. Final report, FFG project GNSS-ATom (ID:840098), 2015

Moeller, G., Ao, C., Adavi, Z., Brenot, H., Sá, A., Hajj, G., Hanna, N., Kitpracha, C., Pottiaux, E., Rohm, W., Shehaj, E., Trzcina, E., Wang, K.-N., Wilgan, K., and Zhang, K.: Sensing small-scale structures in the troposphere with tomographic principles (IAG working group), EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-8469, *https://doi.org/10.5194/ egusphere-egu2020-8469*, 2020

Moeller, G., Ao, C., Adavi, Z., Biondi R., Brenot, H., Sá, A., Hajj, G., Hanna, N., Kitpracha, C., Pottiaux, E., Rohm, W., Shehaj, E., Trzcina, E., Wang, K.-N., Wilgan, K., Zhang W., and Zhang, K.: Tomographic fusion strategies for the reconstruction of atmospheric water vapor, Scientific Assembly of the International Association of Geodesy, Beijing, China, June 28 – July 2, 2021

Sá, A., Rohm, W., Fernandes, R.M. et al. Approach to leveraging real-time GNSS tomography usage. J Geod 95, 8, https://doi.org/10.1007/s00190-020-01464-7, 2021

Shehaj E., Wilgan K., Frey O. and Geiger A, A collocation framework to retrieve tropospheric delays from a combination of GNSS and InSAR. Navigation, Issue 67, p. 823-842, http://dx.doi.org/10.1002/navi.398, 2020

Trzcina E, Rohm W, Estimation of 3D wet refractivity by tomography, combining GNSS and NWP data: First results from assimilation of wet refractivity into NWP. Quart J Roy Meteorol Soc 145(720):1034–1051. *https://doi.org/10.1002/qj.3475*, 2019

Trzcina, E., Hanna, N., Kryza, M., & Rohm, W, TOMOREF Operator for Assimilation of GNSS Tomography Wet Refractivity Fields in WRF DA System. *Journal of Geophysical Research: Atmospheres*, *125*(17), e2020JD032451, 2020

Zhang, W., Zhang, S., Zheng, N. et al. A new integrated method of GNSS and MODIS measurements for tropospheric water vapor tomography. GPS Solutions, 25:79. *https://doi.org/10.1007/s10291-021-01114-1*, 2021a

Zhang, W., Zhang, S., Ding, N. et al. GNSS-RS Tomography: Retrieval of Tropospheric Water Vapor Fields Using GNSS and RS Observations. IEEE Transactions on Geoscience and Remote Sensing, *https://doi.org/10.1109/TGRS.2021.3077083*

WG 4.3.7 Geodetic GNSS-R

Chair: *Sajad Tabibi (Luxembourg)*
Vice-Chair: *Felipe Geremia-Nievinski (Brazil)*

Members

Dave Purnell (Canada), Chung-Yen Kuo (Taiwan), Clara Chew (USA), Estel Cardellach (Spain), Jens Wickert (Germany), Jihye Park (USA), Joerg Reinking (Germany), Karen Boniface (Italy), Kegen Yu (China), Kristine Larson (USA), Manuel Martín-Neira (ESA), Maximilian Semmling (Germany), Nikolaos Antonoglou (Germany), Ole Roggenbuck (Germany), Rashmi Shah (USA), Rüdiger Haas (Sweden), Simon Williams (UK), Thomas Hobiger (Germany), Wei Liu (China)

Activities and publications during the period 2019-2021

The radio signals at L-band broadcasted by Global Navigation Satellite Systems (GNSS) have revolutionized positioning, navigation, and timing. The reflected GNSS-R signals of opportunity have been used as a new remote sensing technique in the last two decades to retrieve environmental variables such as sea level. Geodetic GNSS-R has used sensor platforms near the ground surface for sea altimetry at several locations in recent years. The geodetic GNSS-R working group 4.3.7 of the International Association of Geodesy (IAG) with 21 members, is a part of Sub-Commission 4.3 Atmosphere Remote Sensing under the IAG Commission 4 on positioning and applications. The main objective of the working group is to further demonstrate and consolidate the value of GNSS-R for the geodesy, oceanography, cryosphere, and hydrology communities.

The first inter-comparison campaign on SNR (signal-to-noise ratio)-based GNSS-R for sea level monitoring was established in the IAG period 2015 – 2019 under the JWG (Joint Working Group) 4.3.9. GPS-L1-C/A sea levels for a one-year period of Onsala GNSS-R tide gauge station (GTGU) were submitted by four groups. GTGU is equipped with a Leica GRX1200 receiver and one up-looking Leica AR 25 antenna ~ 4 m above mean sea level. Different processing strategies and settings such as azimuthal masks were used by each group to retrieve sea level. In addition, tropospheric delay correction was discarded for the sake of consistency among different groups. The power spectral density (PSD) distribution demonstrated a good agreement for semi-diurnal tidal constituents between tide gauge and all GNSS-R solutions (Fig. 1). But most solutions overestimated lunar-diurnal constituent due to the leakage from sidereal period aliasing.

The second inter-comparison campaign on geodetic GNSS-R with eight research groups was launched in July 2020 to address further the impacts of large tidal range and multi-GNSS revisit time on tidal constituents on GNSS-R sea level retrievals. Two different GNSS stations with 5-m and 9-m tidal ranges with 10-m and 8.5-m reflector heights in the Netherlands and France were selected for the second geodetic GNSS-R campaign (Fig. 2).

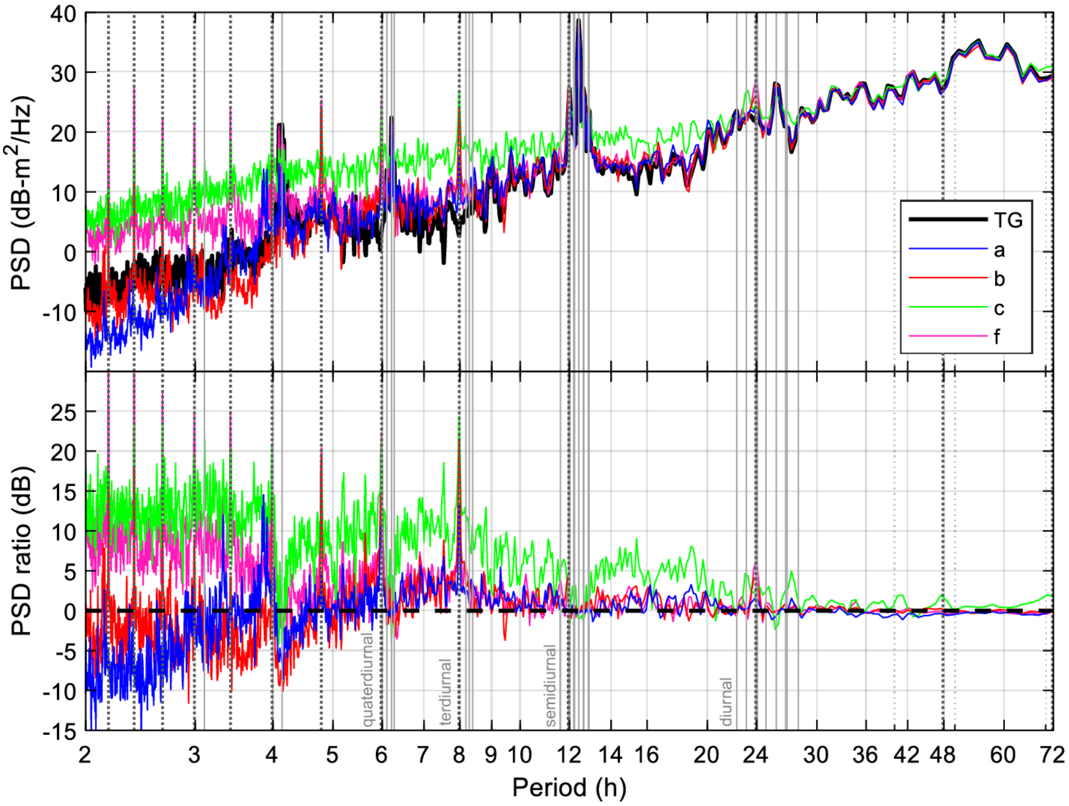


Figure 1: PSD distribution of sea level solutions (Geremia-Nievinski et al. 2020a)

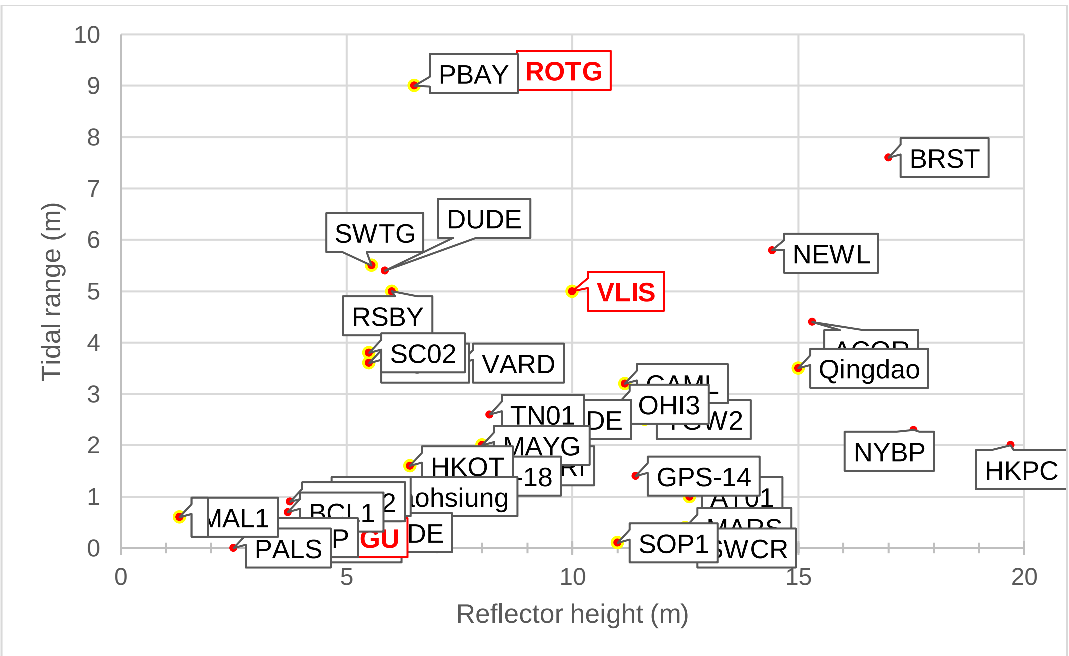


Figure 2: GTGU, VLIS, and ROTG as a function of reflector height and tidal range (Geremia-Nievinski et al. 2020b)

In addition, the processing settings were also provided to the eight groups (Table 1). This was done to ensure that observation conditions are consistent in all processing centers. Otherwise, the performance of GNSS-R sea levels would be a consequence of the choice of satellite visibility mask and the elevation angle range per altimetric retrieval. The azimuthal and elevation angle masks are defined to assure that SNR reflections from the sea surface are obtained.

Table 1: GNSS-R site descriptions; azimuthal masks are in clockwise order

	VLIS (The Netherlands)	ROTG (France)
Lat., Long. (deg)	51.44286, 3.59734	48.71844, -3.966566
Receiver	LEICA GR50	TPS GB-1000
Antenna	LEIAR25.R4	TPSPG_A1+GP
Mean RH (m)	10	8.5
Tidal range (m)	5	9
Azimuth interval (deg.)	30-180	30-300
Sampling rate (Hz)	1	1
Distance to TG (m)	2	2

Five groups submitted their solutions (GPS-L1-C/A; combined GPS-L1-C/A and GLONASS-R1-C/A) for the inter-comparison campaign, but three groups have withdrawn their submissions at their discretion. Currently, the GNSS-R solutions have been compared with TG records (Fig. 4). Using VLIS and ROTG with larger tidal ranges and greater reflector heights compared to the first inter-comparison campaign (GTGU) would help to understand the geodetic GNSS-R sea level products better.

Investigation of external corrections to the sea level solutions such as atmospheric effects is planned for the future activity. In addition, a multi-group combination of geodetic GNSS-R sea levels is envisioned for the geodetic GNSS-R working group 4.3.7.

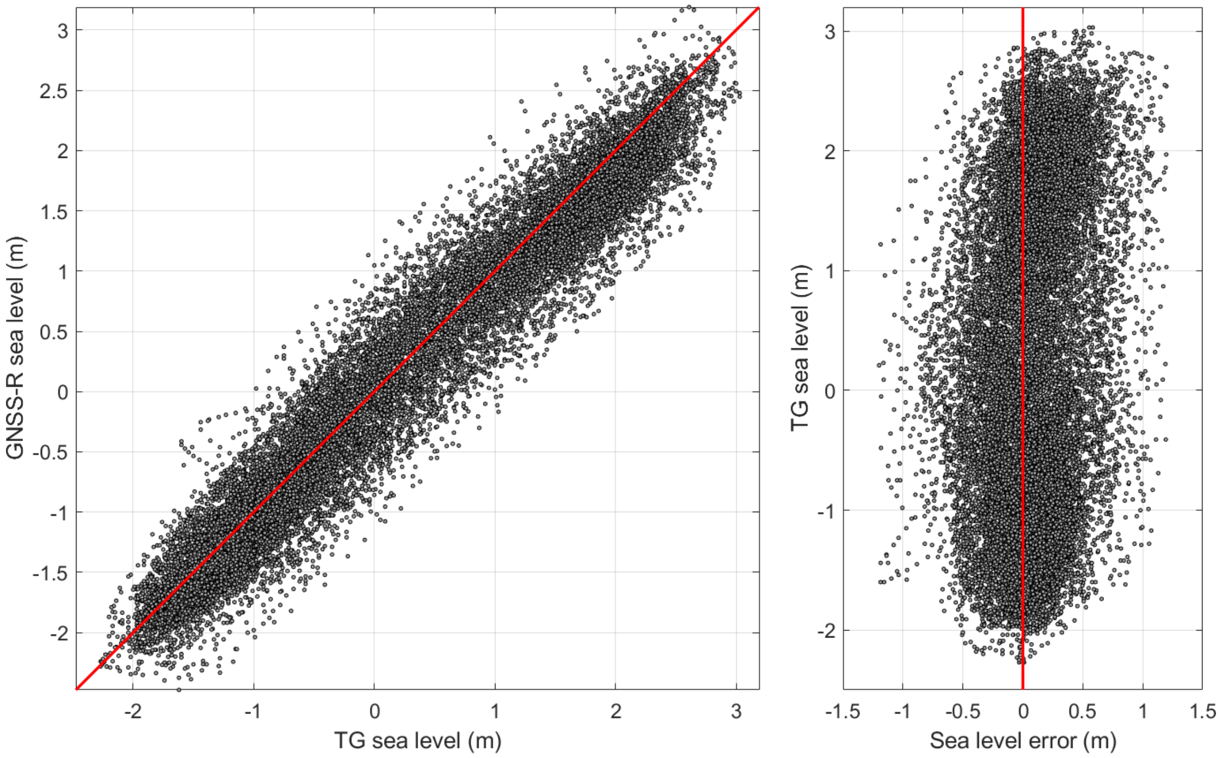


Figure 4: Preliminary scatterplot (left panel) and Van de Casteele diagram (right panel) of sea levels at VLIS show an excellent agreement between GNSS-R and tide gauge records

References

Asgarimehr M, Hoseini M, Semmling M, et al (2021) Remote Sensing of Precipitation Using Reflected GNSS Signals: Response Analysis of Polarimetric Observations. *IEEE Transactions on Geoscience and Remote Sensing* 1–12. https://doi.org/10.1109/TGRS.2021.3062492

Durand M, Rivera A, Geremia-Nievinski F, et al (2019) GPS reflectometry study detecting snow height changes in the Southern Patagonia Icefield. *Cold Regions Science and Technology* 166:102840. https://doi.org/10.1016/j.coldregions.2019.102840

Fagundes MAR, Mendonça-Tinti I, Iescheck AL, et al (2021) An open-source low-cost sensor for SNR-based GNSS reflectometry: design and long-term validation towards sea-level altimetry. *GPS Solut* 25:73. https://doi.org/10.1007/s10291-021-01087-1

Garrison J, Zavorotny VU, Egido A, et al (2020) GNSS Reflectometry for Earth Remote Sensing. In: *Position, Navigation, and Timing Technologies in the 21st Century*. John Wiley & Sons, Ltd, pp 1015–1114, https://doi.or1g/10.1002/9781119458449.ch34

Geremia-Nievinski F, Hobiger T (2019) Site guidelines for multi-purpose GNSS reflectometry stations. *Zenodo,* https://doi.org/10.5281/zenodo.3660744

Geremia-Nievinski F, Hobiger T, Haas R, et al (2020a) SNR-based GNSS reflectometryfor coastal sea-level altimetry: results from the first IAG inter-comparison campaign. *J Geod* 94:70. https://doi.org/10.1007/s00190-020-01387-3

Geremia-Nievinski F, Makrakis M, Tabibi S (2020b) Inventory of published GNSS-R stations, with focus on ocean as target and SNR as observable, *Zenodo*, https://doi.org/10.5281/zenodo.3660521

Hoseini M, Semmling M, Nahavandchi H, et al (2020) On the Response of Polarimetric GNSS-Reflectometry to Sea Surface Roughness. *IEEE Transactions on Geoscience and Remote Sensing* 1–12. https://doi.org/10.1109/TGRS.2020.3031396

Kim S-K, Lee E, Park J, Shin S (2021) Feasibility Analysis of GNSS-Reflectometry for Monitoring Coastal Hazards. *Remote Sensing* 13:976. https://doi.org/10.3390/rs13050976

Kim S-K, Park J (2019) Monitoring Sea Level Change in Arctic using GNSS-Reflectometry. *GPS World*, pp 665–675, https://www.gpsworld.com/a-tidal-shift-monitoring-sea-level-in-the-arctic-using-gnss/

Kim S-K, Park J (2021) Monitoring a storm surge during Hurricane Harvey using multi-constellation GNSS-Reflectometry. *GPS Solut* 25:63. https://doi.org/10.1007/s10291-021-01105-2

Larson KM, Lay T, Yamazaki Y, et al (2021) Dynamic Sea Level Variation From GNSS: 2020 Shumagin Earthquake Tsunami Resonance and Hurricane Laura. *Geophysical Research Letters* 48:e2020GL091378. https://doi.org/10.1029/2020GL091378

Larson KM, MacFerrin M, Nylen T (2020) Brief Communication: Update on the GPS reflection technique for measuring snow accumulation in Greenland. *The Cryosphere* 14:1985–1988. https://doi.org/10.5194/tc-14-1985-2020

Lewis SW, Chow CE, Geremia-Nievinski F, et al (2020) GNSS interferometric reflectometry signature-based defense. *NAVIGATION, Journal of the Institute of Navigation* 67:727–743. https://doi.org/10.1002/navi.393

Nikolaidou T, Santos M, Williams SDP, Geremia-Nievinski F (2020a) A simplification of rigorous atmospheric raytracing based on judicious rectilinear paths for near-surface GNSS reflectometry. *Earth, Planets and Space* 72:91. https://doi.org/10.1186/s40623-020-01206-1

Nikolaidou T, Santos MC, Williams SDP, Geremia-Nievinski F (2020b) Raytracing atmospheric delays in ground-based GNSS reflectometry. *Journal of Geodesy* 94:. https://doi.org/10.1007/s00190-020-01390-8

Nikolaidou T, Santos M, Williams SDP, Geremia-Nievinski F (2021) Development and validation of comprehensive closed formulas for atmospheric delay and altimetry correction in ground-based GNSS-R, *TechRxiv* (preprint), http://doi.org/10.36227/techrxiv.14345153

Park J, Kim S, Wardwell N (2019) Water level monitoring in different regions of the U.S. using GNSS-Reflectometry. In: Earth and Space Science Open Archive. ESSOAr (preprint), http://www.essoar.org/doi/10.1002/essoar.10500340.1

Purnell D, Gomez N, Chan NH, et al (2020) Quantifying the Uncertainty in Ground-Based GNSS-Reflectometry Sea Level Measurements. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13:4419–4428. https://doi.org/10.1109/JSTARS.2020.3010413

Purnell D, Gomez N, Minarik W, et al (2021) Precise water level measurements using low-cost GNSS antenna arrays. *Earth Surface Dynamics* (preprint), https://doi.org/10.5194/esurf-2020-108

Ray RD, Larson KM, Haines BJ (2021) New determinations of tides on the north-western Ross Ice Shelf. *Antarctic Science* 33:89–102. https://doi.org/10.1017/S0954102020000498

Reinking J (2020) Revision of the Atmospheric Modeling for SNR Observations in Ground-Based GNSS Reflectometry. *Preprints.org* (preprint) https://doi.org/10.20944/preprints202012.0564.v1

Reinking J, Roggenbuck O, Even-Tzur G (2019) Estimating Wave Direction Using Terrestrial GNSS Reflectometry. *Remote Sensing* 11:1027. https://doi.org/10.3390/rs11091027

Roggenbuck O, Reinking J (2019) Sea Surface Heights Retrieval from Ship-Based Measurements Assisted by GNSS Signal Reflections. *Marine Geodesy* 42:1–24. https://doi.org/10.1080/01490419.2018.1543220

Roggenbuck O, Reinking J, Lambertus T (2019) Determination of Significant Wave Heights Using Damping Coefficients of Attenuated GNSS SNR Data from Static and Kinematic Observations. *Remote Sensing* 11:409. https://doi.org/10.3390/rs11040409

Strandberg J, Haas R (2020) Can We Measure Sea Level With a Tablet Computer? *IEEE Geoscience and Remote Sensing Letters* 17:1876–1878. https://doi.org/10.1109/LGRS.2019.2957545

Strandberg J, Hobiger T, Haas R (2019) Real-time sea-level monitoring using Kalman filtering of GNSS-R data. *GPS Solut* 23:61. https://doi.org/10.1007/s10291-019-0851-1

Tabibi S, Francis O (2020) Can GNSS-R Detect Abrupt Water Level Changes? *Remote Sensing* 12:3614. https://doi.org/10.3390/rs12213614

Tabibi S, Geremia-Nievinski F, Francis O, van Dam T (2020) Tidal analysis of GNSS reflectometry applied for coastal sea level sensing in Antarctica and Greenland. *Remote Sensing of Environment* 248:111959. https://doi.org/10.1016/j.rse.2020.111959

Williams SDP, Bell PS, McCann DL, et al (2020) Demonstrating the Potential of Low-Cost GPS Units for the Remote Measurement of Tides and Water Levels Using Interferometric Reflectometry. *Journal of Atmospheric and Oceanic Technology* 37:1925–1935. https://doi.org/10.1175/JTECH-D-20-0063.1

Yamawaki MK, Geremia-Nievinski F, Monico JF (2021) High-rate altimetry in SNR-based GNSS-R: Proof-of-concept of a synthetic vertical array. *IEEE Geoscience and Remote Sensing Letters* https://doi.org/10.1109/LGRS.2021.3068091

Sub-commission 1.3: Regional Reference Frames

Chair: Carine Bruyninx (Belgium)

Overview

Sub-commission 1.3 contains six regional Sub-commissions (SC)

- Sub-commission 1.3 a: Europe
- Sub-commission 1.3 b: South and Central America
- Sub-commission 1.3 c: North America
- Sub-commission 1.3 d: Africa
- Sub-commission 1.3 e: Asia-Pacific
- Sub-commission 1.3 f: Antarctica

and one Working Group (WG) "Time-dependent transformations between reference frames in deforming regions".

This mid-term report gathers the contributions of the above regional sub-commissions and WG for the period 2019-2021. As stated in the Terms of Reference, IAG Sub-commission SC1.3

deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organizations.

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:

- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the efforts of the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) towards a sustainable Global Geodetic Reference Frame (GGRF).

The reports of all regional sub-commissions (except Africa) are presented hereafter.

Sub-Commission 1.3a: Europe (EUREF)

Chair: Martin Lidberg (Sweden)

Introduction and Structure

The long-term objective of EUREF, as defined in its Terms of Reference is "the definition, realization and maintenance of the European Reference Systems, in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-Commission projects) as well as EuroGeographics". For more information, see *http://www.euref.eu*.

The results and recommendations issued by the EUREF sub-commission support the use of the European Reference Systems in all scientific and practical activities related to precise georeferencing and navigation, Earth sciences research and multi-disciplinary applications. EUREF applies the most accurate and reliable terrestrial and space-borne geodetic techniques available, and develops the necessary scientific principles and methodology. Its activities are focused on a continuous innovation and on evolving user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- Maintenance of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade of the respective realizations;
- Refining the EUREF Permanent Network (EPN) in close cooperation with the International GNSS Service (IGS);
- Improvement of the European Vertical Reference System (EVRS);
- Contribution to the IAG Project GGOS (Global Geodetic Observing System) using the installed infrastructures managed by the EUREF members.

These activities are reported and discussed at the meetings of the EUREF Governing Board (GB), which take place three times a year, and the annual EUREF Symposia, an event that occurs every year since 1990. The EUREF symposia have an attendance of about 100-120 participants from more than 30 European countries and other continents, representing mainly Universities, Research Centres, and NMCAs (National Mapping and Cadastre Agencies). EuroGeographics (the consortium of the European NMCAs) supports the organization of the EUREF Symposia, reflecting the importance of EUREF for practical purposes. The latest EUREF symposia took place 2018 in Amsterdam, The Netherlands and 2019 in Tallinn, Estonia. The 2020 symposium scheduled for Ljubljana, Slovenia, was cancelled. The 2021 symposium is organized as online event by the Slovenian colleagues.

Members

- *Elmar Brockmann (Switzerland)*
- *Carine Bruyninx (Belgium)*
- *Rolf Dach (Switzerland)*
- *Ambrus Kenyeres (Hungary)*
- *Karin Kollo (Estonia, EUREF secretary, ex-officio)*
- *Juliette Legrand (Belgium)*
- *Martin Lidberg (Sweden, EUREF chair, ex-officio)*
- *Tomasz Liwosz (Poland)*
- *Rosa Pacione (Italy)*
- *Martina Sacher (Germany)*
- *Wolfgang Söhne (Germany, GB chair)*
- *Christof Völksen (Germany)*

A. Araszkiewicz (Poland), *Z. Altamimi* (France), *A. Caporali* (Italy), *M. Poutanen* (Finland), *J. Torres* (Portugal) and *J. Zurutuza* (Spain) are regularly participating to the GB meetings as honorary members and invited guest, resp.

Activities during the period 2019-2021

EUREF Permanent GNSS Network (EPN) Tracking Network, network Coordination, and Central Bureau

Most of the activities covering the European GNSS Network (EPN) are reported on an annual basis in the Technical Reports of the International GNSS Service (IGS). In addition to the overview and summary given here, see Bruyninx et al. (2018) and Bruyninx et al. (2019) for more details.

The EPN Central Bureau (CB, managed by the Royal Observatory of Belgium - ROB) continued to monitor operationally EPN station performance in terms of data availability, correctness of metadata, and data quality (Bruyninx et al., 2019). Its “Metadata Management and Dissemination System for Multiple GNSS Networks“ (M^3G, *https://gnss-metadata.eu*, Bruyninx et al., 2020) allows now also to collect information on data licenses and Digital Object Identifiers (DOI), although only few EPN stations have provided this info so far. M^3G also introduced and Application Program (API) to retrieve and submit metadata from EPN and EPN densification stations and allows to upload and retrieve site pictures.

27 new stations were integrated in the EPN since July 2019 including the first EPN stations in Montenegro and Belorussia (see Figure 1.3a.1). Presently, 82% of the EPN stations are providing Galileo data and 69% provide BeiDou data.

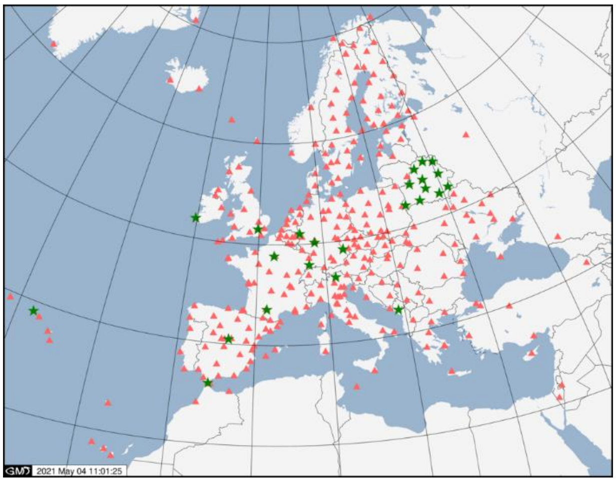


Figure 1.3a.1: EPN tracking stations (status May 2021).
***** indicates new stations included in the network in since July 2019.

In November 2019, the EUREF Governing Board issued an update of the “Guidelines for EPN stations and Operational Centres”:
see
https://epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf.
With this update, from 2020 on, stations submitting RINEX 3 data can discontinue RINEX 2 uploads. Concerning the real-time data, submission of RTCM 3 is preferred over RTCM 2 and

to ensure EPN stations can provide real-time access to the ETRS89, station managers are asked to insert the ETRS89 coordinates in their real-time streams.

EPN Real Time

During the period, the number of EPN stations providing real-time data was continuously growing. End of 2019, 54 % (188 stations) and end of 2020, 53 % (193 stations) established the so-called mount-points. Almost all varieties of RTCM messages (2.x to 3.3) are available from the three EPN broadcasters, with only few stations still providing RTCM 2.x. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) is still growing. The number of stations, which are delivering MSM4 (message type 1074 etc.) or MSM5 (message type 1075 etc.), increased to 66 whereas the MSM7 (1077 etc.) was available for 83 stations. Hence, the stations providing the "legacy" messages 1004 (GPS) and 1012 (GLONASS) significantly reduced to 27. Big improvement was made concerning the source of the data: only three stations remain which provide the data using an intermediate software. All other streams are coming (directly) from the receiver.

The introduction of long mount-point names on the three EPN broadcasters has been completed in 2019. The monitoring of the three EPN broadcasters at the EPN CB was extended, including the availability of data and product streams, the latency of the streams as well as the meta-data. Thanks to this, the consistency between the three EPN broadcasters improved very much.

EPN Analysis Centre Coordination

In years 2019-2021 EPN Analysis Centres Coordinator (ACC) continued to combine GNSS coordinate solutions (final, rapid and ultra-rapid) provided by 16 EPN Analysis Centres (AC). In 2019 11 EPN ACs started using Galileo observations (in addition to GPS and GLONASS) for the generation of the official products. Since August 2020 also SGO AC (Lechner Knowledge Center, Hungary) has started including Galileo observations in its solutions.

In October 2019 the EPN Analysis Centres Workshop was organized to discuss the topics relevant for GNSS data analysis within EPN. It was decided that ACs processing Galileo observations should switch from CODE IGS MGEX products (since November 2019 not consistent with the IGS14 framework) to CODE rapid products. Also, it was demonstrated by CODE AC that using chamber calibrations for Galileo may produce bias in station heights. It was therefore decided, that EPN CB will for the time being not include in the EPN ANTEX file the corrections for systems other than GPS or GLONASS for new individual receiver calibrations provided to EPN.

Since week 2106 (May 17, 2020) all EPN combined solutions have been aligned to the new IGS reference frame – IGb14, the updated version of the previously used IGS14. The IGb14 reference frame contains 15 more EPN reference stations (49 stations in total). After the switch, a slightly better agreement of EPN combined solutions with the IGS reference frame was observed, especially for the vertical component.

The ASI AC (Centro di Geodesia Spaziale G. Colombo, Italy) prepared test solutions using the new software - GipsyX, based on observations of three GNSS (GPS, GLONASS, Galileo). The new solutions have been tested by the ACC and showed good agreement with the combined solution. In January 2021, the solutions computed using GipsyX replaced the former ASI solutions (GPS-only) computed with the GIPSY-OASIS II software.

EUREF Reference Frame Product

EUREF releases each 15 weeks an update of EUREF Reference Frame Product in the latest ITRS/ ETRS89 realization (Bruyninx and Legrand, 2019, Legrand, 2021). Since May 2020, it is expressed in IGb14. The product is available from

https://epncb.oma.be/_productsservices/coordinates/,
ftp://epncb.eu/pub/product/cumulative/

and it consists of positions and velocities of EPN stations as well as a discontinuity list, and associated residual position time series. The EUREF Reference Frame Product agrees with the global IGb14 frame at the sub-mm, resp. 2 mm level for the horizontal and vertical positions and resp. at the 0.1mm/yr and 0.2 mm/yr for the horizontal and vertical velocities.

Not all stations in the EUREF reference frame product are suitable reference stations and therefore EUREF provides a new on-line web tool for assessing the suitability of EPN stations as reference stations (*http://epncb.oma.be/_productsservices/ReferenceFrame/*, Legrand and Bruyninx, 2021). It provides, for a specific input observation period, a restricted list of EPN stations which users can visualize on a map and interactively select the most suitable EPN reference stations to be included in their GNSS network processing. The web tool is based on a station categorization and also includes additional information and plots (position and velocity discontinuities, collocated stations, detrended position time series, selection criteria values (see Figure 1.3a.2), and velocity variability). Following the development of this tool, EUREF also revisited its “Guidelines for EUREF densifications” (Legrand et al., 2021).

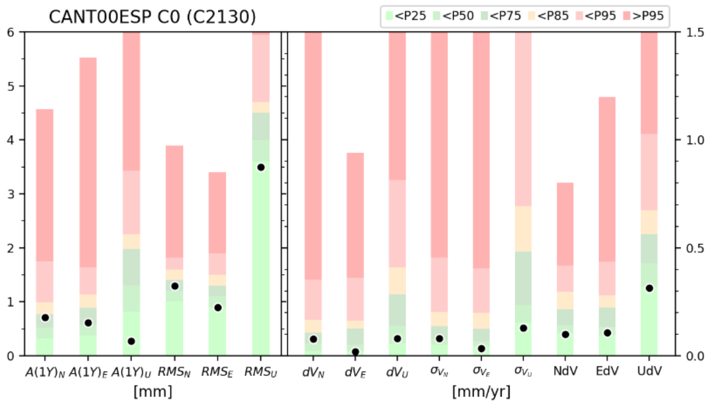


Figure 1.3a.2: Values of the criteria used to define the station categories. Example of the station CANT00ESP.

EPN Troposphere Product

For 341 EPN stations, Zenith Total Delay (ZTD) parameters and horizontal gradients were estimated by the 16 ACs and combined by the Troposphere Coordinator. In 2020, the conversion of the combined ZTD estimates to Integrated Water Vapour (IWV) has been implemented using the necessary auxiliary information, surface air pressure and weighted mean temperature of the atmosphere, from ECMWF operational products provided by the Technical University of Vienna. IWV has been tested against the Nevada Geodetic Laboratory (NGL) IWV estimates. For 2019 and 270 EPN stations the IVW bias ranges from -0,96 kg/m^2 to 0.41 kg/m^2 while the standard deviations are in the order of 0.4 kg/m^2 with maximum / minimum values of 0.91 kg/m^2 and 0.21 kg/m^2. Starting from 2021, the dissemination of the combined

ZTD along with the derived IWV in SINEX_TRO v2.0 format is planned (Pacione and Dousa, 2019).

WG EPN Densification

The EPN Densification (EPND) WG is integrating the available national permanent GNSS networks on the product level. Daily/weekly position SINEX solutions from 28 EPND Analysis Centres are harmonized and combined on the weekly level and using the CATREF software a multi-year position/velocity solution is regularly generated. The EPND network consists of more than 3000 stations. A dedicated web portal had been developed to provide detailed information on EPND and allow access to the combination results (*https://epnd.sgo-penc.hu*). EPND is in close cooperation with EPOS, where the results are used for the generation of the European strain rate map (*https://doi.org/10.23701/sr.0001*) and EPND is also contributing to EGMS (European Ground Motion Service) providing reference for the InSAR analysis.

WG European Dense Velocities

Complementary to the EPN Densification, EUREF introduced a WG on dense velocities. The velocity estimates in ETRF2000, derived by currently 30 contributors, are the direct input to the generation process of a dense velocity field for Europe. In addition to results from GNSS permanent networks, densified solutions stemming from GNSS campaigns, InSAR or levelling are also included. In some countries, as e.g. in the Nordic countries, velocity models are already in use. They can be integrated to indicate possible differences between modelled and observed velocities. Also the results of the EPN Densification project are included. The alignment of the geodetic datum of each input is controlled by overlapping stations. More than 6000 individual station velocities are available for Europe. The description and detailed results are available on (*http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html*).

WG Deformation models

The precise knowledge of the crustal deformations within the EUREF area of interest is identified to be of vital importance from scientific perspective, for reference frame handling, and possibly as a tool for georeferencing of seamless ground motion products from InSAR (e.g. EGMS above). A first version of a European velocity model has been developed based on results from EPN Densification and European Dense Velocities (Steffen et al 2019) and the efforts towards a EUREF product continues.

European Vertical reference System (EVRS)

Since the last reporting period, the levelling data of Ukraine and North Macedonia have been added to the United European levelling network (UELN). Therefore, the network contains now the levelling data of 30 European countries. Furthermore, the measurements of Belgium, Bulgaria (partly), Czech Republic (partly), Italy and Slovenia have been updated. Since the release of EVRF2007, the UELN contains new data in 15 countries (Figure. 1.3a.3).

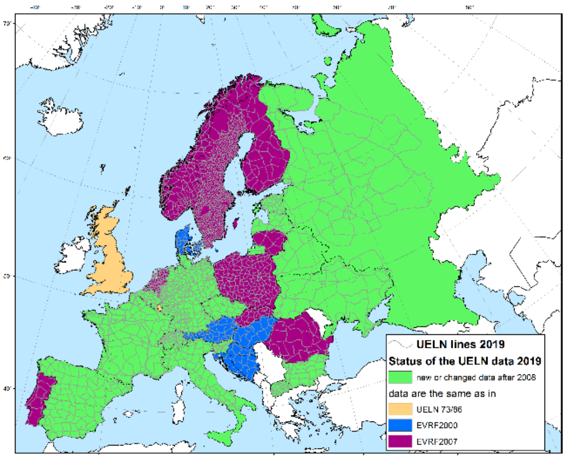


Figure 1.3a.3: UELN lines 2019.

Using these data, a new realization of EVRS has been calculated, which is named EVRF2019. Figure 1.3a.4 shows the differences to EVRF2007. The datum of EVRF2019 is realized by 12 datum points with their heights of the EVRF2007 adjustment. The measurements have been reduced to the epoch 2000 using the model of the land uplift for Fennoscandia and the Baltic region NKG2016LU_lev (Vestøl et al 2016) in Denmark, Sweden, Norway, Finland, Estonia, Latvia, Lithuania, Russia, Belarus and a velocity model for Switzerland. The heights of EVRF2019 are in the zero tidal system, according to IAG resolution No.16 adopted in Hamburg 1983 (Mäkinen, Ihde 2009). Additionally, the results of EVRF2019 have been provided in the mean-tide system – together with the recommendation to use these heights for tasks of oceanography as well as for clock rates. Furthermore, mean-tide heights can be used in the future for comparison with heights in the International Height System IHRS.

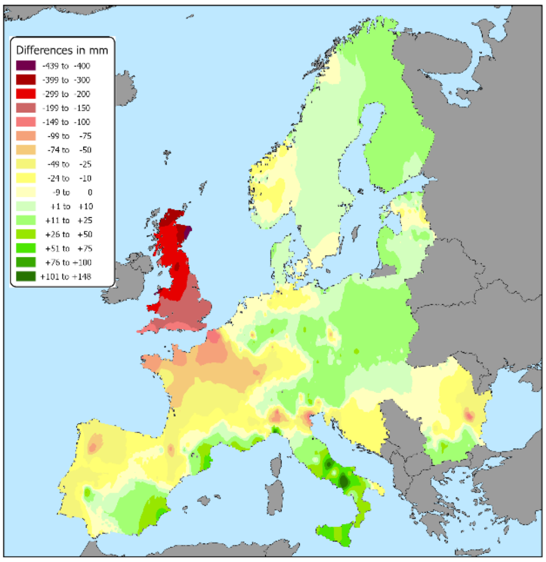


Figure 1.3a.4: Differences EVRF2019-EVRF2007

The mean value of the standard deviation of the adjusted heights is 19 mm. The accuracy of the heights varies in the individual countries between 7 mm and 47 mm. The heights of EVRF2019 are available at: *https://evrs.bkg.bund.de/Subsites/EVRS/EN/EVRF2019/evrf2019.html*. Transformation grids between national European vertical reference frames and EVRF2019 are available at *http://www.crs-geo.eu/*.

Organised Meetings

EUREF Governing Board meetings:

- October 15, 2019, in Warsaw, Poland, hosted by the Warsaw University of Technology
- February 26-27, 2020, in Munich, Germany, hosted by the Bavarian Academy of Sciences and Humanities
- May 28, 2020, virtual
- November 9 and 19, 2020, virtual
- February 16, March 2, 2021, virtual
- May 4 and 7, 2021, virtual

EUREF Annual Symposia:

- May 26-28, 2021 on-line from Ljubljana, Slovenia, (panned) (approx. 100 registered participants) EUREF Analysis Workshop:
- October 16-17, 2019 Warsaw, Poland (approx. 30 participants)

Publications

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E. (2019). GNSS metadata and data validation in the EUREF Permanent Network. GPS Solut 23:106, https://doi.org/10.1007/s10291-019-0880-9

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2019). EUREF Permanent Network. *IGS Technical Report 2018*, eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 95–106. https://doi.org/10.7892/boris.130408

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2020). EUREF Permanent Network. *IGS Technical Report 2019*, eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 111–124. https://doi.org/10.7892/boris.144003

Bruyninx, C., Fabian, A., Legrand, J., and Miglio A. (2020). GNSS Station Metadata Revisited in Response to Evolving Needs, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18634, https://doi.org/10.5194/egusphere-egu2020-18634

Fabian A., Bruyninx C., Legrand J., Miglio A., (2020). GNSS data quality check in the EPN network, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18634, https://doi.org/10.5194/egusphere-egu2020-21489, 2020

Kenyeres A., Bellet J.G., Bruyninx C., Caporali A., De Doncker F., Droscak B., Duret A., Franke P., Georgiev I., Bingley R., Huisman L., Jivall L., Khoda O., Kollo K., Kurt A.I., Lahtinen S., Legrand J., Magyar B., Mesmaker D., Morozova K., Nagl J. , Ozdemir S., Papanikolaouo X., Parseulinas E., Stangl G., Tangen O.B., Valdes M., Ryczywolski M., Zurutuza J., Weber M. (2019). Regional integration of long-term national dense GNSS network solutions. GPS Solut, 23:122, https://doi.org/10.1007/s10291-019-0902-7

Legrand J. (2021). EPN multi-year position and velocity solution C2130, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2130

Legrand J. and Bruyninx C. (2021). Station Classification and Reference Station Selection, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14190, https://doi.org/10.5194/egusphere-egu21-14190

Legrand J., Bruyninx C., Altamimi Z., Caporali A., Kenyeres A., Lidberg M. (2021). Guidelines for EUREF Densifications, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-Guidelines-DENS

Lidberg M., Söhne W., Kollo K. (2021). Advancing the geodetic infrastructure in Europe through EUREF, FIG Working Week 2021, 20-25 June

Mäkinen J. and Ihde, J. (2009).The Permanent Tide in Height Systems. In: Sideris M.G. (eds) Observing our Changing Earth. International Association of Geodesy Symposia, vol 133. Springer, Berlin, Heidelberg

Pacione R. and Dousa J. (2019). SINEX-TRO V2.00 format description, COST Action 1206 Final Action Dissemination Report, eds. J. Jones, G. Guerova, J. Douša, G. Dick, S. de Haan, E. Pottiaux, O. Bock, R. Pacione, R. van Malderen. 537-563

Vestøl O., Ågren J., Steffen H., Kierulf H., Lidberg M., Oja T., Rüdja A., Kall T., Saaranen V., Engsager K., Jepsen C., Liepins I., Paršeliūnas E., Tarasov L. (2016): NKG2016LU, an improved postglacial land uplift model over the Nordic-Baltic region. NKG meeting WG of Geoid and Height Systems. June 2016

Steffen R, Legrand J., Steffen H., Lidberg M., Kenyeres A., Brockmann E., Lutz S. (2019). Towards a Deformation Model for Europe using least square collocation, Presentation at the EUREF Symposia in Tallinn 22-24 May 2019. http://www.euref.eu/symposia/2019Tallinn/01-04-Steffen.pdf

Söhne W. (2019). EPN Real-Time Special Project – Status Report. Presented at the EUREF Symposium 2019.

Sub-Commission 1.3b: South and Central America

Chair: José Antonio Tarrío (Chile)
Vice-Chair: Demián Gomez (US)

Introduction and Structure

SIRGAS is the Geocentric Reference System for the Americas, in Spanish (Sistema de Referencia Geocéntrico para las Américas). Its definition corresponds to the International Terrestrial Reference System (ITRS), and it is realised by regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes the definition and realisation of a vertical reference system based on ellipsoidal heights as geometrical component and geopotential numbers (referred to a global conventional W_0 value) as physical component.

SIRGAS is a member of the Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and corresponds to a Working Group of the Cartography Commission of the PAIGH (Pan-American Institute for Geography and History). The Executive Committee manages the administrative issues, which depends on the Directing Council's main body. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed of one representative of each member country, one of IAG and one of PAIGH, it is also in charge of communicating the SIRGAS recommendations to the national bodies responsible for the local geodetic reference systems. The Working Groups coordinate the scientific and technical activities in close cooperation with the Scientific Council and the representatives of IAG and PAIGH.

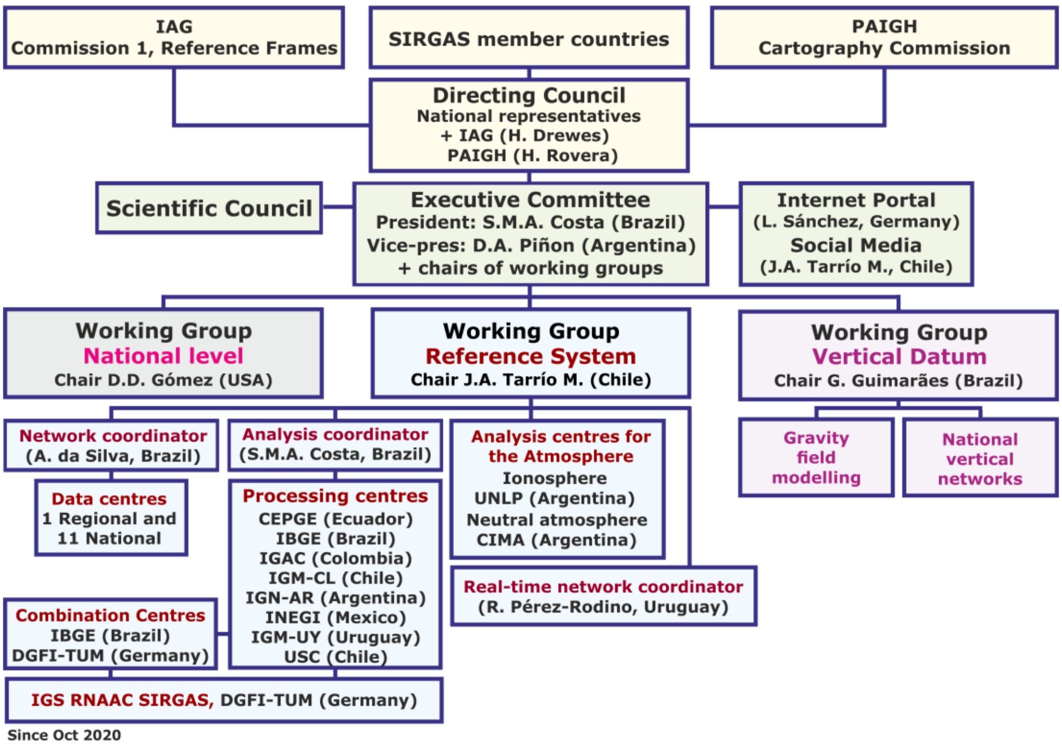


Figure 1.3b.1: Operational structure of SIRGAS

Members

SIRGAS Executive committee

- *Sonia María Alves Costa , Chair (Brasil).*
- *Diego Alejandro Piñón, Vice-Chair (Argentina)*
- *José Antonio Tarrío, SIRGAS-WG1 Chair (Chile)*
- *Demián Gomez, SIRGAS-WG2 Chair (US)*
- *Gabriel do Nascimento Guimarães, SIRGAS-WG3 Chair (Brazil)*

SIRGAS Directing council

- *Hermann Drewes, Representative of IAG*
- *Hector Carlos Rovera Di Landro, Representative of PAIGH*
- *Juan Francisco Moirano; Demian Gómez (Argentina)*
- *Arturo Echalar Rivera; Mario Sandoval Nava (Bolivia)*
- *Luiz Paulo Souto Fortes; Sonia Maria Alves Costa (Brazil)*
- *Juan Pedro Harms; Sergio Rozas Bornes (Chile)*
- *Jose Ricardo Guevara Lima; Francisco Javier Mora Torres (Colombia)*
- *Max Lobo Hernández; Álvaro Álvarez Calderón (Costa Rica)*
- *Alejandro Jiménez Reyes; José Leandro Santos (Dominican Republic)*
- *Edgar Fernando Parra Cárdenas; Jose Luis Carrión (Ecuador)*
- *Carlos Enrique Figueroa; Wilfredo Amaya Zelaya (El Salvador)*
- *Óscar Cruz Ramos; Fernando Oroxan Sandoval (Guatemala)*
- *Rene Duesbury; Hilton Cheong (Guyana)*
- *Bruno Garayt; Alain Harmel (French Guyana)*
- *Luis Alberto Cruz (Honduras)*
- *Enrique Muñoz Goncen, Francisco Medina (Mexico)*
- *Wilmer Medrano Silva, Ramón Aviles Aburto (Nicaragua)*
- *Javier Cornejo, Melquiades Dominguez (Panama)*
- *Daniel Ariar, Joel Roque Trinidad (Paraguay)*
- *Julio Enrique Llanos Alberca, Julio Sáenz Acuña (Peru)*
- *Daniel Piriz (Uruguay)*
- *Dana J. Caccamise II, Daniel R. Roman (USA)*
- *Jose Napoleón Hernández, Melvin Jesús Hoyer Romero (Venezuela)*

SIRGAS Scientific Council

- *Luiz Paulo Souto Fortes (Brazil)*
- *Laura Sanchez (Germany)*
- *Claudio Brunini (Argentina)*
- *María Virginia Mackern (Argentina)*

Activities during the period 2019-2021

During the period 2019-2021, the following achievements associated with maintaining the geodetic reference frame, SIRGAS, were obtained:

(a) Geocentric Reference Frame achievements

Network Processing

In 2020, SIRGAS incorporated 27 new GNSS stations, reaching close to 400 continuous stations (SIRGAS-CON) by the end of the year, of which 67 are included in the International

GNSS Service (IGS) solution. This network realises the region's geodetic reference frame and is consistent with the International Terrestrial Reference Frame (ITRF). The network is operated and processed through the collaborative and continuous work of 13 data centres, 9 official processing centres, and two combination centres. Since august 2020 the Instituto Geográfico Nacional of Perú (IGN-PER) acts as a SIRGAS Experimental Processing Centre. With this new experimental processing centre, SIRGAS is approaching the goal of having a scientific GNSS processing centre in each region's country. Additionally, SIRGAS tropospheric products (tropospheric Zenith Path Delays (ZPD) with an hourly sampling rate) are computed by the SIRGAS Analysis Centre for the Neutral Atmosphere (CIMA), which is operated by the National University of Cuyo and UNCuyo / "Juan Agustín Maza" University.

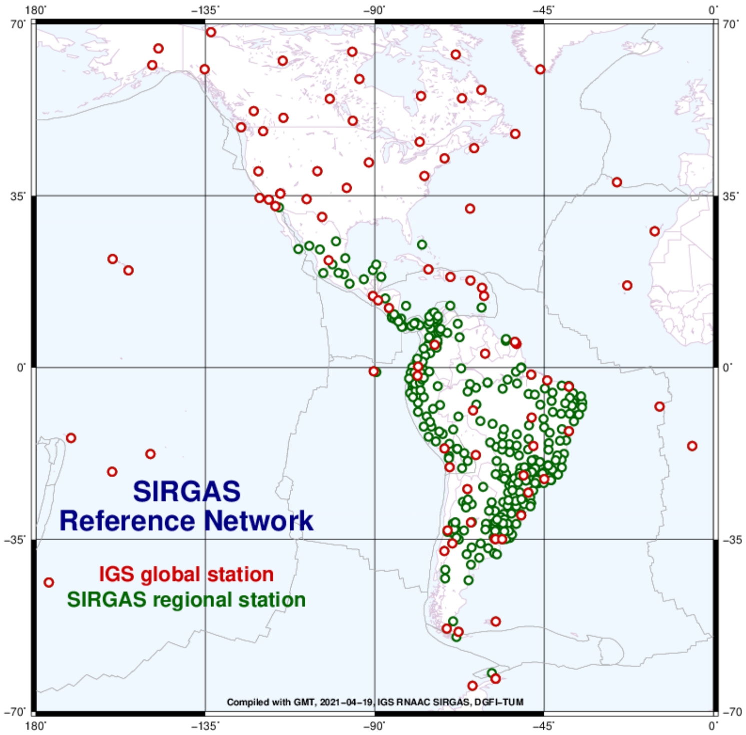


Figure 1.3b.2: Current SIRGAS Reference Network with expansion to North-America

Reprocessing in ITRF2014

To ensure the reliability and stability of the SIRGAS reference frame, in November 2018, the IGS RNAAC SIRGAS (DGFI-TUM) started the reprocessing of the historical data of SIRGAS (from January 2000 to July 2020) using IGS14 (ITRF2014) as the reference frame with antenna model igs14.atx and satellite orbits and clocks in IGS14 set by the Jet Propulsion Laboratory (JPL) of NASA.

Together with the 500 (approximately) SIRGAS stations, IGS global stations co-located with VLBI and SLR were added to support the SIRGAS initiative involving SLR data in the Implementation of the reference frame. This initiative started with a workshop at the SIRGAS2017 Symposium (Mendoza, Argentina) and continued making progress at a second SLR workshop at the SIRGAS2019 Symposium (Rio de Janeiro, Brazil). Further details in Sánchez L. (2020). SIRGAS Regional Network Associate Analysis Centre Technical Report 2019. Villiger A., Dach R. (eds.) International GNSS Service: Technical Report 2019, 125-136, 10.7892/BORIS.144003.

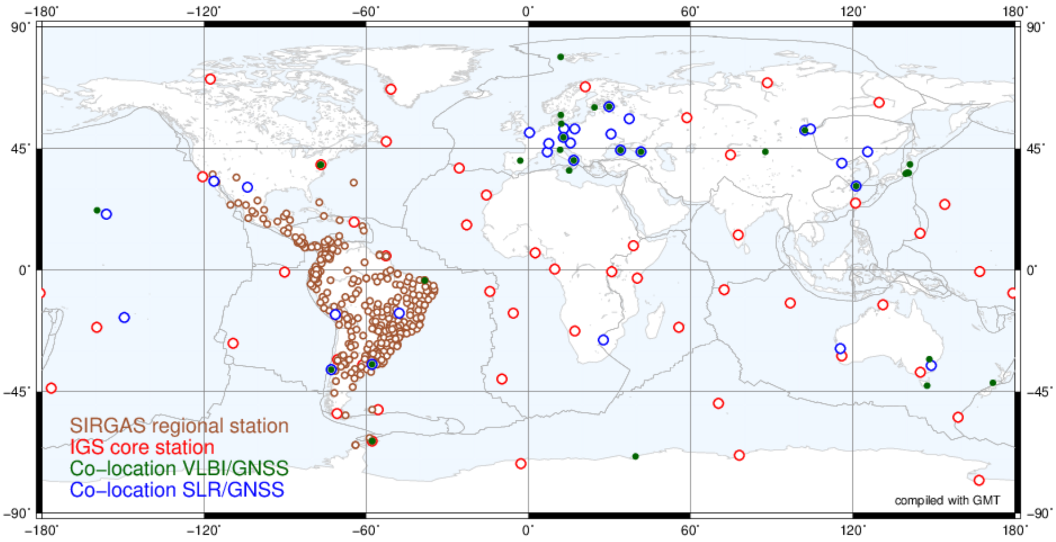


Figure 1.3b.3: GNSS network configuration for the combination of GNSS, SLR, and VLBI normal equations in the realisation of a geocentric geodetic datum in the regional reference frame SIRGAS. VLBI/GNSS (green dots) and SLR/GNSS (blue circles) co-located stations are necessary for the normal equation combination. IGS core stations (red circles) are necessary for a high-quality GNSS data processing

SIRGAS stations included in ITRF2020

The IGS started, in mid-2019, the third reprocessing of its network (1994 - 2020), applying the updated standards and conventions for determining a new version of the ITRF (ITRF2020). The IGS RNAAC SIRGAS (DGFI-TUM), by mutual agreement with the managers/owners of some SIRGAS stations, proposed to the IGS adding 30 additional SIRGAS stations for the region to have available more reference stations for the calculation of the regional frame. The IGS RNAAC SIRGAS (DGFI-TUM), in agreement with the managers/owners of some SIRGAS stations, proposed to IGS add more than 30 SIRGAS stations to the region has more fiducial stations to calculate the regional frame.

National densifications of SIRGAS

In the 2019-2021 period at the national level, several activities were reported, among which the installation of several GNSS stations in Ecuador and Colombia stand out (Fig. 1.3b.4).

Figure 1.3b.4: New GNSS stations in Ecuador and Colombia

The Instituto Geográfico Militar of Ecuador(ECU), through resolution No. 2019-037-IGM-JUR dated Dec 20, 2019, was resolved to adopt the Geocentric Reference System for the Americas (SIRGAS), in replacement of the PSAD56 Local Reference System, in order to provide support to cartographic and positional work in the country. In addition, 7 conversion parameters were made official for the transformation between systems.

This resolution can be found together with several legal documents generated by the IGM(ECU) through the following link:
http://www.geoportaligm.gob.ec/wordpress/?page_id=511

The Instituto Geográfico Agustin Codazzi in Colombia(IGA) densified its network in 15 stations to improve the geodetic infrastructure and the service provided to the community in general.

The Servicio Nacional de Geología y Minería de Chile, together with the geodetic analysis and processing centre of the University of Santiago, carried out the calculations and studies for the change from classical to modern datum (SIRGAS) in its mining cadastre. The above generates the first framework non-static reference for Chile; its name is REDGEOMIN(Red Geodésica para Minería) with EPSG CODE equal to 9694.

(b) Vertical Reference Frame achievements

Advances in IHRF

Concerning the SIRGAS Vertical Reference System (SVRS), there has been substantial progress made involving the incorporation of physical heights, the connection to the geometric components of SIRGAS, the integration of the national vertical networks, their links to the value of the reference potential W_0 of the IHRS, the definition for a specific epoch and the consistent connection with the ITRF.

In the context of the integration to the IHRS/IHRF, SIRGAS has proposed a set of 19 stations in Latin America and the Caribbean and has made progress in implementing these stations.

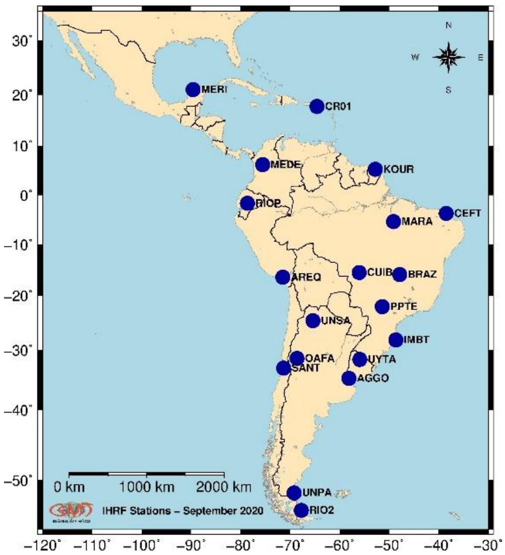


Figure 1.3b.5: Proposal for IHRF stations in the region

A diagnosis has been started in the IHRF stations from the calculation of the potential values using the global gravity models (comparison with the XGM2019 model). This diagnosis is essential to consider which station(s) should be concentrated efforts in terms of studies and improvements of the gravimetric distribution.

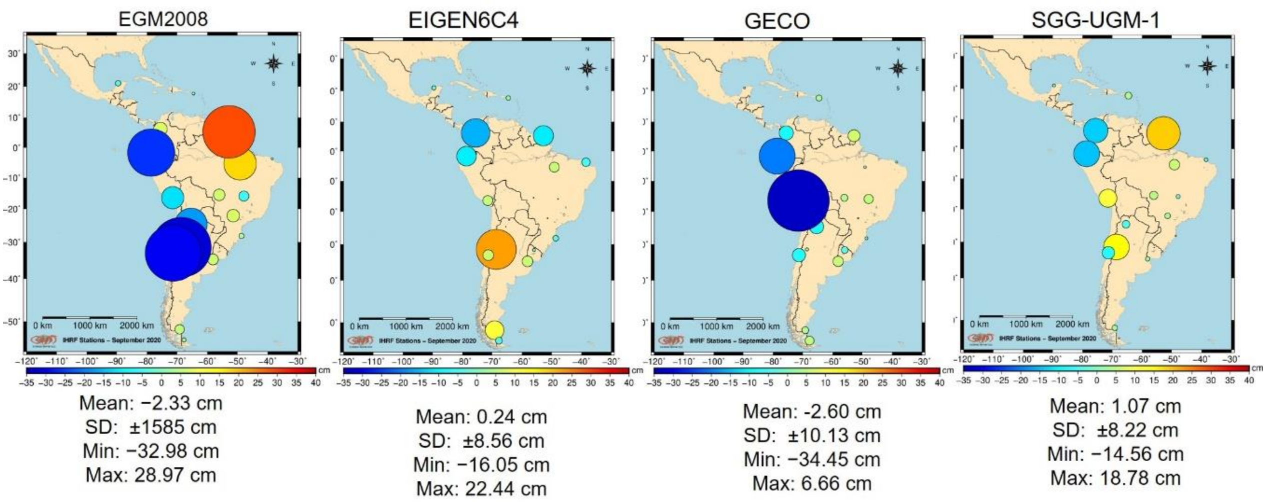


Figure 1.3b.6: Comparison of GGMs with XGM2019

Besides that, in 2021, the SIRGAS WG-III has been started the computation of geopotential values from the geoid or quasi geoid models available in the continent. Finally, the SIRGAS WG-III has been carrying out a scientific project together with the Technical University of Munich (TUM) called *Contributions of high-resolution gravity models in Latin America*. The goal of the project is to assess the geoid models and the levelling/GNSS stations available in Latin America using gravity field models of high resolution and of combining satellites to contribute to the potential calculation at the IHRF stations.

(c) Main contributions of the Centre for neutral atmosphere, CIMA

Tropospheric Products in the GNSS SIRGAS Network

Within the SIRGAS Continuously Operating Network (SIRGAS-CON) weekly processing, Latin-American Analysis Centres operationally estimate tropospheric Zenith Total Delays (ZTD) with an hourly sampling rate. These ZTD are the input data for the weekly SIRGAS combined tropospheric products, computed by the Analysis Centre for the Neutral Atmosphere (CIMA). The Internal precision of SIRGAS final ZTDs is 1mm. They are generated and available in daily SINEX TRO files since January 2014, with a latency of 30 days. They can be downloaded from ftp://ftp.sirgas.org/pub/gps/SIRGAS-ZPD/.

ZTD_{SIRGAS} validation concerning IGS products

A comparison was made between the tropospheric products of SIRGAS (ZTD_{SIR}) and the corresponding ones of the IGS (ZTD_{IGS}) in 60 stations (
Figure 1.3b.), for a period of 7 years (2014 to 2020). The differences between both parameters (ZTD_{IGS}-ZTD_{SIR}) were calculated for each epoch, and the mean values of such differences (bias) were calculated (Figure 1.3b.8). The Mean Bias resulted 0.76 mm with 6.6 mm of mean RMS.

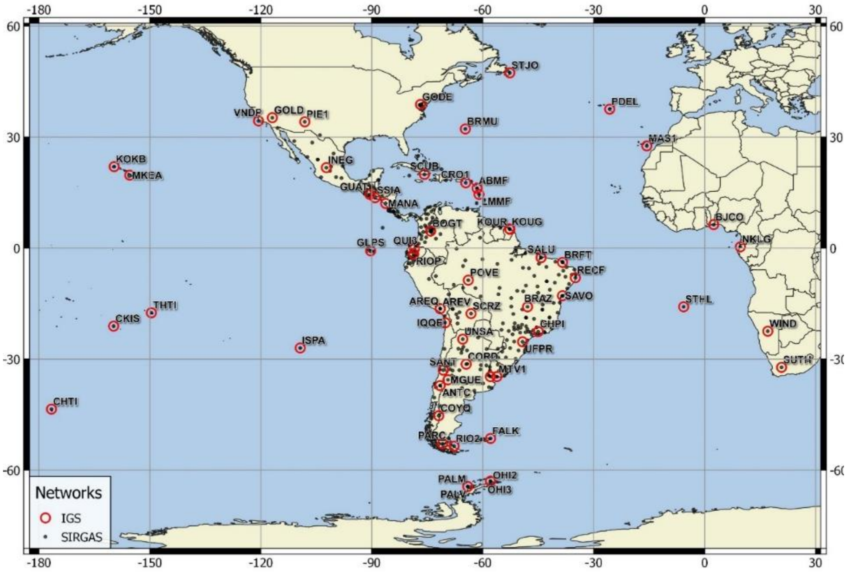


Figure 1.3b.7: $GNSS_{SIR}$ stations / IGS stations (distributed in different regions)

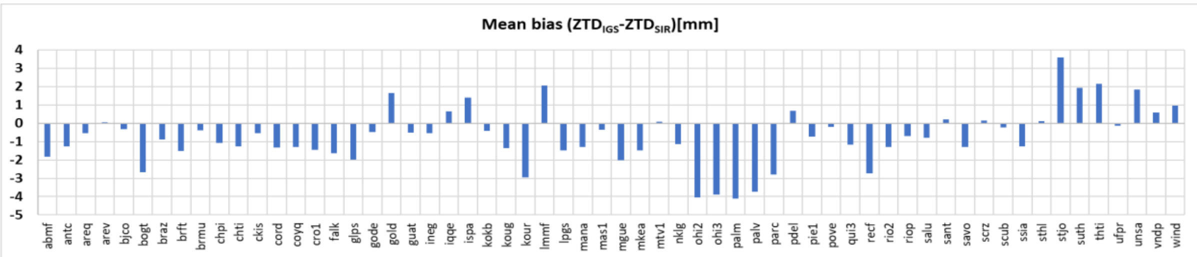


Figure 1.3b.8: Mean bias (ZTD_{IGS}-ZTD_{SIR}) for 60 GNSSSIR stations/IGS stations over a period of 7 years

ZTD_{SIRGAS} validation concerning Radiosonde data

Another comparison was made between the ZTD_{SIR} and the corresponding calculated from the Radiosonde data (ZTD_{Rs}). 42 $GNSS_{SIR}$ stations located within a maximum radius of 30 km from a radiosonde station were selected. This comparison could be performed for the 00 and 12 hrs UTC records due to limited availability of radiosonde records. The mean value and standard deviation were calculated as statistical indicators for the 7 years sampled (Figure 1.3b.9). The mean bias resulted - 8.6 mm with a mean standard deviation of ± 11.4 mm, Mackern et al. (2021).

These results show that the ZTDs estimated at the SIRGAS-CON stations, distributed from South America, Central America, and the Caribbean region, are consistent throughout the region and provide reliable time series of troposphere parameters, which can be used as a reference in future research.

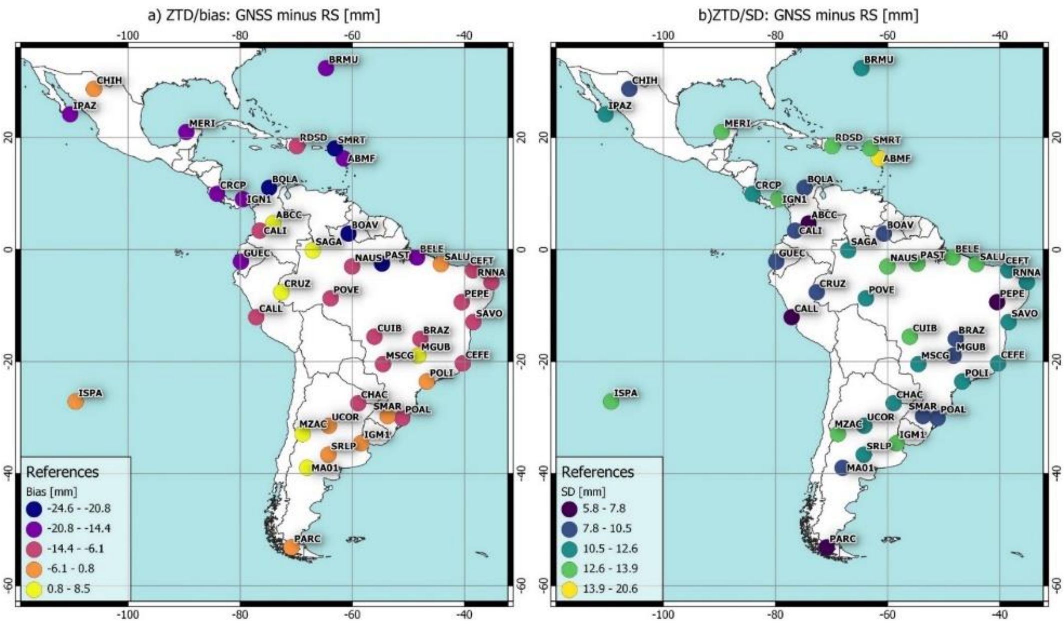


Figure 1.3b.9: a) Mean bias (ZTD_{SIR}-ZTD_{RS}), b) Mean Standard deviation for 42 $GNSS_{SIR}$ stations/RS over period of 7 years

Time series of ZTD_{SIRGAS} parameters

The ZTD final SIRGAS products are available from 2014, with an hourly interval, with a latency of 28 days. There is a corresponding ZTD time series, from 2014 (or since its incorporation) to date (Figure 1.3b.10), for each of the SIRGAS-CON stations,

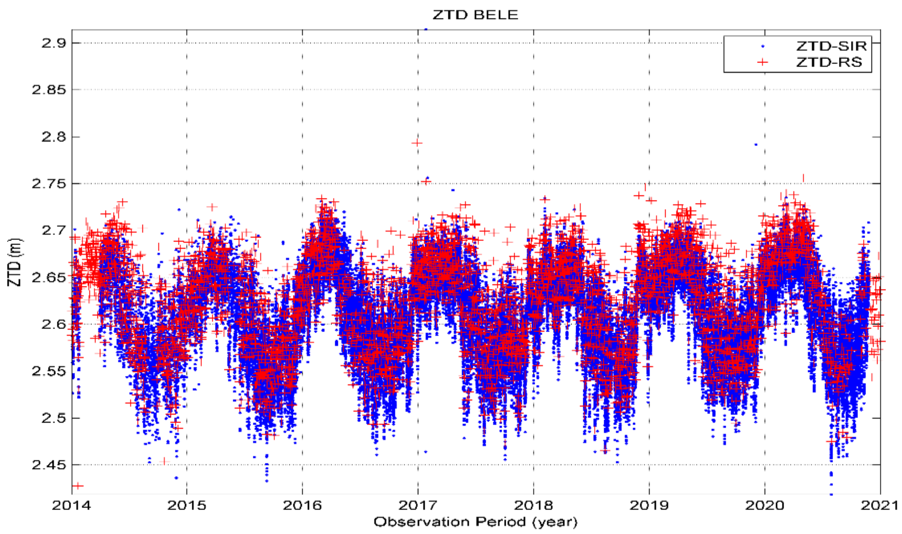


Figure 1.3b.10: ZTD time series (2014-2020) from BELE, Brasil

WG GRFA: "Geodetic Reference Frame for the Americas"

The Authorities of SIRGAS coordinated the development of the Terms of Reference of the new UN: GGIM: America's working group naming "Geodetic Reference Frame for the Americas" (GRFA). These terms were approved through Resolution 2019/6 of the Seventh Session of UN-GGIM: Americas.

Figure 1.3b.11: GRFA working group meeting

The main objectives of the GRFA are:

a) to support the Nations of the Americas so that they respond to the Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) resolution;

b) coordinate the efforts of the Member States to guarantee the sustainability and improvement of the regional geodetic reference frame, acting as a key facilitator of spatial data interoperability, the mitigation of hazards from disasters and sustainable development; and

c) to act as an interface between SIRGAS and the Member States to implement plans that push the development of the regional geodetic infrastructure, the geodetic reference frame of the Americas, and the geodetic capabilities of professional and technical specialists forwards. The Terms of Reference are published in the Spanish and English languages on the UN-GGIM: *http://www.un-ggim-americas.org/assets/modulos/grupoTrabajo.html?grupo=3*.

Organised Meetings

During the period 2019-2021, SIRGAS organised the following meetings:

Symposium SIRGAS2019
The current activities, advances, and new challenges of SIRGAS are reported, discussed, and evaluated in the annual SIRGAS Symposia, which have been held since 1993. This year, thanks to the kind invitation extended by the Brazilian Institute of Geography and Statistics (IBGE) and the Rio de Janeiro State University (UERJ), the SIRGAS 2019 Symposium was held in Rio de Janeiro, Brazil, between Nov 11 and 14, 2019. It was organised with the support of the International Association of Geodesy (IAG) and the Pan-American Institute for Geography and History (PAIGH). In the frame of this Symposium, two additional activities were programmed:

1. "GGOS Days 2019" (Global Geodetic Observing System) was held simultaneously in the same venue (Figure 1.3b.12), and a joint session between the SIRGAS community and GGOS expert representatives was developed on Nov 12 and;
2. The 2nd SLR (Satellite Laser Ranging) Workshop in Latin America took place from Nov 6 to 8, 2019. The main objective was to continue the integration between SIRGAS community (professionals and scientists) with the group of SLR experts. This effort was the continuation of actions initiated during the 1rst SLR SIRGAS workshop held in 2017 in Mendoza, Argentina; which aim was the promotion of the specialisation in the SLR technique, as well as data processing and its combination with GNSS (Global Navigation Satellite System) in the Latin American and international geodetic community context.

Figure 1.3b.12: Participants to GGOS Days 2019

Figure 1.3b.14: Participants of the SIRGAS Symposium 2019. Source: IBGE Rio de Janeiro, Brazil, Nov 11 to 14, 2019

The SIRGAS Symposium 2019 was attended by 164 participants (**Error! Reference source not found.**) from 16 countries (Argentina, Austria, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Germany, Mexico, Panama, Spain, United States, Uruguay and Venezuela). The main topics addressed during the Symposium included SLR in Latin America, colocation techniques (4 presentations); Studies of the Atmosphere and analysis of the Earth System based on SIRGAS Infrastructure (18 presentations); SIRGAS-GGOS Session (18 presentations); the improvement and maintenance of the SIRGAS reference frame (12 presentations); practical applications aimed at the adoption of SIRGAS at the sub-regional and national level and Infrastructure SIRGAS in Real-Time (12 presentations); advances in SIRGAS Unified Vertical Reference System (9 presentations); gravity and geoid (12 presentations); and general reports (4 presentations). In total, 75 oral contributions and 18 posters were presented.

During the meeting of Directing Council held on Nov 13 2019, the results of the elections for president and vice president were reported, who formally assumed at the closing ceremony of the Symposium (Fig. 1.3b.14). Other issues discussed during this meeting will be available on the SIRGAS webpage, section "SIRGAS: Resolutions."

Figure 1.3b.14: New Executive Committee: Sonia Costa from IBGE (Instituto Brasileiro de Geografia e Estatística), Brazil (president) and Diego Piñón from IGN (Instituto Geográfico Nacional), Argentina (vice president)

Workshop SLR SIRGAS 2019

The 2nd SLR Workshop in Latin America was attended by 25 participants (Fig. 1.3b.15) from 8 countries (Argentina, Brazil, Colombia, Costa Rica, Ecuador, Peru, Uruguay, and Venezuela). It was organised as an activity of the SIRGAS Working Group I. On this occasion, the instructor was Dr. Daniela Thaller from the BKG, Germany (Fig.5). The SIRGAS Executive Committee thanks the BKG for the possibility of Dr. Daniela Thaller qualifying SIRGAS community in the SLR data processing and analysis.

Figure 1.3b.15: Participants of the 2nd SIRGAS SLR Workshop, IBGE, Rio de Janeiro, Brazil, November 6 to 8, 2019

Figure 1.3b.16: Dr. Daniela Thaller teaching SLR data processing with Bernese software.

Symposium SIRGAS2020

Considering that all in-person activities in 2020 were cancelled due to the COVID-19 pandemic, SIRGAS promoted Webinars from May to September, 2020 with subjects related to geodetic activities in the region. The records and presentations from all Webinars are available on SIRGAS homepage (www.sirgas.org).

For October, SIRGAS organised a series of Webinars in the place of the annual SIRGAS Symposium, every Friday at 15 UTC. Each Webinar has 3 presentations with topics related to:

- Atmosphere studies and the Earth System analysis (Oct 2).
- SIRGAS reference frame's development and maintenance (Oct 9).

- Practical applications oriented to the adoption of SIRGAS at a sub-regional and national level (Oct 16).
- Height Systems (Oct 23).
- Gravimetry and geoid (Oct 30).

Figure 1.3b.17: SIRGAS 2020 Program

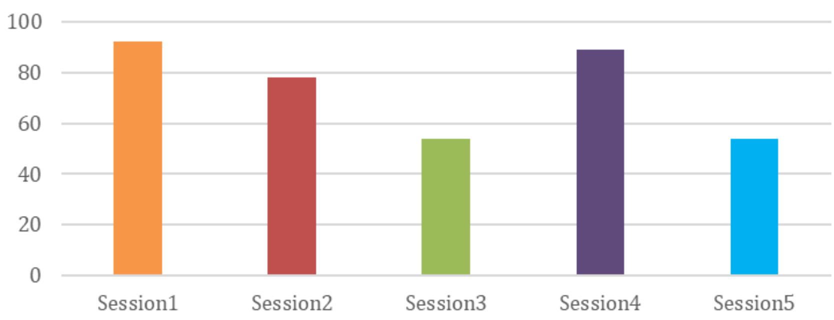


Figure 1.3b.18: Number of participants to SIRGAS2020 Symposium

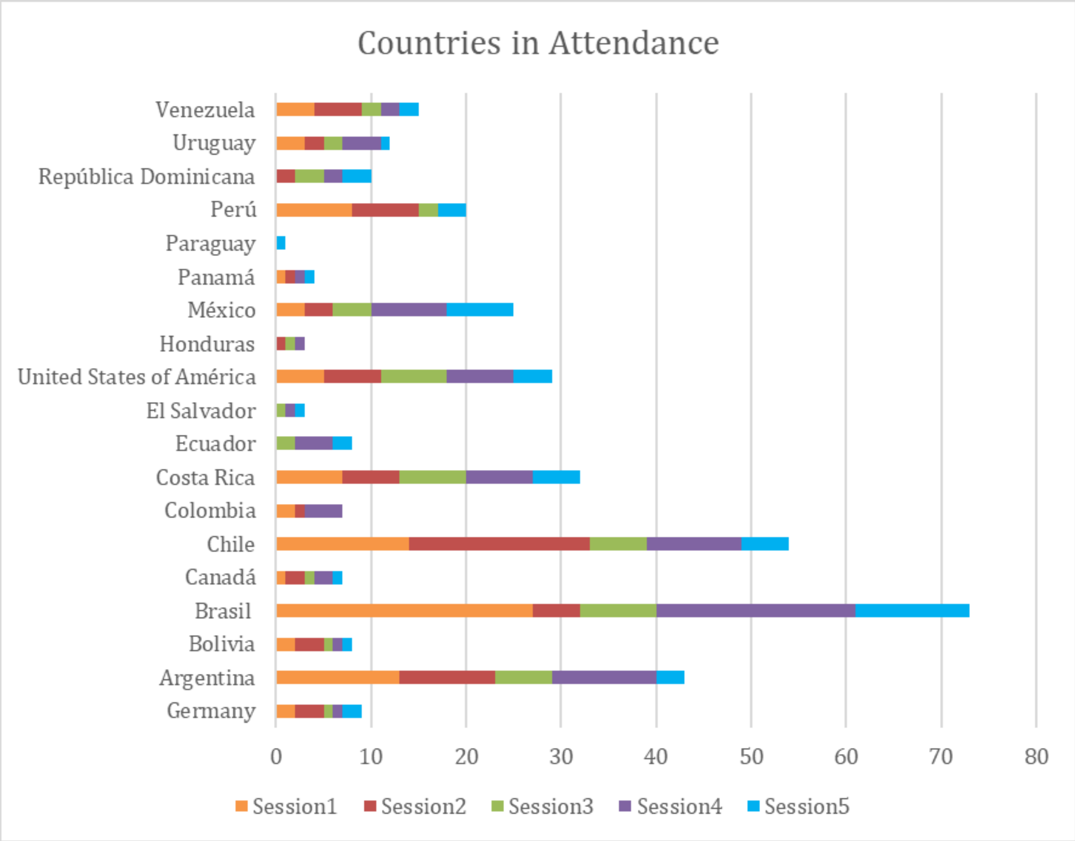


Figure 1.3b.19: Attendees for each country at SIRGAS2000 symposium

The Directing Council and Working Groups meeting were organised in the week between 16 to Nov 19 at 2020. The new SIRGAS Statute was approved during the Directing Council meeting, with the approval of all SIRGAS members, including all countries in North America. During the Working Groups meetings were presented the new structures and coordinators of GT II and GT III and future work for 2021.

Figure 1.3b.20: Working Group III meeting

The International Workshop for the Implementation of the Global Geodetic Reference Frame
The International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America was held in Buenos Aires, Argentina, from Sep 16 to 20, 2019. This workshop is a capacity building activity of the project "Implementation of the United Nations' Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America" of the International Union of Geodesy and Geophysics (IUGG) within the special grants program to celebrate in 2019 the centennial year of the IUGG foundation. The International Association of Geodesy (IAG) is the primary applicant of this project, and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the IUGG National Committees of Argentina, Brazil, Chile, Colombia, and Costa Rica supported it. In addition to the IUGG, IAG, and IASPEI support, the workshop counted on the sponsorship of the International Committee on Global Navigation Satellite Systems (ICG) of the United Nations Office for Outer Space Affairs (UNOOSA). Twenty-eight travel awards for colleagues from fourteen Latin American countries were covered with the money granted by the IUGG. ICG-UNOOSA provided six flight tickets for colleagues from Colombia, Peru, Chile, Brazil, Costa Rica, and Ecuador. The Instituto Geográfico Nacional (IGN) of Argentina and the Argentine-German Geodetic Observatory (AGGO) organised the logistics needed for the successful realisation of the meeting. The support of IUGG, ICG-UNOOSA, IGN, AGGO and all the experts participating in the workshop is highly appreciated.

In total, 130 participants from 20 countries (Argentina, Australia, Bolivia, Brazil, Chile, China, Colombia, Costa Rica, Dominican Republic, France, Germany, Guatemala, Italy, Mexico, Panama, Paraguay, Peru, United States of America, Uruguay, and Venezuela) attended the workshop. With 52 presentations distributed in eight sessions, the meeting brought together politics, international organisations promoting science, the highest level of expertise in Geodesy worldwide, and regional specialists in Geodesy. Jointly, they could provide the Latin American colleagues responsible for the national geodetic reference frames, the scientific and political arguments to convince policymakers about the necessity of investing in geodetic and geophysical infrastructure in their countries.

Figure 1.3b.21: Participants to the International Workshop for the Implementation of the Global Geodetic Reference Frame (GGRF)

This workshop convened for the first time politics (UN-GGIM, UN-GGIM Subcommittee on Geodesy, GEO, ICG-UNOOSA), international organisations promoting science (ICS, IUGG, IAG, IASPEI, FIG, PAIGH), the highest level of expertise in Geodesy worldwide (IAG, IAG Services, GGOS), and regional specialists in Geodesy (SIRGAS, gravity field modelling, geodetic observatories) to identify appropriate strategies to make real the objectives of the UN-GGRF initiative. The topics presented along the five days and the conclusions/recommendations arising from the discussions surely represent the appropriate start point to face the required activities to advance in the establishment of the GGRF in Latin America. Presentations, a list of participants and conclusions of the workshop are available at *http://www.sirgas.org/en/ggrf/*. Laura Sánchez (Deutsches Geodätsiches Forschungsinstitut Technische Universität München, Germany) and Claudio Brunini (Science Director of AGGO) were in charge of carrying out the event.

Outreach

During the 2019-2021 period, SIRGAS has carried out different outreach events, also has participated in the following international conferences:

2021

Establecimiento de la Red Argentina de Monitoreo Satelital Continuo (RAMSAC). D. Piñón. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS (RMBC): Complexidades e dasafios. A. Silva, G. Mantovani, M.A. de Almeida, N. Moura, S. Costa. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Red SIRGAS-CON en Costa Rica. A. Álvarez. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

REDGEOMIN: Red geodésica para la minería en Chile. J.A. Tarrío, J. Inzunza, F. Isla, M. Caverlotti, G. Jeldres, C. Ferraz, R. Urrutia, J. Ojeda. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Estado del Marco de Referencia SIRGAS: desarrollos recientes y nuevos desafíos. S. Costa, D. Piñón. Escuela Regional "Nuevas Técnicas Geodésicas para América Latina y El Caribe". Abril 6, 2021

Tropospheric products validation in the GNSS SIRGAS Network. M.V. Mackern, M.L. Mateo, M.F. Camisay, P. Rosell, G. Granados. Geodesy for Climate Research, Workshop of Inter-Commission Committee on "Geodesy for Climate Research" of the International Association of Geodesy. March 30, 2021 (video avaliable)

El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF). H. Wziontek, S. Bonvalot, E.D. Antokoletz. Webinar SIRGAS, 2021-03-05. Presentatuon also available in YouTube.

2020

Modelar el movimiento de la superficie terrestre: Velocidades continuas y coordenadas por etapas. H. Drewes, Webinar SIRGAS, agosto 20, 2020. Presentation also available in YouTube.

Procesamiento con NRCan PPP en entorno Windows Desktop. D. Gómez, Webinar SIRGAS, July 22, 2020. Presentation also available in YouTube.

Sistema internacional de Alturas IHRS. L. Sánchez, Webinar SIRGAS, June 25, 2020. Presentation also available in YouTube.

Procesamiento de datos GNSS con software libre, a partir de estaciones SIRGAS. B. Barraza, J.A. Tarrío, Webinar SIRGAS, May 29, 2020. Presentation also available in YouTube.

Actividades y productos de los centros de análisis SIRGAS. J.A. Tarrío, Universidad Santiago de Chile, Santigo de Chile. Webinar SIRGAS, May 14, 2020. Presentation also available in YouTube.

2019

Report from developing countries Americas and Caribbean Region. S. Costa. International Association of Geodesy (IAG) Executive Committee Meeting. San Francisco, USA, Dec 7, 2019

Vinculación del marco de referencia nacional de Argentina con el global, la red continental SIRGAS. M.V. Mackern. XII Congreso Nacional de Agrimensura. Mendoza, Argentina. October 9 - 11, 2019.

SIRGAS: The Geocentric Reference System for the Americas. W. Martínez, M.V. Mackern, V. Cioce, R. Pérez Rodino, S.R.C. de Freitas. Workshop for the Implementation of the GGRF in Latin America. Buenos Aires, Argentina. September 16-20, 2019.

Status of the SIRGAS reference frame: recent developments and new challenges. W. Martínez, M.V. Mackern, H. Drewes, H. Rovera, C. Brunini, L. Sánchez, L.P.S. Fortes, E. Lauría, V. Cioce, R. Pérez, S.R.C. de Freitas, S.M.A. Costa, M. Hoyer, R.T. Luz, R. Barriga, W. Subiza. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

Tropospheric products from high-level GNSS processing in Latin America. M.V. Mackern, M.L. Mateo, M.F. Camisay, P.V. Morichetti. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

SIRGAS Social Media

SIRGAS has different accounts in social media:

- Facebook: https://www.facebook.com/SirgasAmericas/
- Twitter: https://twitter.com/SirgasAmericas/
- LinkedIn: https://www.linkedin.com/company/SirgasAmericas/
- a YouTube channel https://www.youtube.com/channel/UCHgFJJ6PPust08GKIlBtUAA

Publications

Sánchez L. (2019). SIRGAS Regional Network Associate Analysis Centre Technical Report 2018. Villiger A., Dach R. (Eds.), International GNSS Service Technical Report 2018 (IGS Annual Report), 109 - 125, 10.7892/boris.130408

Camisay M.F., Rivera J., Mateo, M.L., Morichetti, P.V., Mackern, M.V. (2020). Estimation of integrated water vapor derived from Global Navigation Satellite System observations over Central-Western Argentina (2015-2018). Validation and usefulness for the understanding of regional precipitation events. Journal of Atmospheric and Solar-Terrestrial Physics. 197. 105143, https://doi.org/10.1016/j.jastp.2019.105143

Drewes H. and Sánchez L. (2020). Velocity model for SIRGAS 2017: VEMOS2017, open access, https://doi.org/10.1594/PANGAEA.912350, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI-TUM), IGS RNAAC SIRGAS, 2020, in supplement to: Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi.org/ 10.1007/1345_2020_91

Mackern M.V., Mateo M.L., Camisay M.F., Morichetti P.V. (2020). Tropospheric Products from High-Level GNSS Processing in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi/org/10.1007/1345_2020_121

Sánchez L. (2020). SIRGAS Regional Network Associate Analysis Centre Technical Report 2019. Villiger A., Dach R. (eds.) International GNSS Service: Technical Report 2019, 125-136, https://doi.org/10.7892/BORIS.144003

Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi.org/10.1007/1345_2020_91

Sánchez L., Drewes H. (2020). SIRGAS 2017 reference frame realization SIR17P01, open access, DOI 10.1594/PANGAEA.912349, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI-TUM), IGS RNAAC SIRGAS, 2020, in supplement to: Sánchez L., Drewes H. (2020). Geodetic monitoring of the variable surface deformation in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, https://doi.org/10.1007/1345_2020_91

Tarrío J.A., Soto C., González A., Barraza B., Isla F., and Caverlotti M. (2020). Geodesy in Chile (SIRGAS USC CENTRE): a Place Where the 4D Component Presents its Maximum Expression, GIM International May-June 2020:33, open acces: https://www.gim-international.com/magazine/may-june-2020.

Mackern M.V., Mateo M.L., Camisay M.F., Rosell P.A., Granados, G. (2021). Tropospheric Products validation in the GNSS SIRGAS Network. 1st ICCC "Geodesy for Climate Research "Workshop 2021, March 29-31, 2021.

Sub-Commission 1.3c: North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Daniel Roman (USA)

Introduction and Structure

In collaboration with the IAG community, its service organisations, and the national geodetic organizations of North America, the aims and objectives of this regional Sub-commission are to provide international focus and cooperation for issues involving the horizontal, vertical and three dimensional geodetic control networks of North America. Some of these issues include:

- Densification of the ITRF reference frame in North America and the promotion of its use;
- Definition, maintenance and future evolution of plate-fixed geometric reference frames for North America, including the North American Datum of 1983 (NAD83) and the forthcoming North American Terrestrial Reference Frame of 2022 (NATRF2022).
- Effects of crustal motion, including post-glacial re-bound and tectonic motions along, e.g., the western coast of North America and in the Caribbean;
- Standards for the accuracy of geodetic positions;
- Coordination of efforts with neighbouring IAG SC1.3b for Central and South America to ensure strong ties between each other's reference frames.
- Outreach to the general public through focused symposia, articles, workshops and lectures, and technology transfer to other groups.

Members

- *Michael Craymer (Canada)*
- *Daniel Roman (USA)*
- *Finn Bo Madsen (Denmark)*
- *Babak Amjadiparvar (Canada)*
- *Remi Ferland (Canada)*
- *Joe Henton (Canada)*
- *Mike Piraszewski (Canada)*
- *Dru Smith (USA)*
- *John Galetzka (USA)*
- *Phillip McFarland (USA)*
- *Theresa Damiami (USA)*
- *Lijuan Sun (USA)*
- *Don Haw (USA)*
- *Michael Bevis (USA)*
- *Geoff Blewitt (USA)*
- *Tom Herring (USA)*
- *Jeff Freymueller (USA)*
- *Corné Kreemer (USA)*
- *Richard Snay (USA)*

Activities during the period 2019-2021

The Sub-Commission is currently composed of three working groups:

- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Plate-Fixed North American Reference Frame
- SC1.3c-WG3: Reference Frame Transformations

The following summarizes the activities of each working group, followed by a report of other reference frame activities in Canada and the U.S., during the period 2019-2021. For more information and publications related to the working groups, see the regional Sub-Commission web site at *http://www.naref.org/*.

Note: the acronyms "NAD83" (as used in Canada) and "NAD 83" (as used in the U.S.) will be used interchangeably throughout this report.

WG 1.3c.1: North American Reference Frame Densification (NAREF)
Chair: Michael Craymer (Canada)

The objectives of this working group are to densify the ITRF reference frame in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the cur-rent IGS global network. A cumulative solution of coordinate and velocities will also be determined on a weekly basis. The working group will organize, collect, analyse and combine solutions from individual agencies, and archive and disseminate the weekly and cumulative solutions.

The Canadian Geodetic Survey (CGS) continues to produce weekly coordinate solutions of approximately 600 Canadian and northern U.S. public continuously operating Canadian Active Control System (CACS) stations in Canada, Greenland and the northern U.S. The data is processed using the Bernese GNSS Software v5.2 and final IGS orbits with about a 3 week latency. In addition, weekly solutions are also produced for over 750 commercial RTK stations in Canada. The time series of results for CACS and commercially operated stations are published online at *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php* for public stations and *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/rtk.php* for the commercial RTK stations.

CGS also continues to produce monthly-updated cumulative solutions of all of its weekly coordinate solutions using its own highly efficient combination software. A coordinates and velocities of nearly 900 current and discontinued public and over 1150 commercial stations are generated. In addition, periodic solutions with high accuracy campaign surveys of an additional 250 stations are included to densify the rather spare continuous network for generating an improved crustal deformation model for Canada. Figure 1.3c.1 gives a map of the vertical velocities from the last periodic solution with high accuracy campaign surveys. Several new CACS stations are planned for installation in strategic locations to improve network coverage but only a few new CACS stations could be installed due to COVID-19-related travel restrictions since early 2020.

Although NGS did not participate in the 2nd IGS reprocessing campaign, they have completed the reprocessing of their NOAA CORS Network (NCN) and IGS network stations. The newly reprocessed solution, called the Multi-Year CORS Solution 2 (MYCS2), is aligned to the ITRF2014 frame. MYCS2 supersedes the previous reference frame and realization, which was released in 2011 under the name MYCS1. The final alignment of the no-net-rotation SINEX files to ITRF2014 used 496 solutions from 194 ITRF2014 stations, not including any of the 26 IGS stations with post-seismic behavior. The MYCS2 generally implemented the IERS 2010 Conventions. Horizontal and vertical velocities from MYCS2 are shown in Figure 1.3c.2.

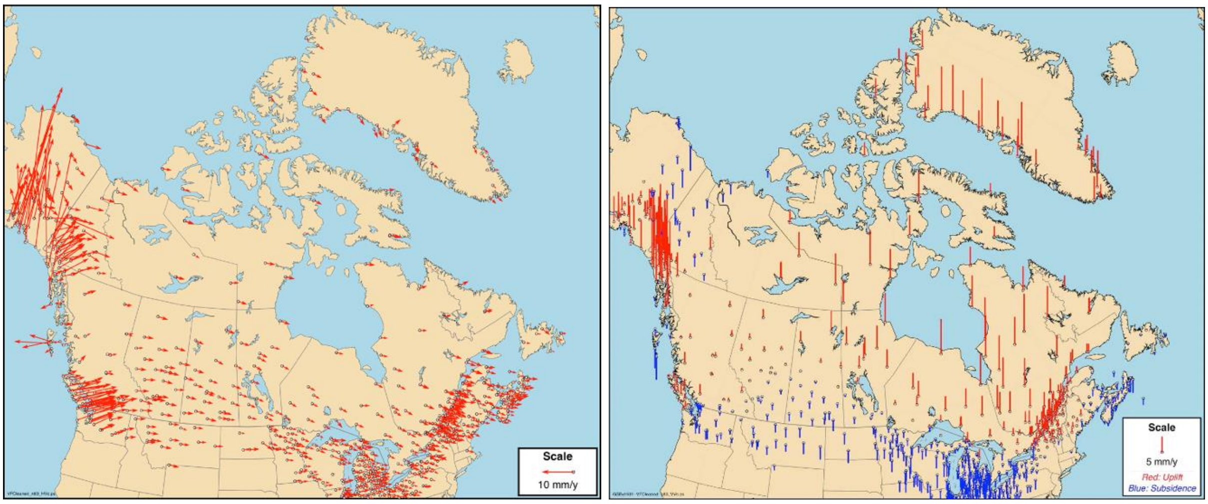


Figure 1.3c.1: Horizontal (left) and vertical (right) velocities for combined CACS and high accuracy campaign stations in Canada forming the current realization of NAD83(CSRS). Velocities are with respect to the NAD83(CSRS) v7 reference frame where a residual plate motion is apparent in the horizontal plot.

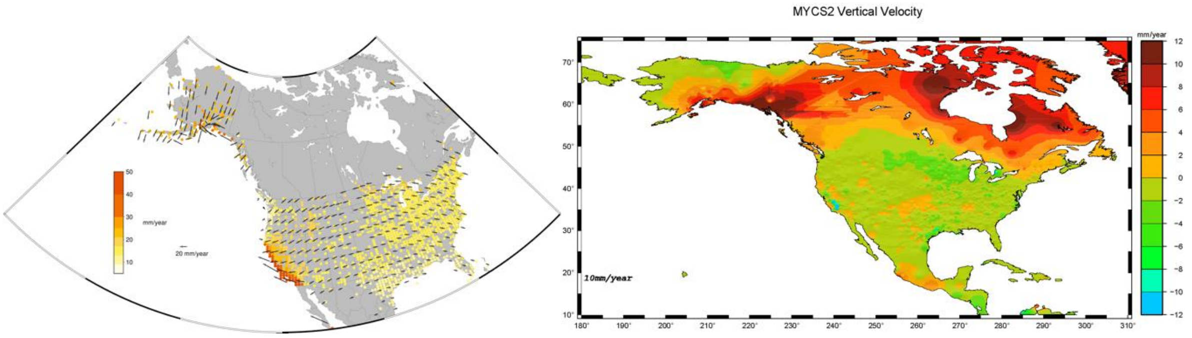


Figure 1.3c.2: Horizontal (left) and vertical (right) velocities in ITRF2014 from final MYCS2 cumulative solution of "repro2" weekly solutions to GPS week 1933. In the vertical plot, warm colors represent uplift and cool colors represent subsidence.

WG 1.3c.2: Plate-Fixed North American Terrestrial Reference Frame of 2022 (NATRF2022)

Chair: Daniel Roman

The objectives of this working group are to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace NAD83 and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared. In addition, similar plate-fixed reference frames will be established for U.S. states and territories on other tectonic plates in the Caribbean and Pacific regions.

Although NAD 83 was the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that it is offset from the actual geocentre (and thus ITRF) by about 2 meters. There is also a residual rotation with respect to North American tectonic plate of about 2 mm/yr at mid latitudes due to an inconsistency in the definition of the transformation from ITRF that now defines NAD 83. These problems make NAD 83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning systems. Additionally, the United Nations Global Geodetic Reference Frame (GGRF) also stipulates adoption of internationally accepted standards of which ISO 19161-1:2020 is the standard for the realization of the ITRS. Consequently, the U.S. has been making plans to replace NAD 83, along with its vertical datum, with a high accuracy geocentric reference frame called the North American Terrestrial Reference Frame of 2022 (NATRF2022). This high accuracy geocentric reference frame will likely be based on the forthcoming ITRF2020 at epoch 2020.0 and fixed to the North American plate. Discussions are also underway in Canada to adopt the same frame. Regardless whether or not the new frame is officially adopted in Canada, CGS will make coordinates and velocities available in both NAD83(CSRS) and NATRF2022, and provide a transformation between the two.

The new NATRF2022 reference frame will be defined by aligning it exactly with the latest realization of ITRF at an adopted reference epoch of 2020.0. It will then be kept aligned to the North American tectonic plate through an estimated Euler pole rotation. Discussions are presently underway on the selection of a set of reference frame stations representing stable North America and on the method of estimating an Euler pole rotation that either best represents the motion of the North American tectonic plate or that minimizes motions of stations outside the plate boundary zone. Investigations are also being made into methods of computing the Euler pole rotation, including a novel, robust approach developed by Kreemer et al. (2017). Remaining intra-frame motions will be modelled for propagating coordinates between epochs both horizontally and vertically.

In addition to defining a new regional reference frame for North America, the U.S. is also planning to define similar plate-fixed frames for the Caribbean and its territories on the Pacific and Mariana plates. The following names have been adopted for these reference frame:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MATRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PATRF2022)

WG 1.3c.3: Reference Frame Transformations in North America
Chair: Michael Craymer

The objectives of this working group are to determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed and to provide tools for implementing these relationships.

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 reference frame was re-defined in 1998 as a 7-parameter Helmert transformation from ITRF96 at epoch 1997.0. (Craymer et al., 2000) Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental time-dependent transformations between ITRF versions as published by the IERS (Soler and Snay, 2004). The NAD83-ITRF transformation was most recently updated to ITRF2014 in January 2017 just prior to adoption of ITRF2014 by the IGS. The updated transformation has been implemented in transformation software at the Canadian Geodetic Survey and U.S. National Geodetic Survey. The transformation will be updated to the forthcoming ITRF2020 once it is released.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a velocity model and transformation software for North

America was developed by Snay and others in 2016. The model integrates velocity fields from various sources to provide North American coverage. The resulting interpolation grid of velocities has been implemented in TRANS4D, an update to the HTDP software that models and predicts horizontal motion for the U.S. Trans4D will likely serve as the initial Intra-Frame Velocity Model (IFVM) for NATRF2022 in the U.S. Investigation has also begun on use of InSAR-based surface deformation modelling tied to the NCN and CACS to serve as a follow on IFVM.

Canada has developed its own national velocity model that incorporates a GIA model to better predict vertical crustal motions in the central and northern regions where GNSS stations are sparse (Robin et al., 2019a, b, c, 2021). The model uses the latest Canadian cumulative solution discussed in SC1.3c-WG1 together with a blending of the ICE-6G and LAUR16 GIA models. The blended GIA model was effectively distorted to fit the GPS velocities thereby providing a more reliable velocity interpolation grid for GIA areas with sparse GNSS coverage. Figure 1.3c.3 illustrates the resulting vertical velocity grid in the NAD83(CSRS) reference frame.

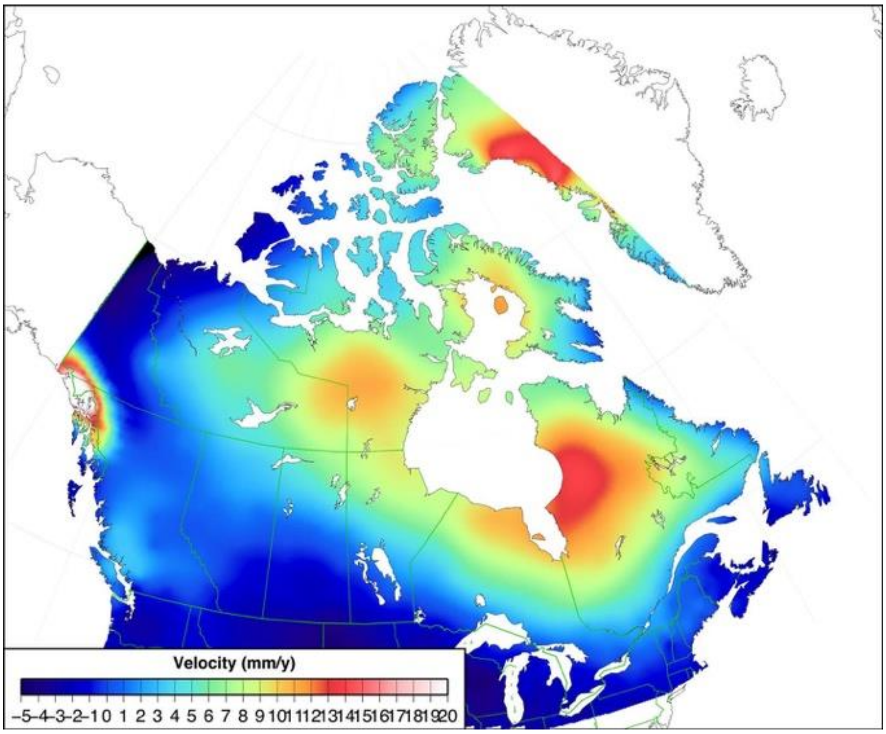


Figure 1.3c.3: Canadian vertical velocity model in NAD83(CSRS) v7 obtained from an integration of GNSS velocities with a GIA model.

Other Activities

NGS is creating a new high-level network of 36 highly stable, highly reliable GNSS tracking stations across the country at a spacing of approximately 800 km that will be contributed to the IGS and ITRF (see Figure 1.3c.4). These 36 stations include a minimum of 3 stations on each tectonic plate upon which the U.S. has significant populations (North American, Pacific, Caribbean, and Mariana) to enable computation of an Euler pole rotation (see SC1.3c-WG2). Of these 36, twenty six (26) are currently operational.

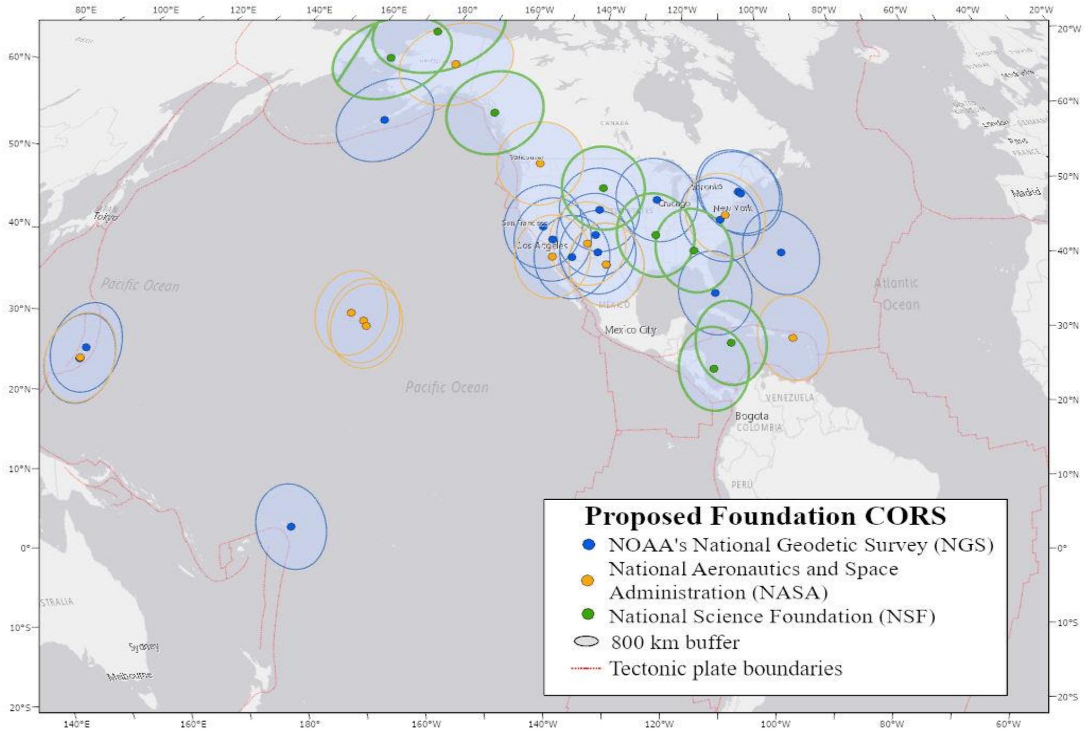


Figure 6.3c.4: Proposed locations for NOAA Foundation CORS (NFCN) sites to serve as IGS stations and link ITRF solutions to MYCS solutions. Of these twnety six (26) are currently operational).

Unlike most of the other stations in the NCN, these sites will be operated by the U.S. National Geodetic Survey (either through direct ownership or MOU’s with other federal agencies) and will be built and operated to IGS standards. Referred to as the NOAA Foundation CORS Network (NFCN), this network is a subset of the larger NCN and will provide a more stable foundation for the reference frame in the U.S. Thirteen of these GNSS stations are already collocated with other techniques such as VLBI and SLR in order to create true GGOS stations. Another nine new collocated stations will be built at other GGOS sites lacking GNSS. The first of these sites was installed in Miami in late 2014 and the others will be built approximately two per fiscal year beginning the winter of 2019. When the project is completed, all NFCN stations will be fully GNSS capable, will support RINEX3, and will have local surveys ties between the different techniques performed to IERS standards about once every 5 years.

CGS has just recently received funding to enhance Canada’s geodetic infrastructure to support future requirements for positioning services, the transportation industry (e.g., autonomous vehicle navigation) and weather modelling and forecasting. The primary objective of this five-year Space-Based Earth Observation (SBEO) project is to densify the existing network of continuously operating GNSS tracking station with about 22 or more real-time stations to support the work of the Canadian Geodetic Survey, Transport Canada and the meteorological branch of Environment and Climate Change Canada. Consideration will also be given to other non-geodetic uses of the GNSS data, such as reflectometry for determining snow depth and soil moisture.

Commercial real-time kinematic network (RTN) services and their networks of base stations have grown significantly over the years. They are effectively providing access to the NAD83 reference frame for many users independent of the public government networks in both Canada and the U.S. Because these networks are not always integrated into the same realization of

NAD83, CGS began a program of validating the coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. CGS continues to provide on-going, monthly-updated multi-year cumulative solutions for 6 of the largest commercial RTN services in Canada; a total of nearly 900 stations (see Figure 1.3c.5). Compliance agreements have been signed with the five largest services where they have committed to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTN services are integrated into the latest realization of NAD83(CSRS). CGS is also monitoring the stability of RTN stations through time series of weekly coordinate solutions published on CGS's public website.

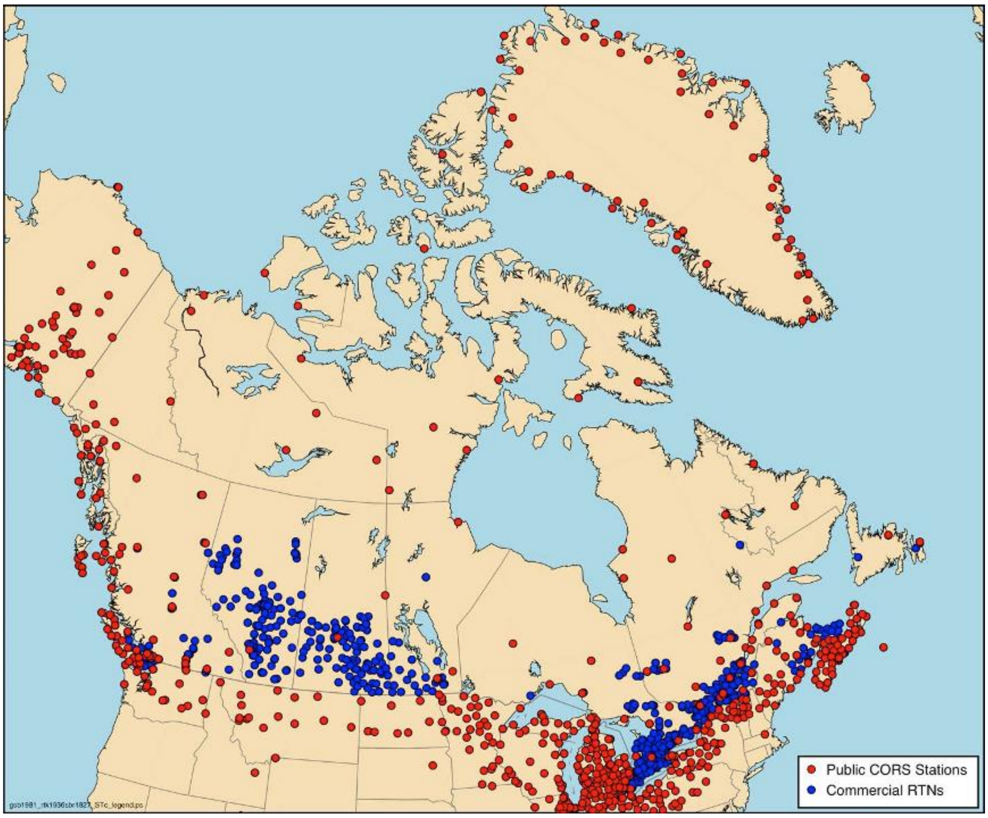


Figure 1.3c.5: Distribution of the six largest commercial RTK networks in Canada (blue dots) in relation to public federal and provincial networks of permanent GNSS stations (red dots). The commercial RTN stations significantly densify the public network in the Prairies.

NGS is also committed to developing an RTN Alignment Service (RAS) for RTN operators and users in the U.S. that will ensure RTN coordinates are consistent with the National Spatial Reference System (NSRS). This is intended to be a two-step procedure by first quantifying the alignment of base stations and then quantifying the alignment of rover positions relative to the NSRS.

Cooperation with other organizations and international integration

There has been much international coordination between NAREF and other groups. The most direct engagement has been with IAG 2.4c – gravity and geoid for Central and North America and the Caribbean. Canada has already adopted a geoid based vertical datum and the U.S. will soon do likewise. The North America-Pacific Geopotential Datum (NAPGD2022) is being jointly developed by Canada, the U.S. and Mexico to serve as a regional vertical datum, which will be accessed via the NATRF2022. As such, there is close cooperation between both 1.3c and 2.4c to ensure compatibility.

Additionally, NAREF is looking to foster closer cooperation and collaboration with the IAG Sub-Commission 1.3b for South and Central America (SIRGAS). Although SC1.3b is still referred to as SIRGAS within the IAG, the SIRGAS organization recently implemented new terms of reference that defines itself as more of a separate scientific non-governmental organization serving all of the Americas. SIRGAS WG I (Reference System) expanded its focus to developing a reference frame for all of the Americas in support of the regional implementation of the UN-GGIM Global Geodetic Reference Frame for all of the Americas. As such, IAG 1.3b and 1.3c members actively participated to ensure that the SIRGAS Reference Frame is tied to the ITRF throughout all of the Americas. And members of NAREF SC1.3c are now official members of both SIRGAS and its WG I and the newly formed UN-GGIM:Americas Working Group 4 of the Geodetic Reference Framework for the Americas (GRFA).

Members of NAREF have also been contributing to the UN-GGIM Sub-Committee on Geodesy (SCoG) and its working groups. NGS and CGS are members of the SCoG. M. Craymer has served as Chair of the SCoG Working Group on Policies, Standards and Conventions until 2020 and D. Roman has recently assumed duties as the Chair of the SCoG Working Group on Education Training and Capacity Building, renamed as the Working Group on Geodetic Capacity Development.

Related to the SCoG standards working group are NAREF contributions to the development of ISO standards and the ISO Geodetic Registry (ISOGR). The Registry is an authoritative collection of definitions of international reference frames and the transformations between them, similar to the privately run EPSG registry. The primary purpose of the ISOGR is to provide an authoritative source of such information for other registries, including EPSG, as well as GIS software developers and end users. Both CGS and NGS have made a significant effort to populate and update the Registry with all current and historical reference frame realizations used in Canada and the U.S. along with the many transformations among them. The Control Body that approves and facilitates the entry of data into the Registry is presently chaired on behalf of the IAG by M. Craymer (Canada) and L. Hothem (U.S.). Under their leadership, registry software has been developed and implemented by Ribose Group. More recently, CGS has funded the migration of the ISOGR to a new, more efficient software platform. The Registry is available at the following link: *http://registry.isotc211org*.

Organised Meetings

2021 Geospatial Summit, Virtual, May 4-5, 2021. https://geodesy.noaa.gov/geospatial-summit/

Geodesy Forum for UN-GGIM:Americas, Geodesy for Sustainable Americas, virtual, May 14, 2021

2021 Annual General Meeting of the Canadian Geodetic Reference System Committee (CGRSC), Virtual, May 26-28, 2021.

Publications

Craymer M., Hothem L. (2019). Geodetic Standards Activities in ISO and the UN-GGIM Sub-Committee on Geodesy. Presented at the 27th IUGG General Assembly, Montreal, July 8-18.

Craymer M., Lamothe P. (2021). NAD83(CSRS): From Static to Dynamic. Association of Canada Land Surveyors Webinar, May 18 (French) & 20 (English).

Donahue B., Lamothe P. (2021). Modernization of the North American Reference System – The U.S. Plan and the Considerations for Canada. Association of Canada Land Surveyors Webinar, January 19 (French) & 21 (English).

Dennis M.L. (2020). The National Adjustment of 2011: Alignment of Passive GNSS Control with the Three Frames of the North American Datum of 1983 at Epoch 2010.00: NAD83 (2011), NAD83 (PA11), and NAD83 (MA11), National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, July 29. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0065.pdf

Erickson C., Banham G., Berg R., Chessie J., Craymer M., Donahue B., Tardiff R., Thériault Y., Véronneau M. (2020). The U.S. is replacing NAD83 with NATRF2022: what this means for Canada. Geomatica, Vol. 73, pp. 74-80. https://doi.org/10.1139/geomat-2019-0021

Federal Register Notice (2020). Upcoming Changes to the National Spatial Reference System (NSRS), 85 FR 44864, 44864, 2020-16068, https://www.govinfo.gov/content/pkg/FR-2020-07-24/pdf/2020-16068.pdf.

Kinsman N., Scott G., Kanazir B., Jordan K., Jalbrzikowski J. (2021). Modernized NSRS Use Cases, webinar, April 08, 2021, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

McFarland P. (2020). Global Reference Frames: What they Are and How/Why NGS Aligns to Them, October 8, 2020, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 1: Geometric Coordinates and Terrestrial Reference Frames, NOAA Technical Report NOS NGS 62, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 2017, Revised April 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0062.pdf

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 2: Geopotential Coordinates and Geopotential Datum, NOAA Technical Report NOS NGS 64, National Geodetic Survey, National Oceanic and Atmospheric Administration, November 2017, Revised February 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0064.pdf

National Geodetic Survey (2021). Blueprint for the Modernized NSRS, Part 3: Working in the modernized NSRS, NOAA Technical Report NOS NGS 67, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 2019, Revised February 2021. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0067.pdf

Robin C., Bremner M., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y. (2019a). An updated NAD83(CSRS) velocity field and hybrid crustal velocity model for Canada. AGU Fall Meeting, San Francisco, Dec. 9-13, Abstract No. G23C-0774

Robin C., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y. (2019b). NAD83(CSRS) v7: A New Realization of NAD83(CSRS) for Canada. Presented at the 27th IUGG General Assembly, Montreal, July 8-18

Robin C., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y., James T. (2019c). Comparing GIA models with an updated velocity field: Towards an improved Canadian Spatial Reference System. Workshop on workshop on Glacial Isostatic Adjustment, Ice Sheets, and Sea-Level Change – Observations, Analysis, and Modelling, Ottawa, September 26

Robin C., Craymer M., Ferland R., James T., Lapelle E., Piraszewski M., Zhao Y. (2021). NAD83v70VG: a new national crustal velocity model for Canada, Geomatics Canada, Open File 62. https://doi.org/10.4095/327592

Smith D. (2019). Blueprint for 2022, Part III: Working in the Modernized NSRS, July 25, 2019, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Smith D. (2020). Exploring and Quantifying the Contribution of Linear Coordinate Functions at NOAA CORS Network Stations to the 2022 Intra-Frame Velocity Model: An Experiment, NOAA Technical Memorandum NOS NGS 83, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, January 31. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0083.pdf

Smith D. (2020). A GPS Based Estimate of the Rotation of the Mariana Plate in both ITRF2008 and ITRF2014, NOAA Technical Report NOS NGS 74, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, August 11. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0074.pdf

Smith D. (2020). Delayed Release of the Modernized NSRS, August 27, 2020, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Smith D. (2020). Biquadratic Interpolation, NOAA Technical Memorandum NOS NGS 84, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, September 2. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0084.pdf

Smith D. (2020). On the Propagation of Formal Error Estimates of Euler Pole Parameters into Modernized NSRS Coordinates, NOAA Technical Memorandum NOS NGS 85, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, September 8. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0085.pdf

Smith D. (2020). Quantifying Systematic Error When Using Axial Rotation Rates Rather Than Geographic Euler Pole Parameters When Describing Tectonic Plate Rotation, NOAA Technical Memorandum NOS NGS 86, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, October 1. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0086.pdf

Smith D., Bilich A. (2019). NADCON 5.01, NOAA Technical Memorandum NOS NGS 81, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, July 30. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0081.pdf

Smith D., Dennis M. (2020). On the Use of Linear Units as a Companion to Horizontal Datum Transformations Performed on Curvilinear Coordinates (or "What does NGS mean when they provide NADCON transformations and error estimates for latitude and longitude in meters?"), NOAA Technical Memorandum NOS NGS 82, National Geodetic Survey, National Oceanic and Atmospheric Administration, Silver Spring, MD, February 26. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0082.pdf

Smith D. (2021). Working in the Modernized National Spatial Reference System, March 11, 2021, https://geodesy.noaa.gov/web/science_edu/webinar_series/2021-webinars.shtml

Sub-Commission 1.3d: Africa (AFREF)

Chair: Elifuraha Saria (Tanzania)

No report was submitted

Sub-Commission 1.3e: Asia-Pacific

Chair: Basara Miyahara (Japan)

Introduction and structure

The objective of sub-commission 1.3e is to improve the regional cooperation that supports the realization and densification of the International Terrestrial Reference frame (ITRF). Its work is carried out in close collaboration with the Geodetic Reference Frame Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP).

The specific objectives of the Sub-commission 1.3e are:

- The densification of the ITRF and promotion of its use in the Asia Pacific region;
- To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- To develop a better understanding of crustal motion in the region;
- To promote the collocation of different measurement techniques, such as GNSS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
- To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Members

- *John Dawson (Australia)*
- *Yamin Dang (China)*
- *Shyam Veer Singh (India)*
- *Basara Miyahara (Japan)*
- *Yi Sang Oh (Republic of Korea)*
- *Mohd Yunus (Malaysia)*
- *Dalkhaa Munkhtsetseg (Mongolia)*
- *Graeme Blick (New Zealand)*

National geospatial information agencies of the Asia-Pacific region are listed here: *https://www.un-ggim-ap.org/content/members*.

Activities during the period 2019-2021

The sub-commission 1.3e has three focuses in the period; densification of ITRF, collaboration with global geodetic community, and geodetic capacity development in the region.

Asia-Pacific Reference Frame (APREF) Project

The purpose of the Asia-Pacific Reference Frame (APREF) project is to create and maintain an accurate geodetic framework to meet the growing needs of society including industries, science programs and the general public using positioning applications in the Asia-Pacific region. The project specifically is:

- Encouraging the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;

- An authoritative source of coordinates, and their respective velocities, for geodetic stations in the Asia-Pacific region;
- Establishing and maintaining a dense velocity field model in Asia and the Pacific for scientific applications and the long-term maintenance of the Asia-Pacific reference frame.

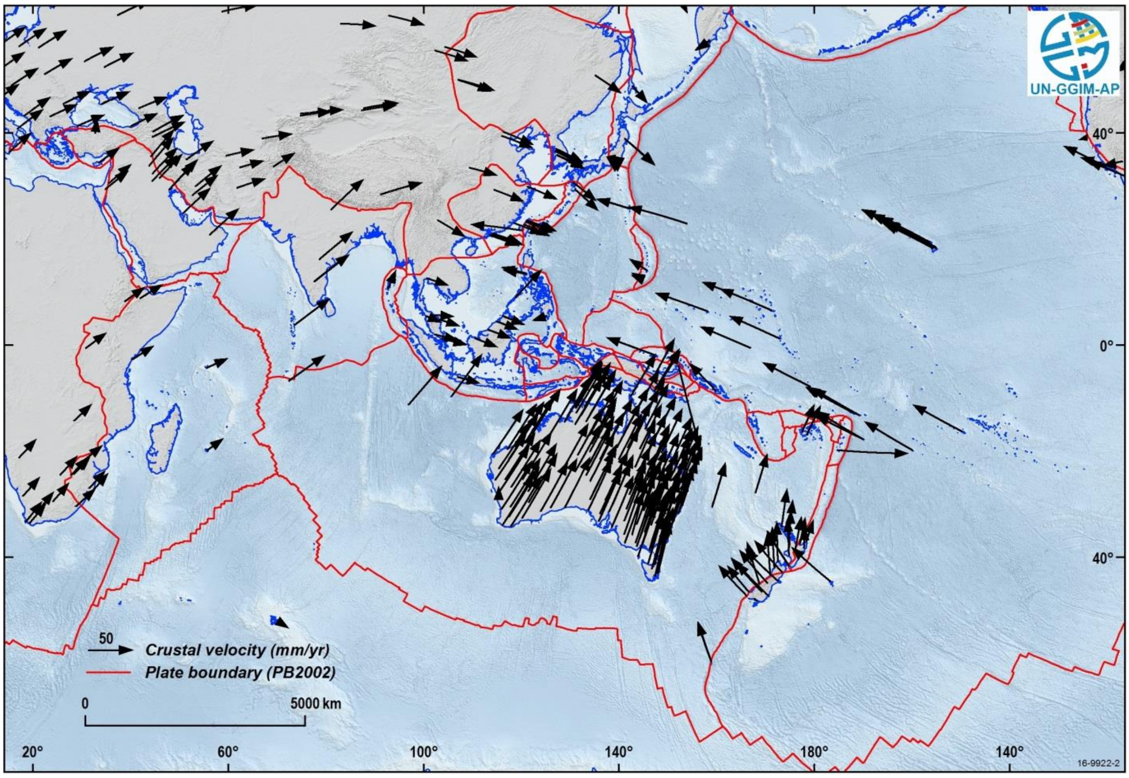


Figure 1.3e.1: APREF GNSS stations

A large number of agencies have and are participating in APREF, the following table summarizes commitments and contributions by member nations/organizations.

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
Afghanistan	National Geodetic Survey (USA)			2
Alaska, USA	National Geodetic Survey (USA)			7
American Samoa	National Geodetic Survey (USA)			1
Australia	Geoscience Australia	✓	✓	139
Australia	Curtin University	✓		1
Australia	Department of Natural Resources, Mines and Energy, QLD			8

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
Australia	Department of Environment, Land, Water and Planning	✓		107
Australia	Department of Infrastructure, Planning and Logistics, Northern Territory			5
Australia	Department of Primary Industries, Parks, Water & Environment, Tasmania			2
Australia	Department of Finance, Services & Innovation, New South Wales			170
Australia	RTK NetWest			12
Australia	IPS Radio and Space Services			3
Australia	Department of Transport and Main Road, Queensland			17
Brunei	Survey Department, Negara Brunei Darussalam			1
China	The Institute of Geodesy and Geophysics, Chinese Academy of Sciences	✓		
Cook Islands	Geoscience Australia and Lands Department of Cook Islands			1
Cook Islands	Geospatial Information Authority of Japan			1
Federated States of Micronesia	Geoscience Australia and Weather Service of the Federated States of Micronesia			1
Fiji	Geoscience Australia and Lands Department of Fiji			1
French Polynesia	Geospatial Information Authority of Japan			1
Guam, USA	National Geodetic Survey (USA)			1
Hong Kong, China	Survey and Mapping Office			14
India	Survey of India			3
Indonesia	Bakosurtanal			8
Iran	National Cartographic Center, Iran			6

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
Iraq	National Geodetic Survey (USA)			6
Japan	Geospatial Information Authority of Japan			8
Japan	Japan Aerospace Exploration Agency			1
Kazakhstan	Kazakhstan Gharysh Sapary			2
Kiribati	Geoscience Australia and Weather Service of Kiribati			1
Kiribati	Geospatial Information Authority of Japan			2
Macau, China	Macao Cartography and Cadastre Bureau			3
Marshall Islands	Geoscience Australia and Weather Service of Marshall Islands			1
Malaysia	Department of Survey and Mapping Malaysia, JUPEM			7
Mongolia	Administration of Land Affairs, Construction, Geodesy and Cartography (ALACGaC)			8
Nauru	Geoscience Australia and Lands Department of Nauru			1
New Zealand	Land Information New Zealand	✓	✓	38
Northern Mariana Islands	National Geodetic Survey (USA)			1
Papua New Guinea	National Mapping Bureau, Papua New Guinea, and Geoscience Australia			2
Philippines	Department of Environment and Natural Resources, National	✓	✓	4

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
	Mapping and Resource Information Authority			
Samoa	Geoscience Australia and Lands Department of Samoa			1
Solomon Islands	Geoscience Australia and Weather Service of Solomon Islands			1
Tonga	Geoscience Australia and Lands Department of Tonga			1
Tuvalu	Geoscience Australia and Weather Service of Tuvalu			1
Vanuatu	Geoscience Australia and Lands Department of Vanuatu			1

APREF data and products are provided with an open access data policy via the internet, following the practice of the International GNSS Service (IGS).

- Daily GNSS RINEX data, see ftp://ftp.data.gnss.ga.gov.au/daily/
- Station log files, see ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/logs/
- Weekly coordinate estimates in SINEX format, see ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/solutions/apref/

Asia Pacific Regional Geodetic Project

For further densification and improvement of access to the ITRF, the group has continued to support the annual Asia Pacific Regional Geodetic Project (APRGP), which is a week-long GNSS campaign throughout the region (see Fig. 1.3e.2). Campaigns were undertaken in 2019 and 2020. A campaign is planned for 2021.

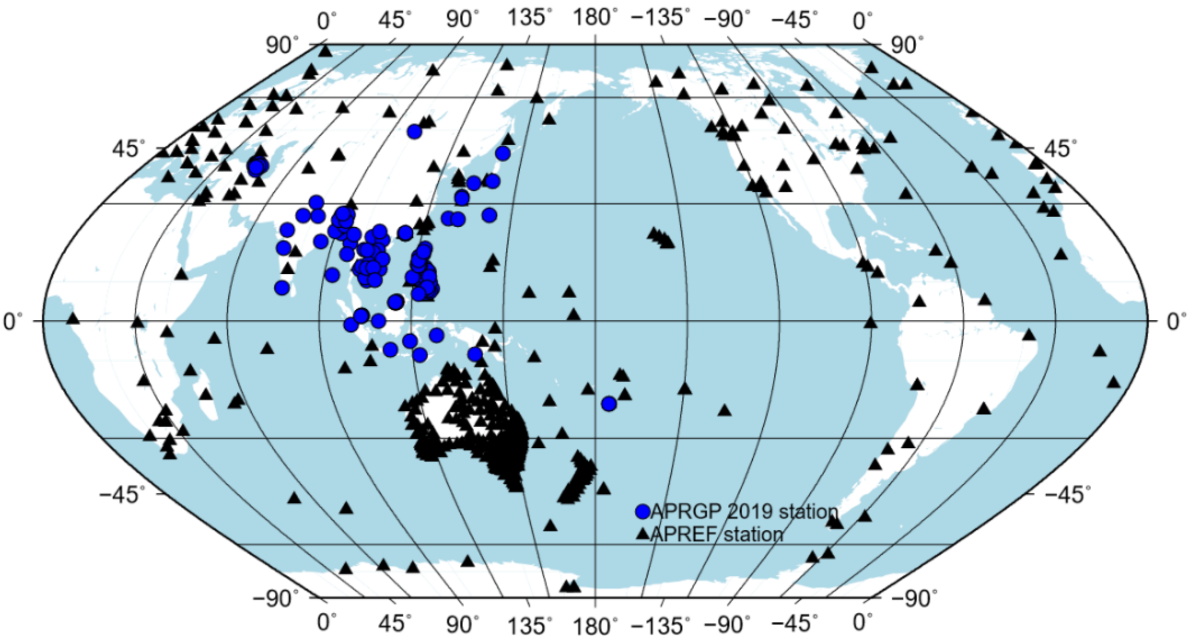


Figure 1.3e.2: Participating stations of the APRGP 2019 GNSS campaign.

Cooperation with other organizations and international integration

Sub-Commission 1.3e made a contribution towards the development of two documents of the UN-GGIM Subcommittee on Geodesy reported to the Tenth Session of UN-GGIM which was held in virtual format.

Outreach and capacity development

Several capacity development events were originally planned, but all of them are cancelled or postponed because of COVID-19 pandemic.

- UN-GGIM-AP, FIG, IAG "Positioning and Datum Modernisation Forum" in 3 November 2019 in conjunction with UN-GGIM-AP 8th Plenary Meeting. It was also the first opportunity to welcome a presentation from the geodetic working group of the UN-GGIM Arab States. Modernization of geodetic reference frames and its issues and challenges were discussed from global, regional and national perspectives. Countries in the region reported their progress, issues and challenges in your geodetic datum.

Figure 1.3e.3: Positioning and Datum Modernisation Forum

- Inaugural "Geodesy4Sendai" Session in 5 November 2019 in conjunction with UN-GGIM-AP 8th Plenary Meeting and GEO Week 2019. It was the first meeting jointly organized by the GEO Geodesy for the Sendai Framework Community Activity and UN-GGIMAP. This session addressed the first project of Geodesy4Sendai – a GNSS-enhanced Tsunami Early Warning "Shield Consortium" whose components are aligned to specific Sendai and SDG targets/indicators and geodesy contribution to Disaster Risk Reduction from regional perspective.
- FIG Technical Seminar on Reference Frame in Practice: Reference Frames, Progress and Challenges in the Asia-Pacific Region, 10 December 2020.

Organized Meetings

Sub-commission 1.3e usually has its annual session at the UN-GGIM-AP Plenary meeting in collaboration with the UN-GGIM-AP Working Group on Geodetic Reference Frame.

- The sub-commission 1.3e held its annual session at the 8th Plenary Meeting of UN-GGIM-AP on 3 November 2019. The national/regional/global issues and challenges on geodetic reference frame were discussed and resolution to tackle them were developed to table them to the Plenary Session.

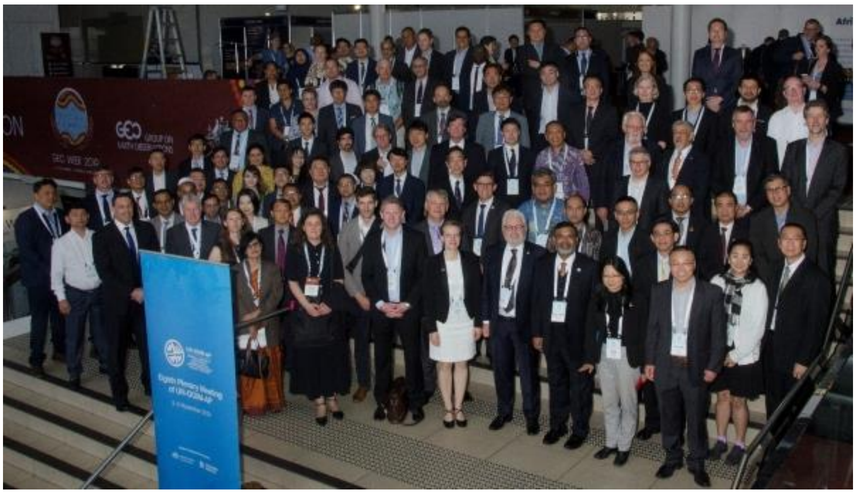


Figure 1.3e.4: 8th Plenary Meeting of UN-GGIM-AP

- The annual session of sub-commission 1.3e was held on 3 November 2020 in virtual format in conjunction with UN-GGIM-AP 9th Plenary Meeting. Although this was the first online session, the session has a larger number of participants than the past sessions and around 70 people participated in it.

Publications

Hu, G. (2019). Report on the Analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2019. Record 2020/27. Geoscience Australia, Canberra.

Hu G., Jia M., Dawson J. (2019). Report on the Asia Pacific Reference Frame (APREF) Project. Record 2019/17. Geoscience Australia, Canberra, https://doi.org/10.11636/Record.2019.017

Sub-commission 4.4: Multi-Constellation GNSS

Chair: *Pawel Wielgosz (Poland)*
Vice Chair: *Jianghui Geng (China)*
Secretary: *Grzegorz Krzan (Poland)*

Overview

GNSS constellation is rapidly developing by growing the number of satellites and available signals and frequencies. In addition to two already operational GPS and GLONASS systems, the new Galileo and BDS systems achieved initial operational capabilities. Both GPS and GLONASS are currently undergoing a significant modernization, which adds more capacity, more signals, better accuracy and interoperability, etc. In addition, a rapid development in the mass-market GNSS chipsets has to be also acknowledged.

These new developments in GNSS provide opportunities to create new high-precision GNSS technologies and applications and also to open new research areas. This, however, results in new challenges in multi-GNSS data processing, which primarily concern the positioning integrity and reliability. Recognizing the central role of GNSS in providing high accuracy positioning information, SC4.4 will foster research activities that address integrity, quality control and relevant applications of GNSS in case of multi-constellation and multi-frequency environment. SC4.4 will coordinate activities to deliver practical and theoretical solutions for engineering and scientific applications. Among those applications there are structural and ground deformation monitoring, precise navigation, GNSS remote sensing, geodynamics, etc.

SC4.4 will also encourage strong collaboration with the IAG Services (primarily IGS) as well as with relevant entities within scientific and professional sister organizations (FIG, IEEE and ION).

Objectives
The major objective of SC4.4 is to promote collective research on GNSS Integrity and Quality Control methods and their novel applications to facilitate timely dissemination of scientific findings, to stimulate strong collaborations among researchers and international organizations and the industry.

Program of Activities

- to identify and investigate important scientific and technical issues in GNSS integrity and quality control methods and their applications,
- to stimulate strong collaborations among researchers,
- to organize international conferences and workshops,
- to promote the use reliable GNSS techniques and products in interdisciplinary scientific research and engineering applications.

Working Group Reports

WG 4.4.1: Quality Control and Integrity Monitoring of Precise Positioning

Chair: Ahmed El-Mowafy (Australia)
Vice Chair: Christian Tiberius (Netherlands)

Members

- Mathieu Jöerger, Virginia Polytechnic Institute and State University, USA
- Juan Blanch, Stanford University, USA
- Safoora Zaminpardaz, RMIT, Australia
- Amir Khodabandeh, University of Melbourne, Australia
- Kan Wang, Curtin University, Australia
- Yang Gao, The University of Calgary, Canada
- Chris Rizos, University of New South Wales, Australia
- Michaela-Simona Circiu, The German Aerospace Centre (DLR), Germany
- Eugene Bang, The German Aerospace Centre (DLR), Germany
- Krzysztof Nowel, University Warmia and Mazuray in Olsztyn, Poland
- Nobuaki Kubo, Tokyo University of Marine Sciences and Technology, Japan

Activities and publications during the period 2019-2020

The study group addresses quality control and integrity monitoring (IM) for precise GNSS positioning using techniques such Precis Point Positioning (PPP), Real-Time Kinematic (RTK), Network RTK, and PPP-RTK. For a real-time user, integrity and performance-based monitoring is essential for protection from faults, either in the system, the signals, augmentation systems, or that caused by jamming or spoofing. It is also vital to alert the user in case that the system cannot reach the target performance.

The Group had online meetings to discuss critical aspects in Integrity Monitoring of Precise Positioning for land applications and its differences from IM in aviation, with the following activities:

- A review of Design rigorous statistical testing regimes and quality control frameworks from mathematical aspects
- Development of some approaches for integrity monitoring for RTK and PPP positioning
- Start characterization study on of the link between the statistical testing and parameter estimation exercised in data processing and the final positioning integrity monitoring so as to develop rigorous quality control frameworks for evaluating the reliability of the position solutions.
- Initial development of statistical testing regimes that are capable of detection and handling of multiple alternative fault hypotheses using the underlying precise positioning models.

Over the past two years, the group members have contributed in journal and conference publications that address quality control and integrity monitoring, and produce a special Issue “Positioning and Navigation in the journal Remote Sensing (Q1) (ed. by A. El-Mowafy, A. Khodabandeh, K. Wang).

The following section summarizes some of the research being carried out, including the research questions, approaches and key findings.

Summary of the research carried out

The implementation of Intelligent Transport System (ITS) technology is expected to significantly improve road safety and traffic efficiency. One of the key components of ITS is precise vehicle positioning. Positioning with decimetre to sub-metre accuracy is a foundational capability for self-driving, and other automated, applications. Global Navigation Satellite System (GNSS) Precise Point Positioning (PPP) is an attractive positioning approach for ITS due to its relatively low-cost and flexibility. However, GNSS PPP is vulnerable to a number of elements, especially those caused by the challenging urban environment, where the ITS technology is most likely needed. To meet the high integrity requirements of ITS applications, it is necessary to carefully analyse potential faults and failures of PPP and to study relevant integrity monitoring methods. In a review paper an overview of vulnerabilities of GNSS PPP is presented to identify the faults that needs to be monitored when developing PPP integrity monitoring methods, which is a fundamental step. These vulnerabilities are categorised into different groups according to their impact and error sources to assist integrity fault analysis, which is demonstrated with failure modes and effects analysis and fault tree analysis methods. Some of them are discussed in detail, in terms of their causes, characteristics, impact on users, as well as related mitigation methods. In addition, research on integrity monitoring methods used for accounting for threats and faults in PPP for ITS applications is briefly reviewed. Both system-level (network-end) and user-level (user-end) integrity monitoring approaches for PPP are briefly discussed, focusing on their development and the challenges in urban scenarios. Some open issues, where further efforts should be focused, are also pointed out.

To assess the impact statistical model selection has on confidence levels of parameter estimators in linear(ized) GNSS models. In the processing of observational data, parameter estimation and statistical testing are often combined. A testing procedure is usually exercised to select the most likely observational model among the hypothesized ones, which is then followed by the estimation of the identified model parameters. The resulting estimator will inherit the uncertainties involved in both estimation and testing which need to be properly taken into account when computing the corresponding confidence level. The approach that is usually followed in practice to determine the confidence level is to compute the probability of the estimator lying in a region around its true value conditioned on the identified hypothesis. Therefore, use is made of the estimator's distribution under the identified hypothesis without regard to the conditioning process that led to the decision of accepting this hypothesis. Therefore, in one contribution, it is shown that for a proper computation of the confidence level in combined estimation-testing procedures, the associated probability should be conditioned not only on the identified hypothesis, but also on the testing outcome that led to the decision of accepting this hypothesis. Therefore, use need to be made of the conditional distribution of the estimator. A numerical analysis of confidence levels is provided with and without accounting for conditioning on testing decision using a number of examples in the context of GNSS single point positioning. It is demonstrated that the customary practice which makes use of unconditional distributions to evaluate the confidence level, may give a too optimistic description of the estimator's quality.

In another article, two fault detection and Exclusion (FDE) approaches are discussed. The first is its application in the observation domain using Chi-square test in Kalman filter processing. The second approach discusses FDE testing in the positioning domain using the solution separation (SS) method, where new FDE forms are presented that are tailored for ITS. In the first form the FDE test is parameterized along the direction of motion of the vehicle and in the cross direction, which are relevant to applications that require lane identification and collision alert. A combined test is next established. Another form of the test is presented considering the maximum possible positioning error, and finally a direction-independent test. A new test that can be implemented in the urban environment is presented, which takes into account multipath effects that could disrupt the zero-mean normal-distribution assumption of the positioning errors. Additionally, a test is presented to check that the position error resulting from the remaining measurements lies within acceptable limits. The proposed methods are demonstrated through a kinematic test run in various environments that may be experienced in ITS.

One can also see that in challenging environments, such as in urban areas, a single navigation system is often difficult to fulfil the precise positioning requirements. Therefore, integrating different navigation systems becomes intrinsic. This integration may include GNSS, the Inertial Navigation Systems (INS), the odometers and the Light Detection and Ranging (LiDAR) sensors. Developing innovative Integrity Monitoring (IM) techniques for the integrated vehicular navigation systems requires knowledge of many aspects including the structure, positioning methodology and the different errors affecting the positioning solution of each individual system and that of the integrated system. Moreover, knowledge is needed of the current mitigation techniques of these errors, possible Fault Detection and Exclusion (FDE) algorithms that can be implemented, and current algorithms for computation of Protection Levels (PLs) that can bind the positioning errors with a specific risk. Therefore, in one paper we have an overview and discussion of these aspects.

In another contribution, a method is presented for prediction of GNSS positioning integrity for ITS journey planning. This information, in addition to other route information, such as distance and time, can be utilized to choose the safest and economical route. We propose to combine the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) technique, tailored for ITS, with 3D city models. Positioning is performed by GNSS Real-Time Kinematic (RTK) method, which can provide the accuracy required for ITS. Demonstration of the proposed approach is performed through a kinematic test in an urban area in Tokyo. The comparison between the prediction method and the actual observations show that the prediction method estimates close satellite geometry and PLs. The method produced PLs that bounds the actual position errors all the time and they were less than the pre-set alert limit.

In one study, a detailed threat model is developed for real-time kinematic (RTK) positioning application of short baselines. The model distinguishes between ambiguity-float and -fixed scenarios, and considers the influences of phase and code multipath as well as between-receiver atmospheric residuals. With the float ambiguities temporally constrained, the bias contribution that propagates with time-updated ambiguities was studied analytically for the horizontal protection level (HPL) in IM. Based on real data from both static and kinematic experiments, HPL was computed along the direction of the semi-major axis of the horizontal error ellipse. In ambiguity-float and -fixed cases, the HPL was mostly several meters and decimetres, respectively. It was found that time-propagated biases play a dominant role in the ambiguity-float HPL, and among them, phase and code multipath had in general the largest contributions. For ambiguity-fixed case, the phase multipath was found to play a dominant role in the HPL. This shows the importance of considering the biases in the RTK IM for both the ambiguity-float and -fixed scenarios. Given a horizontal alert limit (HAL) of 5 m, the availabilities of ambiguity-float solutions were low, i.e., below 50% for the static roof tests and below 5% for the kinematic road tests. For the ambiguity-fixed scenario, with HAL at 0.5 m, integrity availability was nearly 100% for the static roof tests and above 85% for the kinematic road tests.

It is known that for the short-baseline real-time relative kinematic positioning, such as in RTK, the spatially correlated errors, such as the orbital errors and the atmospheric delays are significantly reduced. However, the remaining atmospheric residuals and the multipath that are not considered in the observation model could directly bias the positioning results. Therefore, in one contribution, these biases are analysed with the focus put on the multipath effects in different measurement environments. A new observation weighting model considering both the elevation angle and the signal-to-noise ratios is developed and their impacts on the positional results are investigated. The coefficients of the proposed weighting model are determined for the open-sky and the suburban scenarios with the positional benefits maximised. Next, the overbounding excess-mass cumulative distribution functions (EMCs) are searched on the between-receiver level for the weighted phase and code observations in these two scenarios. Based on the mean and standard deviations of these EMCs, horizontal protection levels (HPLs) are computed for the ambiguity-fixed solutions of real experiments. The HPLs are compared with the horizontal positioning errors (HPEs) and the horizontal ALs (HALs). Using the sequential exclusion algorithm developed for the ambiguity resolution, the full ambiguity resolution can be achieved in around 100% and 95% of the time for the open-sky and the suburban scenarios, respectively. The corresponding HPLs of the ambiguity-fixed solutions are at the sub-dm to dm-level for both scenarios, and all the valid ambiguity-fixed HPLs are below a HAL of 0.5 m. For the suburban scenario with more complicated multipath environments, the HPLs increase by considering extra biases to account for multipath under a certain elevation threshold. In complicated multipath environments, when this elevation threshold is set to 30 degrees, the availability of the ambiguity-fixed solutions could decrease to below 50% for applications requiring HAL as low as 0.1 m.

Spoofing can seriously threaten the use of the Global Positioning System (GPS) in critical applications such as positioning and navigation of autonomous vehicles. Research into spoofing generation will contribute to assessment of the threat of possible spoofing attacks and help in the development of anti-spoofing methods. However, the recent commercial off-the-shelf (COTS) spoofing generators are expensive and the technology implementation is complicated. To address the above problem and promote the GPS safety-critical applications, a spoofing generator using a vector tracking-based software-defined receiver is proposed in this contribution. The spoofing generator aims to modify the raw signals by cancelling the actual signal component and adding the spoofing signal component. The connections between the spreading code and carrier, and the states of the victim receiver are established through vector tracking. The actual signal can be predicted effectively, and the spoofing signal will be generated with the spoofing trajectory at the same time. The experimental test results show that the spoofing attack signal can effectively mislead the victim receiver to the designed trajectory. Neither the tracking channels nor the positioning observations have abnormal changes during this processing period. The recent anti-spoofing methods cannot detect this internal spoofing easily. The proposed spoofing generator can cover all open-sky satellites with a high quality of concealment. With the superiority of programmability and diversity, it is believed that the proposed method based on an open source software-defined receiver has a great value for anti-spoofing research of different GNSS signals.

Selected publications

- Wang K., El-Mowafy A. (2021). Effect of biases in integrity monitoring for RTK positioning, Advances in Space Research,1-18, doi.org/10.1016/j.asr.2021.02.032.
- Hassan, T., El-Mowafy, A. and Wang, K. (2021). A Review of System Integration and Current Integrity Monitoring Methods for Positioning in Intelligent Transport Systems, IET Intelligent Transport Systems, 15(1), 1-18, doi: 10.1049/itr2.12003.
- DU, Y, Wang, J, Rizos, C., El-Mowafy, A. (2021). Potential Faults and Threats in Precise Point Positioning for Intelligent Transport Systems. Satellite Navigation. 2:3, 1-22, doi.org/10.1186/s43020-020-00034-8
- El-Mowafy, A, Kubo, N., Kealy, A. (2020). Reliable Positioning and Journey Planning for Intelligent Transport Systems. Advanced Energy Management, Modelling and Control for Intelligent and Efficient Transport Systems. InTech Publisher,UK, ISBN: 978-1-78984-104-6. DOI: 10.5772/intechopen.90305, pp1-23.
- El-Mowafy A., and Kubo N. (2020). Prediction of RTK positioning integrity for journey planning. J. of Applied Geodesy, 14(4), 431-443, doi: 10.1515/jag-2020-0038.
- Wang K, El-Mowafy A., Rizos C, Wang J. (2020). Integrity Monitoring for Horizontal RTK Positioning: New Weighting Model and Overbounding CDF in Open-Sky and Suburban Scenarios, Remote Sensing, 12, 1173; doi:10.3390/rs12071173, 1-23.
- El-Mowafy, A. (2020). Fault detection and Integrity Monitoring of GNSS Positioning in Intelligent Transport Systems. IET Intelligent Transport Systems, 14(3), 164 – 171. doi:10.1049/iet-its.2019.0248
- El-Mowafy A., Xu, B. and Hsu L-T. (2020). Integrity Monitoring of multi-GNSS Pseudo Range Observations in the Urban Environment Combining ARAIM and 3D City Models. Journal of Spatial Science, 1-18, doi.org/10.1080/14498596.2020.1734109
- Joerger, M., Zhai, Y., Martini, I., Blanch, J., Pervan, B., (2020). ARAIM Continuity and Availability Assertions, Assumptions, and Evaluation Methods. Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2020, pp. 404-420.
- Zaminpardaz, S., Teunissen, P. J.G., Tiberius, C. C.J.M. (2020). On the Evaluation of Confidence Levels with Application to GNSS. Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), September 2020, pp. 2718-2730.
- Khodabandeh, A., Wang, J., Rizos C. and El-Mowafy A. (2019). On the detectability of mis-modeled biases in the network-derived positioning corrections and their user-impact. GPS Solutions, 23: 73. doi:10.1007/s10291-019-0863-x
- El-Mowafy, A. (2019). Impact of Predicting Real-Time Clock Corrections during their Outages on Precise Point Positioning. Survey Review, 51(365): 183-192.
- El-Mowafy, A. (2019). Predicting orbit and clock corrections during their outage in real-time positioning using GPS, GLONASS and QZSS for natural hazard warning systems, Journal of Applied Geodesy, 13(2),69-79.
- El-Mowafy A., Imparato, D., Rizos C., Wang J., Wang, K. (2019). On Hypothesis Testing in RAIM Algorithms: Generalized Likelihood Ratio Test, Solution Separation Test and a Possible Alternative. Measurement Science and Technology, 30(7), 075001, doi.org/10.1088/1361-6501/ab1836.
- Meng Q., Hsu LT, Xu B, Luo X, El-Mowafy A. (2019). A GPS Spoofing Generator Using an Open Sourced Vector Tracking-Based Receiver. Sensors. 2019, 19, 3993; -18, doi:10.3390/s19183993

WG 4.4.3: Reliability of low-cost & Android GNSS in navigation and geosciences

Chair: *Jacek Paziewski (University of Warmia and Mazury in Olsztyn, Poland)*
Vice-Chair: *Robert Odolinski (University of Otago, New Zealand)*

Members

- *Rafal Sieradzki (University of Warmia and Mazury in Olsztyn, Poland)*
- *Martin Hakansson (Royal Institute of Technology Stockholm Sweden)*
- *Amir Khodabandeh (Melbourne University, Australia)*
- *Xiaohong Zhang (School of Geodesy and Geomatics Wuhan University Wuhan, China)*
- *Eugenio Realini (Geomatics Research & Development s.r.l. (GReD), Italy)*
- *Umberto Robustelli (Parthenope University of Naples, Italy)*
- *Vassilis Gikas (NTUA Greece)*
- *Rene Warnant (University of Liege, Belgium)*
- *Xiaopeng Gong (Wuhan University, China)*
- *Augusto Mazzoni (University of Rome La Sapienza, Italy)*
- *Dimitrios Psychas (Fugro, The Netherlands)*
- *Guangcai Li (Wuhan University, China)*
- *Safoora Zaminpardaz (RMIT Australia)*

Main activities during the period 2019-2020

The Working Group 4.4.3 addressed and investigated issues related to the application of low-cost receiver and smartphone GNSS observations to navigation, positioning and selected geoscience applications. The main objectives of current activities were:

- Comprehensive analysis of multi-constellation observations tracked by recent Android smartphones;
- Feasibility study on integer ambiguity fixing with phase observations collected by smartphones;
- Assessment of SPP, DGNSS, PPP and RTK positioning with Android smartphones;
- Review on recent advances and perspectives for positioning and applications with smartphone GNSS observations;
- Development of algorithms and methods for integer ambiguity resolution on low-cost handheld devices.

Over the past two years, the group members have contributed in publications and conference presentations that address this research area. The following section summarizes selected research that were carried out.

1. Characterization of smartphone GNSS observations

In joint study by WG 4.4.3 members (Paziewski et al 2021) we assessed the quality of multi-constellation GNSS observations of selected Android smartphones namely Huawei P30, Huawei P20 and Huawei P Smart as well as Xiaomi Mi 8 and Xiaomi Mi 9. We investigated the properties of phase ambiguities to anticipate the feasibility of precise positioning with integer ambiguity fixing. The results revealed a significant drop of smartphone carrier-to-noise density ratio (C/N0) with respect to geodetic receivers and discernible differences among constellations and frequency bands. We also showed that the higher the elevation of the satellite, the larger discrepancy in C/N0 between the geodetic receivers and smartphones. We depicted that an elevation dependence of the signal strength is not always the case for the smartphones. We discovered that smartphone code pseudoranges are noisier by about one order of magnitude as compared to the geodetic receivers, and that the code signals on L5 and E5a outperform these on L1 and E1, respectively. It was shown that smartphone phase observations are contaminated by the effects that can destroy the integer property and time-constancy of the ambiguities. The long term drifts were detected for GPS L5, Galileo E1, E5a and BDS B1 phase observations of Huawei P30. The investigations also revealed competitive phase noise characteristics for the Xiaomi Mi 8 when compared to the geodetic receivers. At the same time we showed a poor phase signal quality for the Huawei P30 smartphones related to the unexpected long-term drifts of the phase signals.

2. *Performance assessment of multi-GNSS smartphone positioning*

In WG 4.4.3 joint papers by Paziewski et al (2020) and Robustelli et al (2021) the single point positioning performance of three recent multi-frequency and multi-constellation smartphones, namely Xiaomi Mi 8, Xiaomi Mi 9, and Huawei P30 pro was evaluated. The analysis of the GNSS observation quality implied that the commonly employed elevation-dependent function is not optimal for smartphone GNSS observation weighting and suggested an application of the C/N0-dependent one. Regarding smartphone code signals on L5 and E5a frequency bands, it was found that they are characterized with noticeably lower noise as compared to E1 and L1 ones. The single point positioning results confirmed an improvement in the performance when the weights are a function of the C/N0-rather than those dependent on the satellite elevation and that a smartphone positioning with E5a code observations significantly outperforms that with E1 signals. The results showed also important differences in the positioning performance between the smartphones.

In WG 4.4.3 joint paper by Paziewski et al (2021) we showed the coordinate precision level that may be reached in a relative mode for the baseline built of a pair of homogenous smartphones. We analyzed the precision of coordinates obtained in an ambiguity-float solution and the improvement one can gain from integer ambiguity fixing. We proved that it is feasible to obtain a precise solution at cm-level in a smartphone to smartphone relative positioning mode with fixed ambiguities. These outcomes move us towards a collaborative precise positioning with smartphones.

3. Analysis of the state-of-art, challenges and perspectives for positioning and applications with smartphone GNSS observations

The activities of the 4.4.3 Working Group members were also related to the analysis of the state-of-art and anticipation of the future progress in smartphone GNSS positioning and applications. The paper by Paziewski (2020) offers a review of the most recent advances in smartphone GNSS positioning and applications, identifies challenges as well as an outline of possible future developments. Notwithstanding a tremendous progress of low-cost GNSS devices and smartphones, we still recognize a number of limitations that deter their application to the most demanding areas of science and technology. The smartphone GNSS antennas suffer from a low and inhomogeneous pattern of gain, high susceptibility to multipath, lack of phase centre models, and a linear polarization that does not prevent the acquisition of the non-line-of-sight left-hand circularly polarized signals. Moreover, users have to handle highly noisy smartphone observations, the presence of unaligned chipset initial phase biases and other biases that destroy the integer and time-constant properties of carrier-phase ambiguities. However, continuous progress in hardware, algorithms and applications is thought to be maintained in the future. With this development, the presumption of low-performance commonly related to low-cost receivers and smartphones may not hold true, since in the near future such receivers may potentially reach the performance level close to high-grade receivers.

4. Best Integer Equivariant estimation applied to low-cost multi-GNSS data processing

The scope of another study by the members of WG 4.4.3 is on the application of Best Integer Equivariant (BIE) estimation to low-cost GNSS data processing. Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency multi-constellation Real Time Kinematics (RTK) positioning. This study was followed by (Odolinski and Teunissen 2020b), where the authors investigated the corresponding BIE performance for low-cost dual-frequency long baseline multi-GNSS RTK positioning. With the conducted experiment the authors proved that the BIE estimator outperforms Integer Least Squares estimator and the float solutions in terms of positioning accuracy.

Selected publications during the period 2019-2020:

Gabela J., G. Retscher, S. Goel, H. Perakis, A. Masiero, C. K. Toth, V. Gikas, A. Kealy, Z. Koppanyi, W. Błaszczak-Bąk, Y. Li, D. A. Grejner-Brzezinska (2019) Experimental Evaluation of a UWB based Cooperative Positioning System for Pedestrians in GNSS Denied Environment. Sensors, (2019), 19(23)

Odolinski R., and Teunissen P. J. G. (2020a) On the best integer equivariant estimator for low-cost single-frequency multi-GNSS RTK positioning. Proceedings of the International Technical Meeting of the Institute of Navigation (ION). (pp. 499-508). Institute of Navigation. doi: 10.33012/2020.17158

Odolinski R. and Teunissen P.J.G. (2020b) Best integer equivariant estimation: Performance analysis using real data collected by low-cost, single- and dual- frequency, multi-GNSS receivers for short- to long-baseline RTK positioning. Journal of Geodesy, 94, 91.

Paziewski J. (2020) Recent advances and perspectives for positioning and applications with smartphone GNSS observations. Measurement Science and Technology 31(9) 091001

Paziewski J., Fortunato M., Mazzoni A., Odolinski R., (2021), An analysis of multi-GNSS observations tracked by recent Android smartphones and smartphone-only relative positioning results, Measurement. 175 109162

Paziewski J., Pugliano G., Robustelli U., (2020), Performance assessment of GNSS single point positioning with recent smartphones. In: 2020 IMEKO TC-19 International Workshop on Metrology for the Sea Naples, Italy, October 5-7, 2020. pp. 197-201

Retscher G., Gikas V., Hofer H., Perakis H., Kealy A. (2019) "Range validation of UWB and Wi-Fi for integrated indoor positioning", Applied Geomatics, 11:187–195

Retscher G., Kealy A., Gabela J., Li Y., Goel S., Toth C.K., Masiero A., Błaszczak-Bąk W., Gikas V., Perakis H., Koppanyi Z., Grejner-Brzezinska D.A., (2020), A Benchmarking Measurement Campaign in GNSS-denied/challenged Indoor/Outdoor and Transitional Environments. Journal of Applied Geodesy, Vol. 14, No. 2, ISSN 1862-9016

Robustelli U., Baiocchi V., Pugliano G. (2019) Assessment of dual frequency GNSS observations from a Xiaomi Mi 8 android smartphone and positioning performance analysis. Electronics (Switzerland), 2019, 8(1), 91

Robustelli U., Paziewski J., Pugliano G., (2021), Observation quality assessment and performance of GNSS standalone positioning with code pseudoranges of dual-frequency Android smartphones, Sensors, 21(6), 2125

Zhu F., Tao X., Liu W., Shi X., Wang F., Zhang X. (2019) Walker: Continuous and Precise Navigation by Fusing GNSS and MEMS in Smartphone Chipsets for Pedestrians. Remote Sensing, 11(2), 139.

Book chapters:

Gikas V., Retscher G., Kealy A. (2019) “Collaborative Positioning for Urban Intelligent Transportation Systems (ITS) and Personal Mobility (PM): Challenges and Perspectives” in Mobility Patterns, Big Data and Transport Analytics, Elevier Inc., https://doi.org/10.1016/B978-0-12-812970-8.00015-4, pp381–414

Retscher G., A. Kealy, V. Gikas, J. Gabela, S. Goel, Y. Li, A. Masiero, C. K. Toth, H. Perakis, W. Błaszczak-Bąk, Z. Koppanyi, D. A. Grejner-Brzezinska (2020) A Benchmarking Measurement Campaign to Support Ubiquitous Localization in GNSS Denied and Indoor Environments. in: Freymueller J., L. Sanchez (Eds.): Beyond 100: ‘The Next Century in Earth and Space Science’. Proceedings of the 27th IUGG General Assembly2019, Montreal, Canada, July 8-18, 2019, Series: International Association of Geodesy Symposia, Vol. -, Springer-Verlag, Berlin, Heidelberg

Presentations at conferences:

Andrikopoulou E., Spyropoulou I., Perakis H., Gikas V. (2020) “Exploring Contributory Parameters of Pedestrian Movement Using Low Cost GNSS Receiver Data”, 8th Transport Research Arena TRA, Apr. 27–30, Helsinki, Finland

Kealy A., G. Retscher, J. Gabela, Y. Li, S. Goel, C. K. Toth, A. Masiero, W. Błaszczak-Bąk, V. Gikas, H. Perakis, Z. Koppanyi, D. A. Grejner-Brzezinska (2019): A Benchmarking Measurement Campaign in GNSS-denied/challenged Indoor/Outdoor and Transitional Environments. in: Papers presented at the FIG Working Week, April 22-26, 2019, Hanoi, Vietnam, 19 pgs. (paper 9837). Paper received the navXperience award for the best peer review paper within the area of positioning and measurement (FIG Commission 5).

Mascitelli A., Niyonkuru Meroni A., Barindelli S., Manzoni M., Tagliaferro G., Gatti A., ... & Monti Guarnieri A. (2020) TWIGA project activities for the enhancement of heavy rainfall predictions in Africa: low-cost GNSS network deployment and NWP model parameterization. In EGU General Assembly Conference Abstracts p. 16122

Masiero A., H. Perakis, J. Gabela, C. K. Toth, V. Gikas, G. Retscher, S. Goel, A. Kealy, Z. Koppanyi, W. Błaszczak-Bąk, Y. Li, D. A. Grejner-Brzezinska (2020): Indoor Navigation and Mapping: Performance Analysis of UWB-based Platform Positioning. ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXIV ISPRS Congress, June 14-20, 2020, Nice, France.

Paziewski J., Pugliano G., Robustelli U. (2020) Performance assessment of GNSS single point positioning with recent smartphones, IMEKO TC-19 International Workshop on Metrology for the Sea, Parthenope University of Naples, October 5 - 7, 2020

Paziewski J., Fortunato M., Mazzoni A., Odolinski R., Li G., Debelle M., Warnant R., and Gong X. (2021) The quality analysis of GNSS observations tracked by Android smart devices and positioning performance assessment, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-334, https://doi.org/10.5194/egusphere-egu21-334.

Tagliaferro G., Gatti A., & Realini E. (2019) Assessment of GNSS Zenith Total Delay Estimation Using Smart Devices. In Proc. 32nd Int. Tech. Meeting Satell. Division Inst. Navigat. ION GNSS+ pp. 3879-3891

Šegina E., Jemec Auflič M., Peternel T., Zupan M., Jež J., Realini E., ... & Reyes González J. (2020) Validation and interpretation of data obtained by the newly developed low-cost Geodetic Integrated Monitoring System (GIMS). In EGU General Assembly Conference Abstracts p. 5170

Robustelli U., Baiocchi V., Marconi L., Radicioni F., Pugliano G. (2020) Precise point positioning with single and dual-frequency multi-GNSS android smartphones CEUR Workshop Proceedings, 2020, 2626

Retscher G., Li Y., Kealy A., Gikas V. (2020) "The Need and Challenges for Ubiquitous Positioning, Navigation and Timing (PNT) using Wi-Fi", FIG Working Week 2020, Smart Surveyors for Land and Water Management, Amsterdam, The Netherlands, May 10-14, 2020

Meeting and communications during the period 2019-2020

1. A Special Issue „*Multi-GNSS Precise Positioning and Applications"* in Sensors on the objectives of the WG 4.4.3 (ed. R. Odolinski and A. Khodabandeh).
2. A Special Issue „*Recent Advances in Ubiquitous Positioning Systems for Mobility Applications*" in Measurement Science and Technology on the objectives of the WG 4.4.3 (ed. by J. Paziewski, A. Kealy, V. Gikas and J. Geng).
3. A Special Issue „High-Precision GNSS: Methods, Open Problems and Geoscience Applications—Part II" in Remote Sensing on the objectives of the WG 4.4.3 (ed. X. Li, J. Paziewski, M. Crespi).
4. The main meeting of the WG 4.4.3 took place during European Geoscience Union General Assembly that was held in April 2020, in Vienna, Austria (online). The chair of WG 4.4.3 was a convener of the dedicated session G.1.3 "High-precision GNSS: methods, open problems and Geoscience applications" (https://meetingorganizer.copernicus.org/EGU21/session/39911).

JSG 4.4.4: Assessment and validation of IGS products and open-source scientific software

Chair: *Yidong Lou (China)*
Vice Chair: TBD

Members

- Berkay Bahadur (Hacettepe University, Turkey)
- Deimos Ibáñez (Technical University of Catalonia, Spain)
- Feng Zhou (Shandong University of Science and Technology, China)
- Haojun Li (Tongji University, China)
- Weixing Zhang (Wuhan University, China)
- Xiaolei Dai (Wuhan University, China)
- Xiaopeng Gong (Wuhan University, China)

Activities and publications during the period 2019-2021

Main activities:

1. **Assessment of the positioning performance and tropospheric delay retrieval with precise point positioning using products from different analysis centers**

The performance of precise point positioning (PPP) strongly depends on the quality of satellite orbit and clock products. To give a full evaluation of PPP performance with the various publicly available precise satellite orbit and clock products, members in our group comprehensively investigates the positioning performance as well as tropospheric delay retrieval of GPS-, GLONASS-, and Galileo-only PPP with the precise products from eight International GNSS Service (IGS) (i.e., cod, emr, esa, gfz, grg, igs, jpl, and mit) and five multi-GNSS experiment (MGEX) analysis centers (ACs) (i.e., com, gbm, grm, jax, and wum) based on the observations of 90 MGEX tracking stations in a 1-month period (April 2019). The positioning performance in terms of convergence time and positioning accuracy is assessed by coordinate-static and coordinate-kinematic PPP modes, while the tropospheric delay estimation in terms of accuracy is evaluated by coordinate-fixed PPP mode. For GPS-and GLONASS-only PPP with different AC products, the positioning performances are comparable with each other except that with emr, jpl, mit, and jax products. Overall, the positioning performance with cod and com products provided by CODE ranks the first. For Galileo-only PPP, the grm product performs the best. For ZTD estimation, the accuracy derived from GPS-, GLONASS-, and Galileo-only solutions agrees well and the differences in accuracy among different AC products can be negligible.

2. **Galileo-based precise point positioning with different MGEX products**

Considering the remarkable progress of the Galileo constellation in recent years, members from our group evaluated the performance of dual- and single-frequency Galileo-based Precise Point Positioning (PPP) and its contribution to GPS and Galileo integration with different precise products generated by four analysis centers (ACs) within the context of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS). The daily observation dataset collected at ten IGS stations over one month was processed in both static and kinematic modes for Galileo-only, GPS-only and GPS/Galileo PPP scenarios. For dual-frequency PPP, the results demonstrate that while the Galileo-only solutions are highly comparable with GPS-only PPP for the static mode, the mean 3D positioning errors for Galileo-only processes are approximately 1-cm higher than those obtained from GPS-only solutions for all agencies. The analysis to evaluate the influence of Galileo satellites with highly eccentric orbits, namely E14 and E18, on the dual-frequency Galileo-only PPP performance indicates that including or excluding these satellites has an insignificant effect on the results. For single-frequency PPP, which is dependent on the GRAPHIC combination, Galileo-only PPP performs significantly better, approximately 40%, than GPS-only solutions in the static mode, whereas the kinematic Galileo-only and GPS-only PPP solutions are quite close for all agencies except for WHU. Also, the RMS of observation residuals for Galileo in single-frequency PPP was quite lower than that of GPS, which reveals that the observation quality of Galileo code measurements is better than GPS ones. Among the ACs, Galileo-based PPP solutions applying CODE products provided slightly better results than GFZ and CNES/CLS in general, while the processes using WHU products resulted in worse performance both in positioning accuracy and convergence time. Moreover, the integration of Galileo with GPS enhances PPP performance significantly in both static and kinematic modes.

3. Comparative analysis of MGEX products for post-processing multi-GNSS PPP

In recent years, the precise products generated by the International GNSS Service (IGS) as a part of the Multi-GNSS Experiment (MGEX) project have been increasingly used for multi-GNSS applications. Nowadays, six IGS Analysis Centers (ACs) have been providing GNSS products with different features. However, there is still neither a combined solution nor a standard accuracy definition for MGEX products, unlike the standard IGS products. For the GNSS techniques that are directly dependent on precise products, such as Precise Point Positioning (PPP), the quality of these products is a very crucial point in positioning performance. Members from this group have investigated the impact of MGEX products provided by different IGS ACs on post-processing PPP performance in terms of accuracy, availability, and consistency. An experimental test was performed including all possible multi-GNSS combinations of GPS, GLONASS, Galileo, and BeiDou. 24-hour observation datasets collected at ten IGS stations during the 1-month period of May 1–31 were processed with twelve PPP modes using all available precise products. As a first step, an analysis of product availability was carried out for the related MGEX precise products within the test period to be able to assess the impact of the availability on the test results. PPPH software was used to perform the test and the results were statistically assessed as regards positioning error, RMS error and convergence time. The results indicate that the PPP performance may considerably differ depending on the precise products utilized in the PPP process. For the test period, PPP solutions utilizing the precise products generated by GFZ (GeoForschungsZentrum Potsdam) and WU (Wuhan University) agencies have relatively better positioning performance for nearly all processing modes compared to other solutions. The quality and availability of precise products are significant factors which lay behind better PPP performance. On the other hand, while the integration of two or more systems significantly strength the PPP performance, GPS is still the dominant system for PPP and the solutions that do not include GPS constellation have very poor performance. The results also show that MGEX products have different impacts on the PPP performance as varying with the constellation involved in PPP solution and the geographical location of the station.

4. Initial assessment of BDS-3 B2b PPP Service

The China BeiDou global navigation satellite system (BDS-3) has started to provide free and open precise positioning service to users in China and surrounding areas since Jul 2020 on the GEO B2b signal. The initial assessment of BDS-3 PPP-B2b products and the PPP performance over a period of near five months from Jul 26, 2020 to Dec 19, 2020 was carried out by members from this group. Taking the GBM products as reference, the average signal-in-space ranging error (SISRE) of the disseminated orbit and clock products is approximately 82.3 cm (RMS) and 3.9 cm (STD) for BDS-3 satellites, and about 135.8 cm (RMS) and 7.5 cm (STD) for GPS. The average positioning error RMS at six permanent stations in China is about 2.1 (1.8) and 2.6 (2.1) cm in the horizontal and vertical component respectively for BDS-only (BDS+GPS) static PPP. In the kinematic PPP mode, the average positioning error (95%) at the same six stations is about 21.5 (15.2) and 33.4 (30.3) cm in the horizontal and vertical component respectively for BDS-only (BDS+GPS). In addition, two vehicle-based kinematic PPP tests show average position error (95%) of about 23.5 (18.6) and 48.8 (37.1) cm in horizontal and vertical respectively for BDS-only (BDS+GPS) PPP. The assessment results are overall in accordance with the official claim of centimeter-level in static mode and decimeter-level in kinematic mode from BDS-3 PPP service.

5. Activities of group members on open-source scientific software:

Dr. Deimos Ibáñez has finished the upgrade of gLAB software to support multi-constellation and SBAS DFMC. Dr. Deimos Ibáñez has updated gLAB software to v5.5.1 to support new ionospheric models, and fixed the processing problems with the updated ANTEX with multi-constellation and multi-frequency receiver APC. Dr.

Feng Zhou has finished the GAMP II – iPPP-RTK software, which can process GPS, GLONASS, BDS-2/3, Galileo, QZSS, and NavIC with single point positioning (SPP) and precise point positioning (PPP) functionality. Meanwhile, its real-time kinematic (RTK) module is still under development. After GAMP II – iPPP-RTK software is stable, it will be open sourced again in the near future.

Selected publications

Bahadur, B., & Nohutcu, M. (2018). PPPH: a MATLAB-based software for multi-GNSS precise point positioning analysis. GPS solutions, 22(4), 113.

Bahadur, B., & Nohutcu, M. (2020). Impact of observation sampling rate on Multi-GNSS static PPP performance. Survey Review, 1-10.

Bahadur, B., & Nohutcu, M. (2020). Galileo-based precise point positioning with different MGEX products. Measurement Science and Technology, 31 094009

Bahadur, B., & Nohutcu, M. (2020). Real-time single-frequency multi-GNSS positioning with ultra-rapid products. Measurement Science and Technology.

Bahadur, B., Nohutcu, M. (2021) Integration of variance component estimation with robust Kalman filter for single-frequency multi-GNSS positioning, Measurement, 173, 108596, https://doi.org/10.1016/j.measurement.2020.108596

Ge Yulong, Shuo Ding, Weijin Qin, Feng Zhou, Xuhai Yang (2020) Carrier phase time transfer with Galileo observations. Measurement, 159. doi: 10.1016/j.measurement.2020.107799

Ge Yulong, Shuo Ding, Weijin Qin, Feng Zhou, Xuhai Yang, Shengli Wang (2020) Performance of ionospheric-free PPP time transfer models with BDS-3 quad-frequency observations. Measurement, 160. doi: 10.1016/j.measurement.2020.107836

Gong X, Lou Y, Zheng F, Gu S, Shi C, Liu J, Jing G. Evaluation and calibration of BeiDou receiver-related pseudorange biases. GPS Solutions, 2019, 22(4).

Gong X, Gu S, Zheng F, Wu Q, Liu S, Lou Y (2021). Improving GPS and Galileo Precise Data Processing Based on Calibration of Signal Distortion Biases. Measurement. 174. 108981.

Li H, Xiao J, Yang L(2020). Modeling and application of the time-varying GPS differential code bias between C1 and P1 observations. Advances in Space Research, 65(1): 552-559

Li P, Zhou F, Li X (2020) Multi-GNSS inter-frequency clock bias products generation for triple-frequency precise point positioning. Submitted to Measurement, Science and Technology.

Zhang Z, Lou Y, Zheng F, Gu S (2021) ON GLONASS pseudo-range inter-frequency bias solution with ionospheric delay modeling and the undifferenced uncombined PPP. Journal of Geodesy, 95(3)

Zheng F, Gu S, Gong X, Lou Y, Fan L, Shi C. Real-time single-frequency pseudorange positioning in China based on regional satellite clock and ionospheric models. GPS Solutions, 2020, 24, 6 (2020), Bahadur, B., & Nohutcu, M. (2019). Comparative analysis of MGEX products for post-processing multi-GNSS PPP. Measurement, 145, 361-369.

Zheng F, Gong X, Lou Y, Gu S, Jing G, Shi C. Calibration of BeiDou Triple-Frequency Receiver-Related Pseudorange Biases and Their Application in BDS Precise Positioning and Ambiguity Resolution. Sensors, 2019,19(6): 3500

Zhou F, Dong D, Li P, Li X, Schuh H (2019) Influence of stochastic modeling for inter-system biases on multi-GNSS undifferenced and uncombined precise point positioning. GPS Solutions, 23(3): 59.

Zhou F, Xinyun Cao, Yulong Ge, Weiwei Li (2020) Assessment of the positioning performance and tropospheric delay retrieval with precise point positioning using products from different analysis centers. GPS Solutions, 24(1): 12. doi: 10.1007/s10291-019-0925-0

WG 4.4.5: GNSS Interference and Spoofing

Chair: *Lakshay Narula (USA)*
Vice Chair: *Sriramya Bhamidipati (University of Illinois Urbana-Champaign, USA)*

Members

- *Aanjhan Ranganathan (Northeastern University, USA)*
- *Andriy Konovaltsev (DLR, Germany)*
- *Chengjun Guo (University of Electronic Science and Technology, China)*
- *Christina Popper (NYU Abu Dhabi, UAE)*
- *Fabian Rothmaier (Stanford University, USA)*
- *James T. Curran (USA)*
- *Jason Gross (West Virginia University, USA)*
- *Joon Wayn Cheong (University of New South Wales, Australia)*
- *Kai Jansen (Ruhr-Universität Bochum, Germany)*
- *Mathieu Joerger (Virginia Tech, USA)*
- *Pau Closas (Northeastern University, USA)*
- *Samer Khanafseh (Illinois Institute of Technology, USA)*
- *Shinan Liu (University of Chicago, USA)*

Main activities and achievements during the period 2020-2021

1. Working Group Virtual Meetings & Seminars

The working group participated in a series of virtual meetings and seminars during the past year in light of the travel restrictions imposed by the pandemic. A brief summary of the virtual sessions organized as part of this working group is as follows:

- *June 2020*: On leveraging crowd-sourced ADS-B data to detect and localize GNSS spoofing attacks by Dr. Kai Jansen.
- *July 2020*: On spoofing GNSS/INS-based location tracking systems by Dr. Aanjhan Ranganathan.
- *November 2020*: On spoofing detection with direction-of-arrival measurements from a dual-polarized antenna by Fabian Rothmaier.
- *April 2021*: On reliable, low-cost spoofing detection with smartphone devices by Shinan Liu.

These meetings were 60—90 minutes in duration and attended by 10—12 members across different time zones. The invited speaker talks were followed by extensive discussion and feedback.

2. Working Group Activities & Initiatives

The working group has undertaken a few initiatives to support the research activities being performed by the group members.

- Acquired access to historical ADS-B database from adsbexchange.com to support research on detection and localization of GNSS spoofing attacks in-the-wild.
- Initiated work on development of a global GNSS interference situational-awareness map with crowd-sourced reporting of interference events along with associated evidence, data recordings, etc.

3. GNSS Spoofing Detection with ADS-B data

Over the past year, members of the working group have investigated the utility of ADS-B Out data for detection of GNSS interference activity. These efforts have followed two lines of research. On the one hand, Jansen et al. (2021) have developed a non-invasive crowd-sourced trust evaluation system to detect GNSS and ADS-B spoofing attacks on air-traffic surveillance. Taking advantage of the redundancy of geographically distributed ADS-B receivers, they have implemented verification tests to pursue security by wireless witnessing with the goal of protecting otherwise unsecured GNSS and ADS-B systems. The proposed system is shown to be effective in detecting both GNSS and ADS-B spoofing on real-world aircraft ADS-B data.

In contrast to the crowd-sourced security proposal above, Kujur et al. (2020a) have pursued a different line of investigation for on-board GNSS spoofing detection with the aid of an inertial navigation system (INS). They imagine a scenario where the spoofer tracks the ADS-B Out positions of the aircraft to execute a covert GNSS spoofing attack. In response, they propose a method to intentionally perturb the reported ADS-B positions such that a spoofed trajectory generated using these ADS-B data will be detectable by cross-examination against an INS. Furthermore, they analytically quantify the magnitude of ADS-B modulation that will be sufficient for spoofing detection.

4. First Results from Three Years of Interference Monitoring from Low-Earth Orbit

As massive low-earth orbit (LEO) broadband constellations are taking shape, the use of these satellites as probes for global GNSS interference monitoring has surfaced as an exciting new possibility. Observation of terrestrial GNSS interference from LEO is a uniquely effective technique for characterizing the scope, strength, and structure of interference and for estimating transmitter locations. Such details are useful for situational awareness and interference deterrence. Murrian et al. (To appear, 2021) have presented the results of a three-year study of global interference, with emphasis on a particularly powerful interference source active in Syria since 2017. Via Doppler positioning using a GPS receiver on the International Space Station (ISS), an estimate of the interference source's location is obtained whose horizontal errors are less than 1 km with 99% confidence. Such an accurate localization of a GNSS interference source from LEO is without precedent in the open literature.

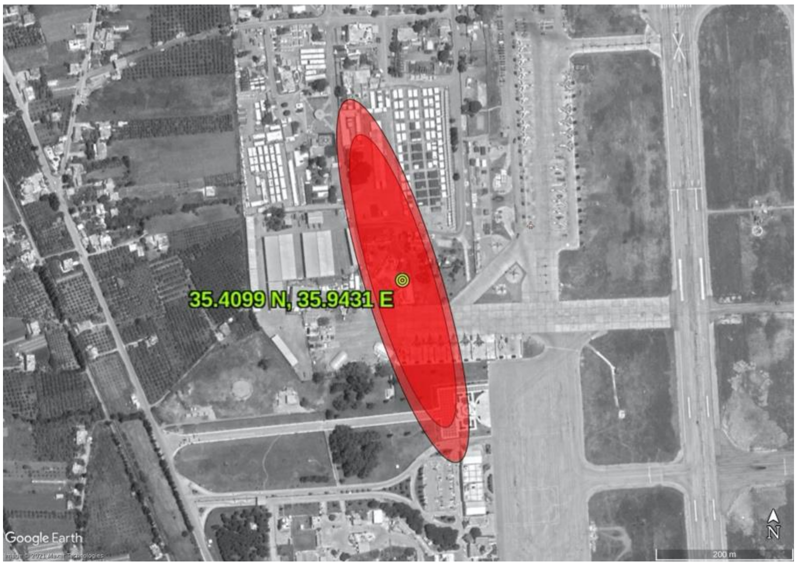


Figure 7. Estimated transmitter location overlaid on formal-error 95% and 99% horizontal error ellipses. The location is coincident with an airbase on the coast of Syria. The semi-major axis of the 95% ellipse is 220 meters.

5. Optimal Hypothesis Tests for GNSS Spoofing Detection

Several GNSS spoofing detection methods have been developed in the GNSS literature over the last 15 years. Over the last year, individual research from a member of the working group has made two notable contributions towards *optimal* combinations of such statistics to maximize the sensitivity of the detection tests. In the first contribution, Rothmaier et al. (2021a) have developed the most sensitive, broadly applicable implementation of an optimal direction of arrival based spoofing detector that provides up to 10x reduction in missed detections compared to the open literature with guaranteed false alert probability, and is robust against a scenario where only a subset of the satellites is being spoofed. In the second contribution, Rothmaier et al. (To appear, 2021b) have created a general statistical inference framework for optimal detection using an arbitrary number of metrics that could have been formulated based on a broad variety of spoofing detection techniques developed in the literature thus far. They have identified that an optimal hypothesis test based on a combination of received signal power, correlation function distortion, and pseudorange residuals is both low-cost and extremely powerful.

Selected publications during the period 2020-2021:

Lo, S., Chen, Y. H., Rothmaier, F., Zhang, G., & Lee, C. (2020, January). Developing a Dual Polarization Antenna (DPA) for High Dynamic Applications. In *Proceedings of the 2020 International Technical Meeting of The Institute of Navigation* (pp. 1001-1020).

Pérez-Marcos, E., Kurz, L., Cuntz, M., Caizzone, S., Konovaltsev, A., & Meurer, M. (2020, April). ITAR Free Smart Antenna Array for Resilient GNSS in Aviation. In *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)* (pp. 606-611).

LaMountain, G., & Closas, P. (2020, April). Maneuver Optimization for Synthetic Aperture based DOA estimation of GNSS Jammers. In *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)* (pp. 44-49).

Turner, M., Wimbush, S., Enneking, C., & Konovaltsev, A. (2020, April). Spoofing Detection by Distortion of the Correlation Function. In *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)* (pp. 566-574). IEEE.

Kujur, B., Khanafseh, S., & Pervan, B. (2020a, April). Detecting GNSS spoofing of ADS-B equipped aircraft using INS. In *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)* (pp. 548-554). IEEE.

Rothmaier, F. (2020, September). Optimal Sequential Spoof Detection based on Direction of Arrival Measurements. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*.

Kujur, B., Khanafseh, S., & Pervan, B. (2020b, September). A Solution Separation Monitor using INS for Detecting GNSS Spoofing. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*.

Borhani-Darian, P., Li, H., Wu, P., & Closas, P. (2020, September). Deep Neural Network Approach to Detect GNSS Spoofing Attacks. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*.

Kor, R.X.T., Iannucci, P.A., Narula, L., & Humphreys, T.E. (2020, September). A Proposal for Securing Terrestrial Radio-Navigation Systems. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*.

Bhamidipati, S., & Gao, G.X. (2020, September). GPS Spoofing Mitigation and Timing Risk Analysis in Networked PMUs via Stochastic Reachability. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*.

Lee, D. K., Miralles, D., Akos, D., Konovaltsev, A., Kurz, L., Lo, S., & Nedelkov, F. (2020, November). Detection of GNSS Spoofing using NMEA Messages. In *2020 European Navigation Conference (ENC)* (pp. 1-10). IEEE.

Liu, S., Cheng, X., Yang, H., Shu, Y., Weng, X., Guo, P., ... & Yang, Y. (2021) Stars Can Tell: A Robust Method to Defend against GPS Spoofing Attacks using Off-the-shelf Chipset. In *Proceedings of the 30th USENIX Security Symposium (USENIX Security 21)*.

Rothmaier, F., Chen, Y.-H., Lo, S., & Walter, T. (2021a). GNSS Spoofing Detection through Spatial Processing. *Navigation, Journal of the Institute of Navigation*.

Rothmaier, F., Chen, Y., Lo, S., & Walter, T. (To appear, 2021b). A Framework for GNSS Spoofing Detection through Combinations of Metrics. *IEEE Transactions on Aerospace and Electronic Systems*.

Rothmaier, F., Chen, Y. H., Lo, S., & Walter, T. (2021c). GNSS Spoofing Mitigation in the Position Domain. In *Proceedings of the 2021 International Technical Meeting of The Institute of Navigation* (pp. 42-55).

Murrian, M. J., Narula, L., Iannucci, P. A., Budzien, S., O'Hanlon, B. W., Psiaki, M. L., & Humphreys, T. E. (Under review, 2021). First Results from Three Years of GNSS Interference Monitoring from Low Earth Orbit. *Navigation, Journal of the Institute of Navigation*.

Jansen, K., Niu, L., Xue, N., Martinovic, I., & Pöpper, C. (2021, February). Trust the Crowd: Wireless Witnessing to Detect Attacks on ADS-B-Based Air-Traffic Surveillance. In *Proceedings of the Network and Distributed System Security Symposium (NDSS)*.

Inter-Commission Committee on Theory (ICCT)

http://icct.kma.zcu.cz

President Pavel Novák (Czech Republic)
Vice President: Mattia Crespi (Italy)

Structure

Joint Study Group T.23:	Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables
Joint Study Group T.24:	Integration and co-location of space geodetic observations and parameters
Joint Study Group T.25:	Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics
Joint Study Group T.26:	Geoid/quasi-geoid modelling for realization of the geopotential height datum
Joint Study Group T.27:	Coupling processes between magnetosphere, thermosphere and ionosphere
Joint Study Group T.28:	Forward gravity field modelling of known mass distributions
Joint Study Group T.29:	Machine learning in geodesy
Joint Study Group T.30:	Dynamic modelling of deformation, rotation and gravity field variations
Joint Study Group T.31:	Multi-GNSS theory and algorithms
Joint Study Group T.32:	High-rate GNSS for geoscience and mobility
Joint Study Group T.33:	Time series analysis in geodesy and geodynamics
Joint Study Group T.34:	High resolution harmonic analysis and synthesis of potential fields
Joint Study Group T.35:	Advanced numerical methods in physical geodesy
Joint Study Group T.36:	Dense troposphere and ionosphere sounding
Joint Study Group T.37:	Theory and methods related to combination of high-resolution topographic/bathymetric models in geodesy

Overview

Terms of Reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System (GGOS). In accordance with the IAG by-laws, the first two 4-year periods were reviewed in 2011. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure.

The main objectives of the ICCT are:

- to be the international focal point of theoretical geodesy,
- to encourage and initiate activities to further geodetic theory,
- and to monitor research developments in geodetic modelling.

ICCT's Steering Committee 2019-2023

President	*Pavel Novák* (Czechia)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Commission 1	*Christopher Kotsakis* (Greece)
Commission 2	*Mirko Reguzzoni* (Italy)
Commission 3	*Janusz Bogusz* (Poland)
Commission 4	*Allison Kealy* (Australia)
GGOS	*Michael Schmidt* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)
IAG	*Bofeng Li* (China)
IAG	*Marcelo Santos* (Canada)

During the 2019-2021 period, the ICCT Steering Committee did not meet physically due to travel restrictions imposed by the COVID-19 pandemic. ICCT-related business was discussed at several on-line meetings of the IAG's Executive Committee which could be considered as substitution of the ICCT Steering Committee meetings as their memberships largely overlap. The ICCT President informed members of the IAG Executive Committee about the structure of the ICCT, activities of its joint study groups and about planning the jubilee X. Hotine-Marussi Symposium on Mathematical Geodesy which will be organized by ICCT in 2022. The next meeting of the Committee will be organized during the Scientific Assembly of IAG, Beijing, China, in June-July 2021.

ICCT Website

The ICCT website is hosted at *http://icct.kma.zcu.cz* by the web server of the Department of Geomatics, University of West Bohemia in Pilsen, Czechia, and is powered by the MediaWiki Engine (similar to that used for the Wikipedia, a free, web-based multilingual encyclopaedia project). Due to this setup, the content of the ICCT Website can easily be edited by any authorized personnel (members of the ICCT Steering Committee and Chairs of the Study Groups). Thus, the website can be used by for fast and easy communication of ideas among the members of the Study Groups.

X. Hotine-Marussi Symposium

The highlight of ICCT activities within the four-year period between two consecutive IUGG General Assemblies is the organization of the Hotine-Marussi Symposium on Mathematical Geodesy. Since the inception of ICCT, the already existing series of the Hotine-Marussi Symposia had fallen under the responsibility of ICCT. Previous ICCT-organized symposia include VI. (2006, Wuhan), VII. (2009, Rome), VIII (2013, Rome) and IX. (Rome, 2018) symposia. The venue of the last three Hotine-Marussi Symposia was the Faculty of Engineering of the Sapienza University of Rome. The jubilee X. Hotine-Marussi Symposium should be held in Milano, 13-17 June 2022. Anticipated session topics will approximately follow the current joint study group structure of ICCT.

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Session dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at EGU General Assemblies 2020 and 2021 in Vienna. Other sessions on particular topics of theoretical geodesy related to joint study groups' activities are usually included in scientific programs of other IAG meetings (meetings of the

IAG commissions, GGOS or meetings of the IAG services). However, the pandemic situation in 2020-2021 significantly influenced organization of many scientific meetings (they were either cancelled or postponed, only some were organized in the on-line mode).

Summary on Activities of Joint Study Groups

The activities of the ICCT are related namely to research activities carried out by members of its joint study groups. Their midterm reports specify main research areas under investigation, achieved results and outputs (namely publications and presentations). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the level of co-operation and/or interaction between its members is not necessarily the same for all the joint study groups. Some of the study groups extended its memberships.

Most importantly, JSG's chairmen delivered their report in time which confirms the main idea behind the current ICCT structure: involving young enthusiastic researchers as new study group chairmen who actively cooperate internationally at research topics which matter to current geodesy. Based on to-date activities of the groups, it is very likely they will remain operational until 2023 with the X. Hotine-Marussi Symposium on Mathematical Geodesy planned for 2022 highlighting the remaining two years of the period 2019-2023.

Joint Study Group T.23: Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables

Chair: *Michal Šprlák (Czechia)*

Members

Sten Claessens (Australia)
Mehdi Eshagh (Sweden)
Ismael Foroughi (Canada)
Peter Holota (Czechia)
Juraj Janák (Slovakia)
Otakar Nesvadba (Czechia)
Pavel Novák (Czechia)
Vegard Ophaug (Norway)
Martin Pitoňák (Czechia)
Michael Sheng (Canada)
Natthachet Tangdamrongsub (USA)
Robert Tenzer (Hong Kong)

1. Activities of the group

Members of JSG T.23 primarily focused on mutual cooperation and published their research findings in international journals on geodesy, geophysics and planetary sciences (e.g., Earth-Science Reviews, Geophysical Journal International, Icarus, Journal of Geodesy, or Planetary and Space Science). This effort has resulted in 21 peer-reviewed articles that suggests an active collaboration of the group members and actual research topic.

The list of selected peer-reviewed publications is provided below. The research articles addressed five (out of seven) objectives of JSG T.23 in a broader sense. Ophaug and Gerlach (2020) investigated error propagation in regional geoid determination using spherical splines, least-squares collocation, and Stokes's formula. Goli et al. (2019b) studied the effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. Precise and efficient numerical procedures were developed and applied for regional geoid determination by the one-step integration method (Goli et al. 2019a), Stokes-Helmert method (Foroughi et al. 2019), and the KTH approach (Varga et al. 2021). Pitoňák et al. (2019, 2020a, b) proposed functional models for optimal combination of distinct gravitational field quantities by spectral weighting and least-squares.

Novák et al. (2019) reviewed spherical integral formulas transforming the volumetric density to higher-order gravitational gradients up to the third order. Šprlák et al. (2020a) employed Newton's integral in the spectral domain to solve direct and inverse problems for the Moon. Šprlák et al. (2020b) derived spherical integral estimators relating the line-of-sight gravitational acceleration to an arbitrary order radial derivative of the gravitational potential and performed regional inversion with synthetic and realistic GRAIL observations.

Spheroidal integral transformations, which are particularly important for the gravitational field modelling of oblate or prolate planetary bodies, were presented in four contributions. Ghobadi-Far et al. (2019) formulated a rigorous spheroidal approach for the surface mass estimation. Holota and Nesvadba (2019a, b) discussed Neumann's problem formulated for the exterior of an oblate ellipsoid of revolution. Šprlák et al. (2020c) developed a rigorous spheroidal forward modelling technique.

Other research contributions reached beyond the specified objectives of JSG T.23 as the theoretical apparatus of integral transformations may be used for numerous applications, e.g., in geophysics. Chen and Tenzer (2020) formulated Parker-Oldenburg's method for the estimation of the density interface depth in the spherical approximation. Vajda et al. (2020) presented a comprehensive view of the origin, significance, and implications of topographic effects in gravimetry. Sheng et al. (2019) introduced and validated a global laterally varying topographical density model for the Earth. Rathnayake et al. (2020) analysed interpretational properties of Bouguer gravity maps and Tenzer et al. (2020) investigated geoid-to-quasigeoid separation due to the laterally variable density distribution. Eshagh et al. (2020) developed a mathematical model for describing the stress propagation from the sub-lithosphere through the lithosphere and used GRACE products to demonstrate applicability of this model.

Members of JSG T.23 actively presented their research findings at major international conferences (e.g., 27th IUGG General Assembly or the annual meetings organized by EGU and AGU). The list of selected oral and poster presentations is provided below.

Except for the scientific activities, members of JSG T.23 organised international conferences. Namely, Holota and Nesvadba organized the session G1.1 called "Recent Developments in Geodetic Theory", which is regularly held at the EGU General Assemblies.

2. Achievements and results

Cooperation among the members of JSG T.23 resulted in several notable achievements, e.g., 1- Foroughi et al. (2019) employed the UNB geoid determination approach and determined a sub-centimetre geoid model in the Auvergne test area. 2- Ghobadi-Far et al. (2019) derived a one-to-one relationship between ellipsoidal spectra of surface mass and gravitational potential for the spheroidal geometry. This mathematical relationship allows accurate determination of surface mass from time-variable gravitational field models. 3- The review papers by Novák et al. (2019) and Vajda et al. (2020) were published in the prestigious journal Earth-Science Reviews (impact factor 9.72). 4- Sheng et al. (2019) compiled the first laterally varying topographical density model for the Earth with associated error estimates. 5- Šprlák et al. (2020b) estimated a global laterally varying crustal mass density model for the Moon. This lunar density model was parametrised by spherical harmonics and is available at the ICGEM webpage. 6- Šprlák et al. (2020c) computed the first spheroidal gravitational field models generated by the crustal masses of the Moon and the dwarf planet 1 Ceres.

3. Interactions with the IAG Commissions and GGOS

Members of JSG T.23 collaborated with researchers from JSG T.26 "Geoid/quasi-geoid modelling for realization of the geopotential height datum" and JWG 2.2.2 "Error assessment of the 1 cm geoid experiment" of Commission 2.

4. Refined plans for the period of 2021-2023

Travel restrictions were introduced due to COVID-19 pandemic. This influenced direct participation of JSG T.23 members at conferences and resulted in a smaller amount of oral or poster presentations. Otherwise, research cooperation is ongoing through online tools and was not considerably affected. As such, we do not propose any changes in the activities and objectives of the JSG.

5. Publications

Selected peer-reviewed publications

Chen W, Tenzer R (2020) Reformulation of Parker-Oldenburg's method for Earth's spherical approximation. *Geophysical Journal International* 222(2): 1046-1073

Eshagh M, Fatolazadeh F, Tenzer R (2020) Lithospheric stress, strain and displacement changes from GRACE-FO time-variable gravity: case study for Sar-e-Pol Zahab Earthquake 2018. *Geophysical Journal International* 223(1): 379-397

Foroughi I, Vaníček P, Kingdon RW, Goli M, Sheng M, Afrasteh Y, Novák P, Santos MC (2019) Sub-centimetre geoid. *Journal of Geodesy* 93(6): 849-868

Ghobadi-Far K, Šprlák M, Han S-C (2019) Determination of ellipsoidal surface mass change from GRACE time-variable gravity data. *Geophysical Journal International* 219(1): 248-259

Goli M, Foroughi I, Novák P (2019a) Application of the one-step integration method for determination of the regional gravimetric geoid. *Journal of Geodesy* 93(9): 1631-1644

Goli M, Foroughi I, Novák P (2019b) The effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. *Studia Geophysica et Geodaetica* 63(1): 35-54

Holota P, Nesvadba O (2019a) Galerkin's matrix for Neumann's problem in the exterior of an oblate ellipsoid of revolution: Gravity potential approximation by buried masses. *Studia Geophysica et Geodaetica* 63(1): 1-34

Holota P, Nesvadba O (2019b) Green's function method extended by successive approximations and applied to Earth's gravity field recovery. In: Novák P, Crespi M, Sneeuw N, Sansò F (eds) IX Hotine-Marussi Symposium on Mathematical Geodesy. *International Association of Geodesy Symposia* 151: 33-39, Springer, Cham.

Novák P, Pitoňák M, Šprlák M, Tenzer R (2019) Higher-order gravitational gradients for geoscientific applications. *Earth-Science Reviews* 198: 102937

Ophaug V, Gerlach C (2020) Error propagation in regional geoid computation using spherical splines, least-squares collocation and Stokes's formula. *Journal of Geodesy* 94(12): 120

Pitoňák M, Novák P, Šprlák M, Tenzer R (2019) On combining the directional solutions of the gravitational curvature boundary-value problem. In: Novák P, Crespi M, Sneeuw N, Sansò F (eds) IX Hotine-Marussi Symposium on Mathematical Geodesy. *International Association of Geodesy Symposia* 151: 41-47 Springer, Cham.

Pitoňák M, Novák P, Eshagh M, Tenzer R, Šprlák M (2020a) Downward continuation of gravitational field quantities to an irregular surface by spectral weighting. *Journal of Geodesy* 94(7): 62

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020b) Validation of GOCE-based gravitational gradients grids by spectral combination method. In: Proceedings of the International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Technical University, Brno, Czech Republic, pp. 28-36.

Rathnayake S, Tenzer R, Novák P, Pitoňák M (2020) Effect of the lateral topographic density distribution on interpretational properties of Bouguer gravity maps. *Geophysical Journal International* 220(2): 892-909

Sheng MB, Shaw C, Vaníček P, Kingdon RW, Santos M, Foroughi I (2019) Formulation and validation of a global laterally varying topographical density model. *Tectonophysic*s 762: 45-60

Šprlák M, Han S-C, Featherstone W (2020a) Crustal density and global gravitational field estimation of the Moon from GRAIL and LOLA satellite data. *Planetary and Space Science* 192: 105032

Šprlák M, Han S-C, Featherstone W (2020b) Integral inversion of GRAIL inter-satellite gravitational accelerations for regional recovery of the lunar gravitational field. *Advances in Space Research* 65(1): 630-649

Šprlák M, Han S-C, Featherstone W (2020c) Spheroidal forward modelling of the gravitational fields of 1 Ceres and the Moon. *Icarus* 335: 113412

Tenzer R, Chen W, Rathnayake S, Pitoňák M (2020) The effect of anomalous global lateral topographic density on the geoid-to-quasigeoid separation. *Journal of Geodesy* 95(1): 12

Vajda P, Foroughi I, Vaníček P, Kingdon R, Santos M, Sheng M, Goli M (2020) Topographic gravimetric effects in earth sciences: Review of origin, significance and implications. *Earth-Science Reviews* 211: 103428

Varga M, Pitoňák M, Novák P, Bašić T (2021) Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. *Journal of Geodesy* 95(5): 53

Selected oral and poster presentations

Ghobadi-Far K, Han S-C, Šprlák M, Papanikolaou T, Loomis B (2019) On the along-track data analysis of GRACE and GRACE Follow-On KBR and LRI data. GRACE Follow-On Science Team Meeting, October 8-10, Pasadena, California, USA.

Ghobadi-Far K, Šprlák M, Han S-C (2019) Comparison of spherical and ellipsoidal cryospheric mass change estimated from GRACE time-variable gravity data. Global Isostatic Adjustment Training School, August 26-30, Gävle, Sweden.

Ghobadi-Far K, Šprlák M, Han S-C (2019) Conversion of GRACE time-variable gravity data into surface mass change on the ellipsoid. GRACE Follow-On Science Team Meeting, October 8-10, Pasadena, California, USA.

Holota P (2019) Divergence of gradient and the solution domain in gravity field studies. Presented at the Wissenschaftliches “Kolloquium Ein und ein halbes Jahrhundert internationale Zusammenarbeit der Geodäten und Geophysiker” organized by the Leibniz-Sozietät der Wissenschaften zu Berlin e.V. in cooperation with the Helmholtz-Zentrum Potsdam - GFZ, 15 February, Potsdam, Germany.

Holota P, Nesvadba O (2019) Integral representation and Green’s function method in gravity field studies. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Holota P, Nesvadba O (2019) On the construction of Green’s function when combining terrestrial data and global models for Earth’s gravity field recovery. European Geosciences Union General Assembly, April 7-12, Vienna, Austria.

Holota P, Nesvadba O (2019) Using the Green’s function method for solution domains with a complicated boundary in Earth’s gravity field studies. European Geosciences Union General Assembly, April 7-12, Vienna, Austria.

Holota P, Nesvadba O (2020) Differential geometry and curvatures of equipotential surfaces in the realization of the World Height System. European Geosciences Union General Assembly, May 4-8, online.

Holota P, Nesvadba O (2020) Laplacian structure, solution domain geometry and successive approximations in gravity field studies. European Geosciences Union General Assembly, May 4-8, online.

Holota P, Nesvadba O (2021) Laplacian structure mirroring surface topography in determining the gravity potential by successive approximations. European Geosciences Union General Assembly, April 19-30, online.

Novák P, Pitoňák M, Šprlák M, Tenzer R (2019) Higher-order gradients of the gravitational potential: theory and applications. AGU Fall Meeting, December 9-13, San Francisco, USA.

Ophaug V, Gerlach C (2019) Error propagation in regional geoid computation using spherical splines, least-squares collocation, and Stokes's formula. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Pitoňák M, Tenzer R, Šprlák M, Novák P (2019) On formal accuracy of global gravitational models of telluric planets and Moon. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020) An overview on the spectral combination of integral transformations. European Geosciences Union General Assembly, May 4-8, online.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020) Validation of GOCE-based gravitational gradients grids by spectral combination method. International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Brno, Czech Republic.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2021) Validation of calibrated GOCE gravity gradients GRD_SPW_2 by least-squares spectral weighting. European Geosciences Union General Assembly, April 19-30, online.

Šprlák M, Han S-C, Featherstone WE (2019) High-resolution gravitational field of the Moon from GRAIL inter-satellite tracking and LOLA topography data. 19th Australian Space Research Conference, September 30 – October 2, Adelaide, Australia.

Šprlák M, Ghobadi-Far K, Han S-C (2020) Determination of surface mass from GRACE and GRACE-FO. In: Proceedings of the International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Technical University, Brno, Czech Republic, p. 52.

Joint Study Group T.24: Integration and co-location of space geodetic observations and parameters

***Chair**: Krzysztof Sośnica (Poland)*

Members

Tzu-Pang Tseng (Australia)
Daniela Thaller (Germany)
Radosław Zajdel (Poland)
Grzegorz Bury (Poland)
Erik Schnoemann (Germany)
Florian Dilssner (Germany)
Dariusz Strugarek (Poland)
Mathis Blossfeld (Germany)
Julian Zeitlhöfler (Germany)
Mateusz Drożdżewski (Poland)
Toshimichi Otsubo (Japan)
Susanne Glaser (Germany)
Janina Boisits (Austria)
Urs Hugentobler (Germany)
Hongjuan Yu (China)

1. Activities of the group

In the framework of JSG T.24 activities, the following topics were examined:

- Co-location of Global Navigation Satellite System (GNSS) microwave and Satellite Laser Ranging (SLR) observations onboard Galileo and GLONASS satellites for improving the quality of precise GNSS orbits and future reference frame realizations based on space ties (e.g., Bury et al. 2021).
- Analysis of geocenter coordinates derived from SLR observations to LAGEOS, GPS, GLONASS, and Galileo observations, as well as DORIS and GRACE data (Kosek et al. 2020; Zajdel et al. 2021; Yu et al. 2021b).
- Integration of GPS, GLONASS, and Galileo data to derive daily and sub-daily Earth rotation parameters: polar motion and length-of-day excess with an analysis of system-specific systematic errors emerging from satellite orbit modelling (Zajdel et al. 2020, 2021).
- Integration of SLR observations to various Low Earth Orbiters (LEO) with precise GPS-based orbits, such as Sentinel-3A/B, SWARM, GRACE, TanDEM-X, with geodetic LAGEOS and LARES satellites and Galileo data to derive SLR station coordinates, geocenter motion, and Earth rotation parameters (Strugarek et al. 2019, 2021).
- Realization of SLR reference frames based on integrated observations to active LEO and passive LAGEOS satellites in different approaches of the network realization: constrained approach and unconstrained SLR-PPP approach (Strugarek et al. 2019).
- Analysis of SLR-derived low-degree gravity field coefficients including the Earth’s oblateness term with a comparison to geophysical models and climate-driven constituents (Yu et al. 2021a).
- Improving the consistency and identification of systematic effects between Galileo, GPS, GLONASS, and BeiDou solutions (Hadaś et al. 2019, Kaźmierski et al. 2020, Sośnica et al. 2020, Zajdel et al. 2019a).

- Analysis of the impact of general relativistic effects on GNSS and LAGEOS orbits with assessing the order of magnitude for orbital perturbations caused by the Schwarzschild, Lense-Thirring, and de Sitter effects (Sośnica et al. 2021).
- Investigation of the best reference frame constraining approaches: no-net-translation and no-net-rotation and the network effects for GPS, GLONASS, and Galileo combined solutions, as well as SLR-based LAGEOS solutions (Zajdel et al. 2019a, 2019b).
- Precise orbit determination and validation of the combination methodology of the GNSS satellite orbits for, e.g., IGS repro3 and future ITRF realizations, based on SLR-to-GNSS data and intensive ILRS campaigns (Bury et al. 2019, 2020, Sośnica et al. 2020).
- Improving a consistency between SLR and other space geodetic techniques by modelling and properly handling tropospheric delays with horizontal gradients (Drożdżewski et al. 2019).

2. Achievements and results

The achievements of the IAG study group concern three main aspects:

- Development of the methodology for the integration of space geodetic techniques onboard GNSS satellites, especially GNSS and SLR, for future terrestrial frame realizations with the co-location in space.
- Identification and modeling of systematic effects in geodetic observations and parameters.
- Determination of global geodetic parameters, such as geocenter motion, the Earth's oblateness term, and Earth's rotation parameters based on multi-technique and multi-constellation solutions.

The results were discussed during the meetings, disseminated during workshops and scientific conferences, and finally published in a number of peer-reviewed papers, see Publications. The activities included the organization of a dedicated session of the IAG Scientific Assembly 2021 "Terrestrial and space geodetic ties for multi-technique combinations" with 17 abstracts in the session.

3. Interactions with the IAG Commissions and GGOS

The International GNSS Service (IGS) Analysis Centre Coordinator (ACC), in the framework of IGS experimental Multi-GNSS Orbit Combination, provided the initial orbit products based on new combination procedures. ITRF2020 will be the very first reference frame that includes the Galileo system. In the framework of the JSG T.24 activities, a number of tests have been conducted to check the Galileo applicability to realize terrestrial reference frames, determination, and quality assessment of Galileo-based global geodetic parameters. Moreover, the procedures for the orbit combination were tested using SLR observations to Galileo, GLONASS, BeiDou, and QZSS together with IGS ACC (Sośnica et al. 2020), confirming the superior quality of combined Galileo orbits for IGS contribution to ITRF2020, which is of fundamental interest of IAG Commission 1. A series of intensive GNSS tracking campaigns were launched by the International Laser Ranging Service (ILRS). The ILRS data were employed for the GNSS orbit validation and SLR-GNSS co-location in space and to improve GGOS products. The topics related to identifying the systematic effects and biases in SLR data caused by tropospheric effects and improving the consistency of SLR and GNSS tropospheric products were studied in the framework of the cooperation with IAG JSG "Intra- and Inter-Technique Atmospheric Ties".

4. Refined plans for the period of 2021-2023

The activities for 2021-2023 include:

- To investigate possibilities to enhance the consistency between space geodetic techniques and parameters throughout the international collaboration, the realization of joint scientific projects, and publishing papers.
- To launch a proposal for two state-of-the-art review papers on co-location onboard LEO and GNSS and combination of global geodetic parameters co-authored by JSG members.
- To promote sessions and presentation of the research results at international symposia related to Earth sciences (IAG/IUGG, EGU, AGU, EUREF, IGS, ILRS) and organization of a dedicated workshop.
- To establish a web page with information concerning the co-location in space, the combination of global geodetic parameters and the exchange of ideas, provision and updating the bibliographic list of references of research results and relevant publications from different combination centers.

5. Publications

Bury G, Sośnica K, Zajdel R, Strugarek D, Hugentobler U (2021) Determination of precise Galileo orbits using combined GNSS and SLR observations. *GPS Solutions* 25(11), https://doi.org/10.1007/s10291-020-01045-3.

Bury G, Sośnica K, Zajdel R, Strugarek D (2020) Toward the 1-cm Galileo orbits: challenges in modeling of perturbing forces. *Journal of Geodesy* 94(16), https://doi.org/10.1007/s00190-020-01342-2.

Bury G, Zajdel R, Sośnica K (2019) Accounting for perturbing forces acting on Galileo using a box-wing model. *GPS Solutions* 23(74), https://doi.org/10.1007/s10291-019-0860-0.

Drożdżewski M, Sośnica K, Zus F, Balidakis K (2019) Troposphere delay modeling with horizontal gradients for satellite laser ranging. *Journal of Geodesy* 93(10): 1853-1866, https://doi.org/10.1007/s00190-019-01287-1.

Hadaś T, Kaźmierski K, Sośnica K (2019) Performance of Galileo-only dual-frequency absolute positioning using the fully serviceable Galileo constellation. *GPS Solutions* 23(108), https://doi.org/10.1007/s10291-019-0900-9.

Kaźmierski K, Zajdel R, Sośnica K (2020) Evolution of orbit and clock quality for real-time multi-GNSS solutions. *GPS Solutions* 24(111), https://doi.org/10.1007/s10291-020-01026-6.

Kosek W, Popiński W, Wnęk A, Sośnica K, Zbylut-Górska M (2020) Analysis of systematic errors in geocenter coordinates determined from GNSS, SLR, DORIS, and GRACE. *Pure and Applied Geophysics* 177: 867-888, https://doi.org/10.1007/s00024-019-02355-5.

Sośnica K, Zajdel R, Bury G, Bosy J, Moore M, Masoumi S (2020) Quality assessment of experimental IGS multi-GNSS combined orbits. *GPS Solutions* 24(54), https://doi.org/10.1007/s10291-020-0965-5.

Sośnica K, Bury G, Zajdel R, Kaźmierski K, Ventura-Traveset J, Prieto-Cerdeira R, Mendes L (2021) General relativistic effects acting on the orbits of Galileo satellites. *Celestial Mechanics and Dynamical Astronomy* 133(14): 1-31, https://doi.org/10.1007/s10569-021-10014-y.

Strugarek D, Sośnica K, Arnold D, Jäggi A, Zajdel R, Bury G (2021) Determination of SLR station coordinates based on LEO, LARES, LAGEOS, and Galileo satellites. *Earth, Planets and Space* 73(87): 1-21, https://doi.org/10.1186/s40623-021-01397-1.

Strugarek D, Sośnica K, Arnold D, Jäggi A, Zajdel R, Bury G, Drożdżewski M (2019) Determination of global geodetic parameters using satellite laser ranging measurements to Sentinel-3 satellites. *Remote Sensing* 11(19): 2282, https://doi.org/10.3390/rs11192282.

Yu H, Chen Q, Sun Y, Sośnica K (2021a) Geophysical signal detection in the Earth's oblateness variation and its climate-driven source analysis. *Remote Sensing*, 13(10): 2004, https://doi.org/10.3390/rs13102004.

Yu H, Sośnica K, Shen Y (2021b) Separation of geophysical signals in the LAGEOS geocenter motion based on singular spectrum analysis. *Geophysical Journal International*, 225(3): ggab063, 1-25, https://doi.org/10.1093/gji/ggab063.

Zajdel R, Sośnica K, Dach R, Bury G, Prange L, Jäggi A (2019a) Network effects and handling of the geocenter motion in multi-GNSS processing. *Journal of Geophysical Research-Solid Earth* 124(6): 5970-5989, https://doi.org/10.1029/2019JB017443.

Zajdel R, Sośnica K, Bury G, Dach R, Prange L (2020) System-specific systematic errors in earth rotation parameters derived from GPS, GLONASS, and Galileo. *GPS Solutions* 24(74), https://doi.org/10.1007/s10291-020-00989-w.

Zajdel R, Sośnica K, Drożdżewski M, Bury G, Strugarek D (2019b) Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS. *Journal of Geodesy* 93(11), https://doi.org/10.1007/s00190-019-01307-0.

Zajdel R, Sośnica K, Bury G (2021) Geocenter coordinates derived from multi-GNSS: a look into the role of solar radiation pressure modeling. *GPS Solutions* 25(1), https://doi.org/10.1007/s10291-020-01037-3.

Zajdel R, Sośnica K, Bury G, Dach R, Prange L, Kaźmierski K (2021) Sub-daily polar motion from GPS, GLONASS, and Galileo. *Journal of Geodesy* 95(3), https://doi.org/10.1007/s00190-020-01453-w.

Joint Study Group T.25: Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics

Chair: *Robert Tenzer (Hong Kong)*

Members

Lars Sjöberg (Sweden)
Mohammad Bagherbandi (Sweden)
Carla Braitenberg (Italy)
Mirko Reguzzoni (Italy)
Aleksej Baranov (Russia)
Franck Ghomsi (Cameroon)
Róbert Čunderlík (Slovakia)
Wenjin Chen (China)

1. Activities of the group

The seismic tomography is primarily used to provide images of the Earth's inner structure based on the analysis of seismic waves due to earthquakes and (controlled) explosions. Until now, however, large parts of the world are not yet covered by seismic data. To address this problem in such regions, the gravity data together with topographic, bathymetric and lithospheric density structure models have been used to interpret the Earth's inner structure.

Our study group have been focusing on studies of the lithospheric structure in different parts of the world, including the Indian Ocean, Antarctica, Fennoscandia and parts of the African lithosphere. In the near future we will conduct the study of the lithosphere for the whole African continent. We also updated the Antarctic seismic crustal model. Selected major results of our activities are presented in Section 2.

Members of the study group also participated with other researchers on the determination of the effective elastic thickness of the lithosphere and the lithospheric stresses (Eshagh et al. 2020; Gido et al. 2019a). Substantial effort has been given also to development and improvement of methods and numerical approaches to solve gravimetric forward and inverse problems in physical geodesy and geophysics.

2. Achievements and results

During the first half of the working period our group delivered a number of results, covering various problems in gravimetric and seismic geophysics that are summarized next.

Chen and Tenzer (2020) modified the Parker-Oldenburg's method for the Earth's spherical approximation and developed the relevant software package. The software for the gravimetric forward and inverse modelling using this method is available at:
https://academic.oup.com/gji/article/222/2/1046/5824632 (in supplementary data).

Ghomsi et al. (2021) investigated Cameroon's geological structures by applying the gravity separation and using seismic crustal models. The regional and residual gravity anomalies obtained after applying the spectral analysis were found to be consistent with a regional tectonic configuration, highlighting structural faults, such as the Kribi-Campo Fault, the geophysical over-thrust zone between the Adamawa Plateau and the Congo Craton, see Fig. 1. They applied different forward gravity modelling techniques and compared their performance my means of realistically identify known geological and tectonic units. Their results demonstrated that the forward modelling based on incorporating available geological and geophysical information improved the interpretational quality of residual and regional gravity maps for the study area. The residual gravity anomalies highlighted, see Fig. 2, main sedimentary basins, the Cenozoic volcanism, Cretaceous rift system of the Benue Trough and old cratonic units (the Congo Craton, the Saharan Metacraton and the metacratonized Adamawa Plateau).

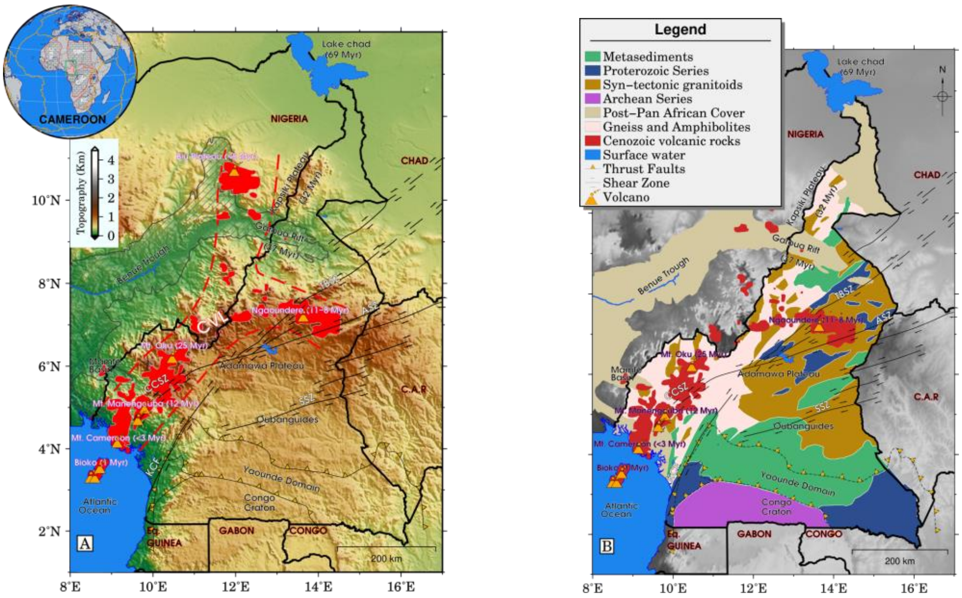


Figure 1: Regional maps of **(a)** topography and **(b)** geological structure of Cameroon.

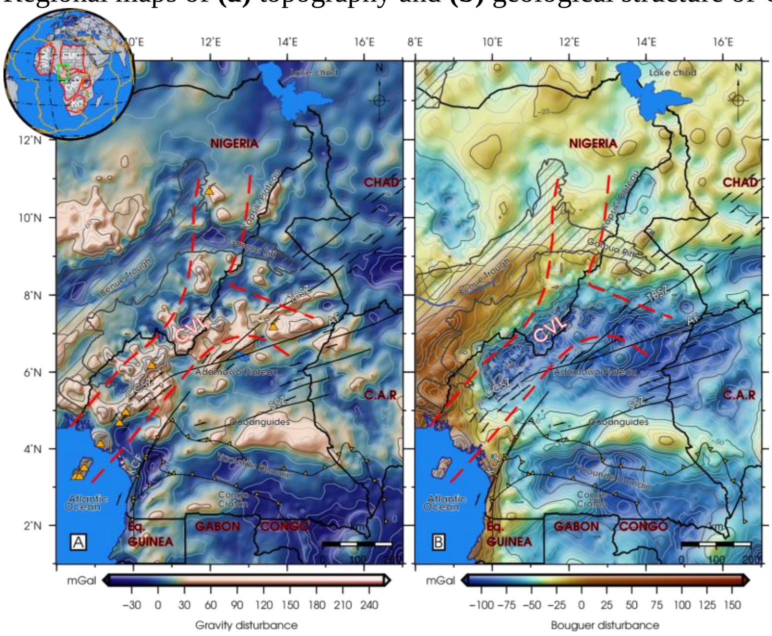


Figure 2: Maps of **(a)** the free-air gravity anomalies and **(b)** the Bouguer gravity anomalies.

Baranov et al. (2020) updated the seismic crustal model for Antarctica. They found large differences between East and West Antarctica, see Fig. 3. In East Antarctica, a high P-wave velocity (v_P >7 km/s) layer in the lower crust is absent. The P-wave velocity in the lower crust changes from 6.1 km/s beneath the Lambert Rift to 6.9 km/s beneath the Wilkes Basin. In West Antarctica, a thick mafic lower crust is characterized by large P-wave velocities, ranging from 7.0 km/s under the Ross Sea to 7.3 km/s under the Byrd Basin. In contrast, velocities in the lower crust beneath the Transantarctic and Ellsworth-Whitmore Mountains are ~6.8 km/s. The P-wave velocities in the upper crust in East Antarctica is within the range 5.5-6.4 km/s. The upper crust of West Antarctica is characterized by the P-wave velocities 5.6-6.3 km/s. The P-wave velocities in the middle crust vary within 5.9-6.6 km/s in East Antarctica and within 6.3-6.5 km/s in West Antarctica. A low-velocity layer (5.8-5.9 km/s) is detected at depth of ~20-25 km beneath the Princes Elizabeth Land.

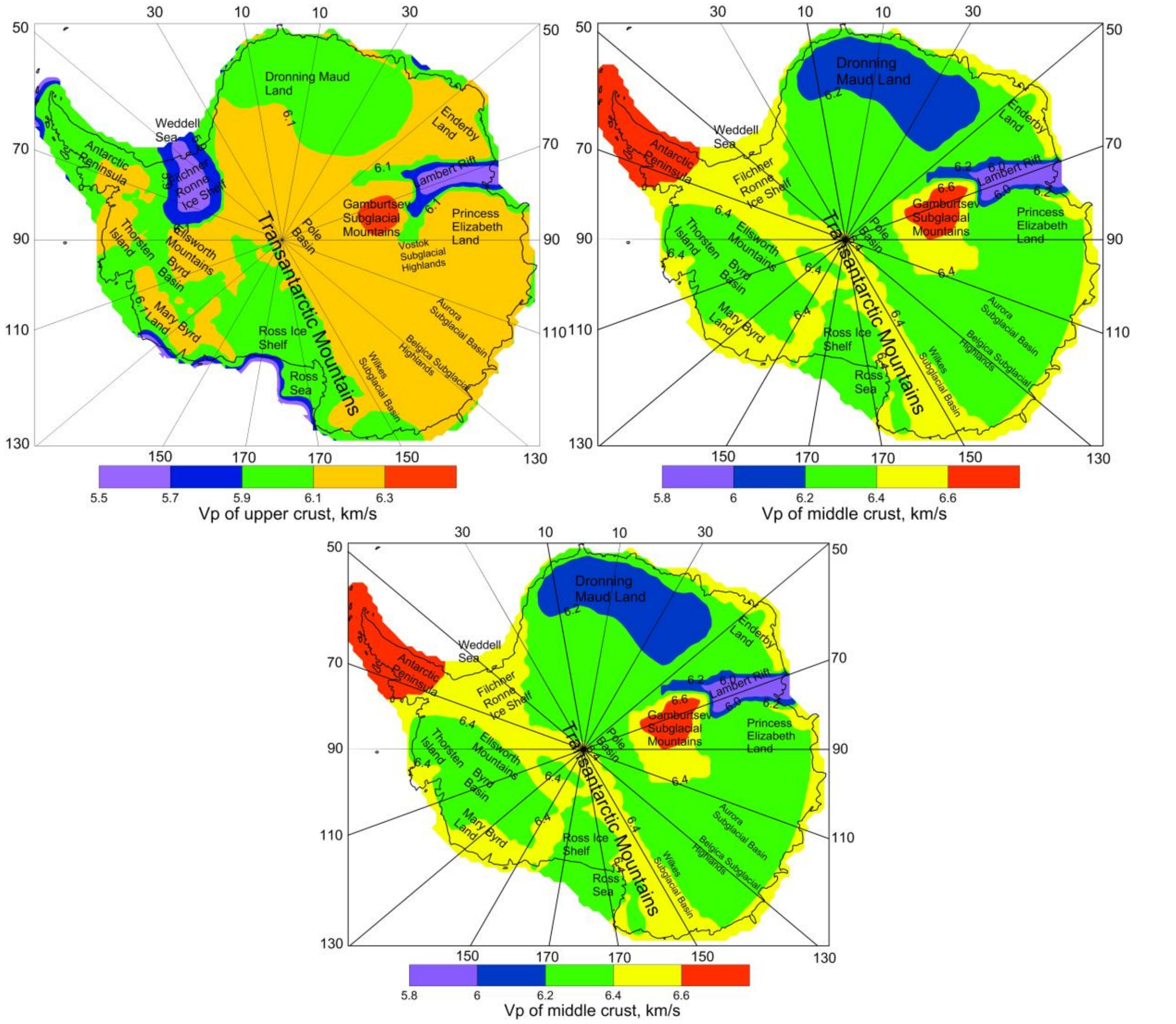


Figure 3: P-wave velocities in the upper, middle and lower crusts. Black lines show seismic profiles.

Abrehdary and Sjöberg (2021b) combined seismic and gravimetric data within Antarctica in estimating the Moho density contrast. According to their result, The Moho density contrast varies from 81 kg/m^3 in the Pacific Antarctic ocean ridge to 579 kg/m^3 in the central continent with a general mean value of 403 kg/m^3. A Moho depth and density contrast model for ocean areas using gravimetric-altimetry data was published by Abrehdary and Sjöberg (2020) with depths varying from 7.3 to 53 km (in Gulf of Bothnia) and density contrasts varying between 20 kg/ m^3 (north of Iceland) and 570 kg/m^3 (in the Baltic Sea). Abrehdary and Sjöberg (2021a) presented a new Moho depth model for Fennoscandia. Sjöberg and Abrehdary (2021) estimated the uncertainty of the crustal depth model CRUST1.0 from several other models, yielding standard error variations of 3.2-6 and 2-5 km for continental and oceanic crusts, respectively.

Rathnayake et al. (2020) investigated the effect of the lateral topographic density on interpretational properties of the Bouguer gravity map. Their result show that the anomalous topographic density distribution modifies the Bouguer gravity pattern in some parts of the world. Even if this effect is globally mostly within ±25 mGal, large values are detected in Himalaya, Tibet, central Andes and along the East African Rift System. They also demonstrated that errors in the Bouguer gravity data attributed to topographic density uncertainties are mostly less than ±15 mGal, but in mountainous regions could reach large values exceeding even ±50 mGal.

Gido et al. (2019a) investigated sub-lithosphere horizontal stress in the Earth's mantle and its secular rate, due to the dominating deformation of the crust in Fennoscandia e.g., by the ongoing mantle convection and Glacial Isostatic Adjustment (GIA), using gravimetric method. According to Sjöberg (1983) the gravity field change in Fennoscandia reflects some geodynamical phenomena like the GIA and mantle convection. However, this gravity signal is likely mixed with other effects like plate tectonics, etc. Therefore, they used certain spherical harmonic degrees of the disturbing potential in order to filter the gravity signals related to the lower mantle and core masses. Bowin (2000) model shows that the spherical harmonic degrees between 5 and 40 belong to about 100 to 1600 km depth, where asthenosphere and mantle are located. Therefore, they used this harmonic window (i.e. the degrees 5 to 40) to determine the horizontal stress. Generally, there are different geodynamical phenomena those can be the reasons for the current horizontal stress in the study region such as mantle convection, horizontal and vertical land motion due to plate tectonics and the GIA, and it is very complicated to separate and distinguish the gravity signals due to mantle convection and land motion. To prove the outcomes of Bowin's model, they performed a correlation analysis using a land uplift model. Their result revealed that the spherical harmonic degrees between 5 to 40 have the highest correlation (0.87) between land uplift and the obtained horizontal stress, which support the use of degrees 5 to 40 to determine the horizontal stress in this study. The main outcome of their study is demonstrated in Fig. 4. The secular rate of the sub-crustal horizontal stress obtained using GRACE monthly data is plotted in Fig. 4a. As seen, the GPS stations outside the uplift dome experience more horizontal stress changes than the stations inside the dome. Generally, for regions where the geoid goes up, mass increases, and it probably also reflects mass transport from lower layers of the Earth (i.e. sub-crustal mass transportation) and erosion phenomena. The likely reason that the stress changes more in the periphery region is that the thinner lithosphere produces higher stress change, which is due to less flexure of the lithosphere and erosion. Furthermore, Fig. 1c shows that there is significant correlation between the secular rate of the stress and seismic activities in Fennoscandia.

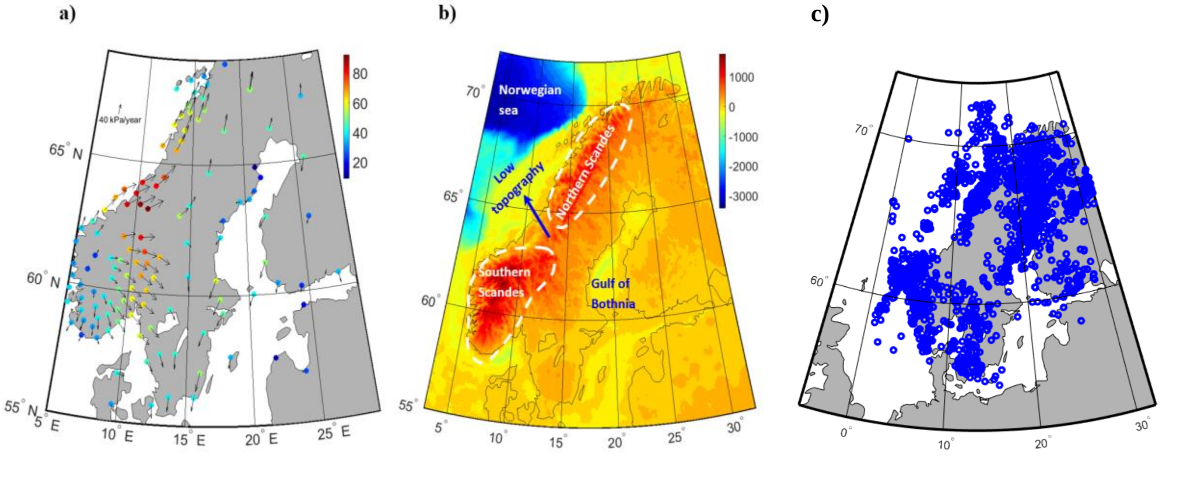


Figure 4: (a) Secular rate of sub-crustal horizontal stress due to mantle convection (tectonics). Secular rates of the horizontal stress are shown as colour circles (kPa/year) and direction of the horizontal stress changes with black arrows (mm/year), (**b**) topography/bathymetry of Fennoscandia using DTM2006 (Pavlis et al. 2007) up to degree and order 2160 (metre) and (**c**) shows seismic activity for 10 years (2007-2017) using FENTEC (Finnish Institute of Seismology, University of Helsinki).

Sjöberg and Bagherbandi (2020) used GRACE monthly data during 2003-2016 to estimate the upper mantle density (with a mean value of 3402.5 kg/m^3) and a surface gravity change of -0.172 μGal/mm of uplift in Fennoscandia.

Gido et al. (2019b) studied permafrost thawing and its associated gravity change in terms of Ground water storage (GWS) changes, and organic material changes have been studied using the GRACE solutions and other satellite and ground-based observations in the northern high-latitude regions. The estimation of permafrost changes in this region requires combining information from various sources, particularly using the gravity field change, surface temperature change, and GIA. The most significant factor for careful monitoring of this phenomena is its possible contribution for releasing an additional enormous amount of greenhouse gases emitted to the atmosphere, most important ones are the carbon dioxide (CO_2) and the methane that are currently stored in the frozen ground. Hence, studying thawing permafrost is very important, not only from a perspective of localized geo-hazard such as erosion, damage to buildings and infrastructure but also with respect to its possible global impact due to greenhouse gas emissions.

Bagherbandi and Gido (submitted) studied the relationship between the isostatic balance and seismicity, and the probable main reasons of geodynamics processes, e.g. seismic activities, by analyzing the isostatic state in the study area covering parts of northeast Africa and Arabian Peninsula using a combined Moho model. Moreover, they estimated the sub-crustal stress and its relationship with seismicity by using the gravimetric method introduced in Gido et al. (2019a). The most important phenomenon that occurs in this region is the East African continental rifting, see Fig. 5, mainly caused by the horizontal extensional forces in the lithosphere. Moreover, there are a number of active volcanoes in the East African Rift Zone. The movement of the African plates, i.e. Nubian and Somali, can lead potentially to the formation of new plate boundaries in the study area, which are the reason for such seismic activities in the form of earthquakes and volcanism. The so often-called "African Superswell" phenomena, i.e. the raise up of the mantle plume and consequently causes the rift, can also result in land uplift, and volcanism, see Fig. 6. The main goal of their study was to better understood how isostasy and Moho parameters (depth and density contrast) explain the rift valley configuration.

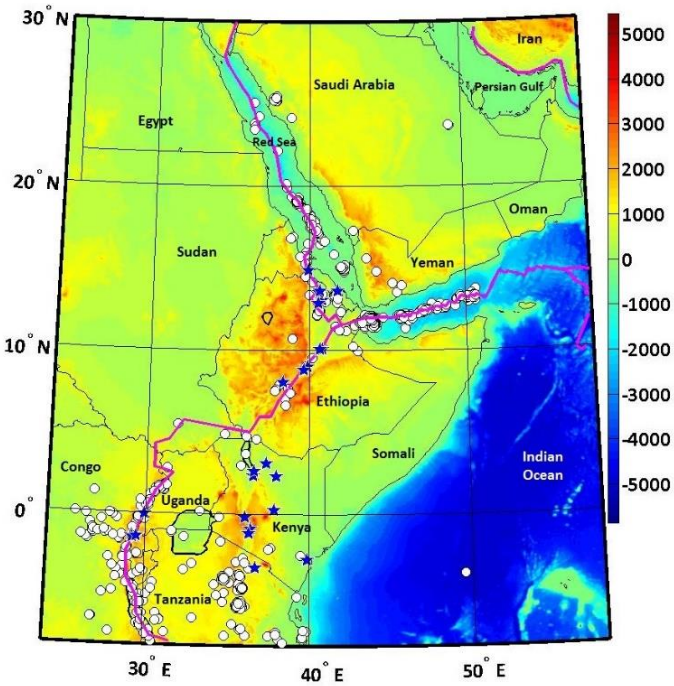


Figure 5: General map of study area showing ETOPO1 digital elevation, main plate tectonic boundaries (solid magenta colour), volcanic areas (blue stars) and earthquakes larger than 4 Richter magnitude scale between 2008-2018 (white colour circles).

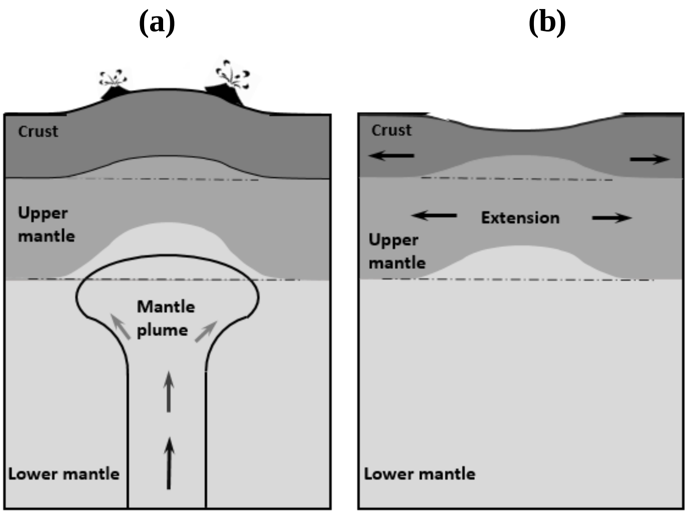


Figure 6: Schemes of (**a**) mantle plume (active rifting), and (**b**) extension-related rift (passive rifting, right) in the African rift region (revised after Merle 2011).

Kaban et al. (2021) investigated the sediment structure in the Congo basin. They presented a map of sedimentary thickness for the whole Congo basin, based on the inversion of the decompensative gravity anomalies. Contrary to the conventional Bouguer or isostatic gravity anomalies, the effect of the isostatic compensation of sediments is reduced in the decompensative anomalies, which provides a possibility to recover the full effect of low-density sediments. The calculated decompensative correction reaches ±70 mGal and exceeds the amplitude of the isostatic anomalies, especially in the long wavelengths. The final decompensative anomalies are negative over the whole basin and their patterns well correspond to its tectonic fragmentation. By inverting these anomalies with the predefined density-depth relationship, they obtained the sedimentary thickness map for the whole Congo basin. According to their results, the maximum basement depth exceeding 10 km is found in the Lokoro basin and basins in the South. In the Lomami basin, thickness of sediments reaches about 6.5 km. They also detected a new deep basin adjacent to the Lokonia High (on the SW side) that they proposed to name as the Salonga basin.

Tadiello and Braitenberg (2021) used gravity data to create a 3D lithosphere density model on the basis of a high-resolution seismic tomography model. Their results demonstrated a highly complex density distribution in good agreement with the different geological domains of the Alpine area represented by the European Plate, the Adriatic Plate and the Tyrrhenian basin. The Adriatic-derived terrains (Southalpine and Austroalpine) of the Alps are typically denser (2850 kg/m^{-3}, whilst the Alpine zone, composed of terrains of European provenance (Helvetic and Tauern Window), presents lower density values (2750 kg/m^{-3}). They also try to explain the existence of well-known positive gravity anomaly located south of Dolomites. Based on the modelled density, they suggested that the anomaly is related to two different sources; the first involves the middle crust below the gravity anomaly and is represented by localized mushroom-shaped bodies interpreted as magmatic intrusions, while a second wider density anomaly affects the lower crust of the southern Alpine realm and could correspond to a mafic and ultramafic magmatic underplating (gabbros and related cumulates) developed during Paleozoic extension.

Delvaux et al. (2021) reconstructed the stratigraphy and tectonic evolution of the Congo basin using all available and geological seismic data (reflection and refraction seismics, borehole and field data). They interpreted almost 2600 km of seismic reflection profiles and well log data located inside the central area of the Congo basin (the "Cuvette Centrale"). Their results indicate that the depth to the basement varies quite significantly, defining a series of structural highs and depocenters that developed throughout the history of the basin. The major controlling factors for the development of the Congo basin are, besides the deep geodynamic processes, the inherited heterogeneity of the pre-Neoproterozoic basement, the tectonic evolution of Rodinia, Gondwana and Pangea amalgamation and breakup, and environmental conditions influenced by the drifting through the South Pole towards its present-day equatorial position and global climatic fluctuations between icehouse and greenhouse conditions.

Bobrov and Baranov (2019) built 2D mantle models of thermochemical convection with non-Newtonian rheology and phase transitions, in the presence of floating deformable continents and oceanic crust. All the stages of supercntinent cycle were studied: assembly, evolution of supercontinent, its breakup and divergence of continents. The results demonstrate certain irregularity of supercontinent cycle. The typical shear stresses in the mantle are less than 30 MPa; in the subduction zones and on the continent borders they are 100–250 MPa. Before the breakup maximum shear stress generated in the supercontinent can reach 200 MPa. In this paper, we have worked out the rheology and modelling of the continents for further use in spherical modelling.

Baranov et al. (2019) and Shebalin and Baranov (2020) revealed the connection between ocean tides and seismicity. A total of 16 sequences of M ≥6 aftershocks of Kamchatka and 15 sequences of M ≥6 aftershocks of New Zealand and also background seismicity were examined. The heights of the ocean tides at various locations were modelled using FES 2004. An increase in aftershock rate is observed by more than two times at high water after main M≥6 shocks in Kamchatka. For New Zealand, they also observed an increase in aftershock rate at high water after thrust type main shocks with M ≥6. After normal-faulting main shocks there was the tendency of the rate increasing at low water. For the aftershocks of the strike slip main shocks they observed a less evident impact of the ocean tides on their rate. This suggests two main mechanisms of the impact of ocean tides on seismicity rate, an increase in pore pressure at high water, or a decrease in normal stress at low water, both resulting in a decrease of the effective friction in the fault zone.

Chuvaev et al. (2020) investigated the spherical mantle convection based on SMEAN2 seismic tomography model. Calculations demonstrate the structure of mantle flows in modern Earth, see Fig. 7. Under the continents, with the exception of East Africa, Southeast and East Asia and West Antarctica, there are downward mantle flows and negative temperature anomalies. The descending mantle flow under Eurasia and the ascending flow under the Arctic push North Eurasia to the south is causing stresses in the crust and orogenic processes within Eurasia. Another powerful downward mantle flow occurs between North and South America in the Caribbean subduction zone. Ancient cratons are characterized by cold regions in the mantle beneath them. Under East Africa, there is a positive temperature anomaly and an upward mantle flow, responsible for the East African Rift System. A similar anomaly is also found in the Baikal rift zone. A global ascending mantle flow forms under the Pacific Ocean.

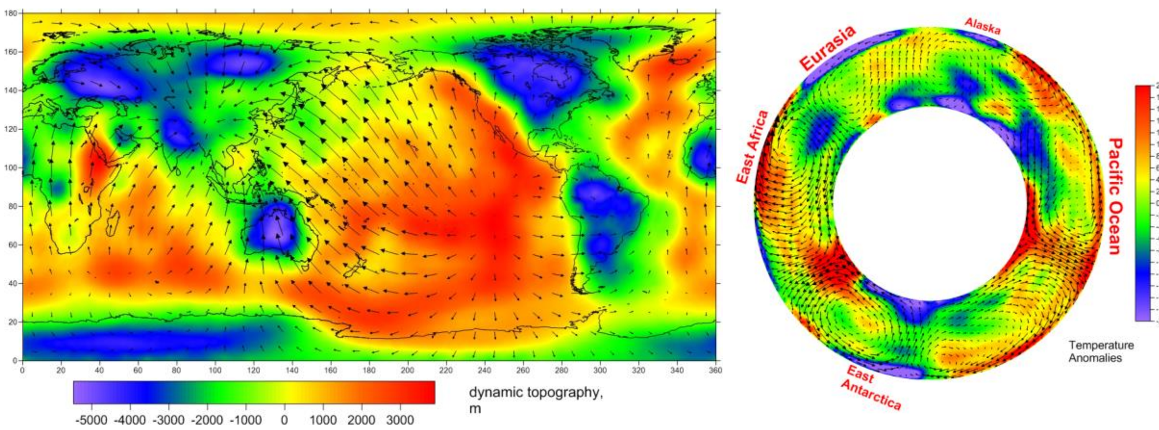
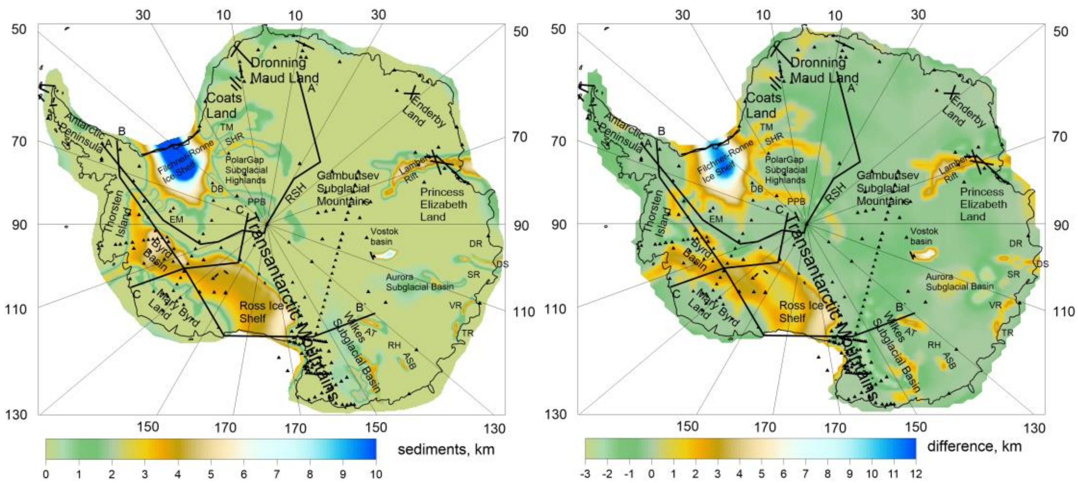


Figure 7: Mantle flow model.

Baranov et al. (submitted) built sediment model for Antarctica based on seismic, relief (BEDMACHINE), radar, gravity and magnetic data. Their results revealed significant sediment accumulations in Antarctica with several types of sedimentary basins: parts of the Beacon Supergroup and more recent rifting basins, see Fig. 8. West Antarctica has wide sedimentary basins: the Ross basin (thickness 2-6 km), the Filchner-Ronne basin (2-12 km) with continuations into East Antarctica, the Bentley Subglacial Trench and the Byrd basin (2-4 km). The deepest Filchner-Ronne basin has a complex structure with multi-layered sediments. East Antarctica is characterized by vast sedimentary basins such as the Pensacola-Pole (1-2 km), Coats Land (1-3 km), Dronning Maud Land (1-2 km), Vostok (2-7 km), Aurora (1-3 km), Astrolabe (2-4 km), Adventure (2-4 km), and Wilkes (1-4 km) basins, along with narrow deep rifts filled by sediments: JutulStraumen (1-2 km), Lambert (2-5 km), Scott, Denman, Vanderford and Totten (2-4 km) rifts. Average thickness of sediments for the whole continent is about 0.77 km. The new model, ANTASed, provides significant improvements over CRUST 1.0 for Antarctica and reveals new sedimentary basins. Differences between ANTASed and CRUST 1.0 reach +12/-3 km.



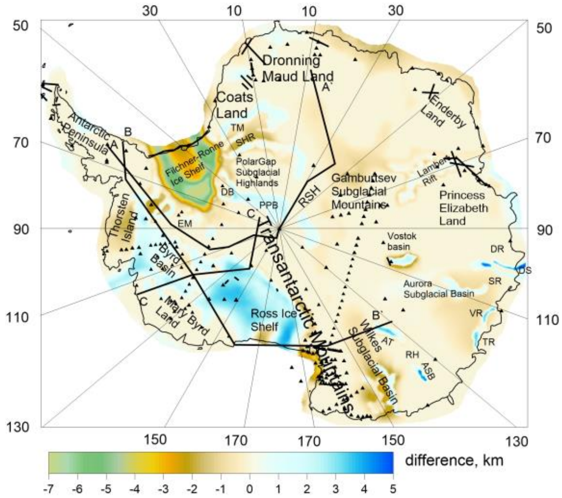


Figure 8: (a) Map of sediment thickness for Antarctica. Black triangles represent seismic stations and black lines seismic profiles. PPB – Pensacola-Pole Basin, EM – Ellsworth Mountains, BB – Byrd Basin, BST – Bentley Subglacial Trench, SHR – Shackleton Range, TM – Theron Mountains, SR – Scott rift, DR – Denman rift, VR – Vanderford rift, TR – Totten rift, AT – Adventure Trench, ASB – Astrolabe Subglacial Basin, RH – Resolution Highlands, DB – Dufek Block, RSH – Recovery Subglacial Highlands. (b) Difference between ANTASed and CRUST1.0 (Laske et al, 2013). (c) Difference between ANTASed and the preliminary sediment model by Baranov et al. (2018).

4. Refined plans for the period of 2021-2023

Due to the COVID-19 restrictions, the current progress in achieving all expected research outcomes has been delayed.

5. Publications

Abrehdary M, Sjöberg LE (2020) Estimating a combined Moho model for marine areas via satellite altimetric – gravity and seismic crustal models. *Studia Geophysica et Geodaetica* 64: 1-25 (open access).

Abrehdary M, Sjöberg LE (2021a) A new Moho depth model for Fennoscandia with special correction for the Glacial isostatic effect. *Pure and Applied Geophys*ics, on-line 15 Feb 2021.

Abrehdary M, Sjöberg LE (2021b) A Moho density contrast model in Antarctica determined by satellite gravimetry and seismic data. *Geophysical Journal Int*ernational 225: 1952-1962

Bagherbandi M, Gido NAA (submitted) A study on the relationship between isostatic equilibrium and seismicity: A case study in Africa.

Baranov A, Baranov S, Shebalin P (2019) A quantitative estimate of the effects of sea tides on Aftershock activity: Kamchatka. *Journal of Volcanology and Seismology* 13(1): 56-69, doi: 10.1134/S0742046319010020

Bobrov A, Baranov A (2019) Thermochemical mantle convection with drifting deformable continents: main features of supercontinent cycle. *Pure and Applied Geophysic*s 176(8): 3545-3565, doi:10.1007/s00024-019-02164-w.

Baranov A, Tenzer R, Morelli A (2020) Updated Antarctic crustal model. *Gondwana Research* 89: 1-18; doi:10.1016/j.gr.2020.08.010.

Baranov A, Morelli A, Chuvaev A (submitted) ANTASed – a new sediment model for Antarctica.

Baranov A, Tenzer R, Ghomsi F (in preparation) Moho map for Africa from seismic, elevation and tectonic structure.

Chen W, Tenzer R (2020) Reformulation of Parker-Oldenburg's method for Earth's spherical approximation. *Geophysical Journal International* 222(2): 1046-1073; doi: 10.1093/gji/ggaa200

Chuvaev A, Baranov A, Bobrov A (2020) Numerical modeling of mantle convection in the Earth using cloud technologies. *Computational Technologies* 25(2): 103-117; doi:10.25743/ict.2020.25.2.009

Shebalin P, Baranov A (2020) Aftershock rate changes at different ocean tide heights. *Frontiers in Earth Science* 8; doi: 10.3389/feart.2020.559624

Delvaux D, Maddaloni F, Tesauro M, Braitenberg C (2021) The Congo Basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data. *Global and Planetary Change* 198: 103407.

Eshagh M, Fatolazadeh F, Tenzer R (2020) Lithospheric stress, strain and displacement changes from GRACE-FO time-variable gravity: case study for Sar-e-Pol Zahab Earthquake 2018. *Geophysical Journal International*, doi: 10.1093/gji/ggaa313.

Ghomsi FEK, Ribeiro-Filho N, Baldez R, Tenzer R, Martins CM, Chisenga C, Nguiya S, Nouayou R (2021) Identification of Cameroon's geological structures through a gravity separation and using seismic crustal models. *Journal of African Earth Sciences* 173: 104027.

Gido NAA, Bagherbandi M, Sjöberg LE (2019a) A gravimetric method to determine horizontal stress field due to flow in the mantle in Fennoscandia. *Geoscience Journal* 23, https://doi.org/10.1007/s12303-018-0046-8.

Gido NAA, Bagherbandi M, Sjöberg LE, Tenzer R (2019b) Studying permafrost by integrating satellite and in situ data in the northern high-latitude regions. *Acta Geophysica* 67, https://doi.org/10.1007/s11600-019-00276-4.

Gido NAA (2020) Monitoring lithospheric motions by satellite geodesy. PhD. dissertation, KTH Royal Institute of Technology. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-279064.

Kaban MK, Delvaux D, Maddaloni F, Tesauro M, Braitenberg C, Petrunin AG, El Khrepy S (2021) Thickness of sediments in the Congo basin based on the analysis of decompensative gravity anomalies. *Journal of African Earth Science* 179: 104201

Rathnayake S, Tenzer R, Novák P, Pitoňák M (2020) Effect of the lateral topographic density distribution on interpretational properties of Bouguer gravity maps. *Geophysical Journal International* 220(2): 892-909

Reguzzoni M, Sampietro D, Rossi L (2020) The gravimetric contribution to the Moho estimation in the presence of vertical density variations. Rendiconti Lincei. *Scienze Fisiche e Naturali* 31: 69-81

Sjöberg LE, Abrehdary M (2021) The uncertainty of CRUST1.0 Moho depth and density contrast models. *Journal of Applied Geod*esy, published on-line.

Sjöberg LE, Bagherbandi M (2020) Upper mantle density and surface gravity change in Fennoscandia determined from GRACE monthly data. *Tectonophysics* 782-783: 228428

Tadiello D, Braitenberg C (2021) Gravity modeling of the alpine lithosphere affected by magmatism based on seismic tomography. *Solid Earth* 12(2): 539-561

Joint Study Group T.26: Geoid/quasi-geoid modelling for realization of the geopotential height datum

Chair: *Jianliang Huang (Canada)*

Members

Jianliang Huang (Canada), chair
Jonas Ågren (Sweden)
Riccardo Barzaghi (Italy)
Heiner Denker (Germany)
Bihter Erol (Turkey)
Christian Gerlach (Germany)
Christian Hirt (Germany)
Juraj Janák (Slovakia)
Tao Jiang (China)
Robert W. Kingdon (Canada)
Xiaopeng Li (USA)
Urs Marti (Switzerland)
Ana Cristina de Matos (Brazil)
Pavel Novák (Czech Republic)
Laura Sanchez (Germany)
Matej Varga (Croatia)
Marc Véronneau (Canada)
Yanming Wang (USA)
Xinyu Xu (China)

1. Activities of the group

For the period of 2019-2021, the JSG has made remarkable achievements towards its objectives despite the COVID-19 pandemic:

- Contributed to the strategy for the realization of the International Height Reference System (IHRS), (Sánchez et al. 2021), and the Colorado geoid computation experiment (Wang et al. 2021).
- Improved the data combination methods for the geoid modelling (Erol et al. 2020a; Liang et al. 2020a 2020b; Işık et al. 2021; Varga et al. 2021; Grigoriadis et al. 2021). These methods include spherical harmonic modelling, LSC and the least-squared kernel modification. LSC was the most used method for the combination of airborne and terrestrial gravity data.
- Investigated impact of denser terrestrial datasets on geoid modelling (Erol et al. 2020b).
- Characterized, stabilized and performed the downward continuation of high-altitude airborne GRAV-D gravity data (Li et al. 2021; Grigoriadis et al. 2021; Varga et al. 2021). LSC, RLC and RBF methods showed stable and reliable DC results.
- Developed a novel regional RTM approach reducing approximation errors by the classical RTM technique due to the harmonic correction and the spectral inconsistence (Bucha et al. 2019).
- Advanced error estimation of the three commonly used geoid modelling techniques, i.e., Stokes's integration, least-squares collocation and modelling using radial basis functions (Ophaug and Gerlach 2020).
- Identified the data requirement for dynamic geoid/quasi-geoid modelling using GRACE models, GIA models, GLDAS, and RACMO2.3 in Canada (Huang et al. 2019).

2. Achievements and results

Combining multiple types of gravity data

Erol et al. (2020a) investigated the role of the global geopotential model selection in accuracy of regional geoid model determination using a least-squares modification of Stokes's integral with additive corrections method. In the content of this research article, the progress in geopotential model accuracies and thus the regional geoid models with data contribution of GOCE satellite mission was emphasized. In conclusion, the improvement in regional geoid model accuracies depending on the appropriate selection of the global geopotential model and its optimal expansion degree was figured out through the numerical test results. This paper also depicts methodological documentation of geopotential model selection in regional geoid modelling studies.

Liang et al. (2020a) proposed a new method for regionally improving GGMs with GNSS /levelling data. First, the GNSS/levelling data is converted to disturbing potential data with inverse Bruns's formula. Then the systematic errors in disturbing potential data are removed with a 3-parameter correction surface. Afterwards, the disturbing potential data on the Earth's surface are downward continued to the surface of an inner sphere with inverse Poisson's integral equation. At last, the final Regionally Improved Geopotential Model (RIGM) could be recovered from the disturbing potential data using least-squares method. Four RIGM models for Qingdao (QD) in China are determined based on four different sets of GNSS/levelling data points to validate the capability of the method. The STD of height anomaly errors of RIGM-QDs is nearly 25% on average smaller than EGM2008 on checkpoints, see Table 1.

Table 1: Statistics of the height anomaly errors of RIGM-QD models and EGM2008 on the 12 checkpoints in centimetres.

Model	Min	Max	Mean	STD
RIGM-QD-1	2.10	32.80	18.33	7.99
EGM2008[1]	-9.00	27.70	17.07	11.05
RIGM-QD-2	6.40	34.10	18.21	7.62
EGM2008[2]	-8.20	28.00	18.01	9.91
RIGM-QD-3	7.10	27.00	19.01	6.20
EGM2008[3]	-10.00	32.90	19.74	9.10
RIGM-QD-4	11.60	32.60	21.04	6.812
EGM2008[4]	4.70	31.90	20.48	8.67

Based on the least-squares formulas of the ellipsoidal harmonic analysis and coefficient transformation (EHA-CT) method, Liang et al. (2020b) developed a new model SGG-UGM-2 up to the degree 2190 and order 2159 by combining the observations of GOCE, the normal equation of GRACE, marine gravity data derived from satellite altimetry data, and EGM2008-derived continental gravity data. The GPS/levelling data in mainland China and the USA are used to validate SGG-UGM-2 together with other models, such as EIGEN-6C4, GECO, EGM2008 and SGG-UGM-1 (the predecessor of SGG-UGM-2). Compared to other models, the model SGG-UGM-2 shows a promising performance in the GPS/levelling validation. All GOCE-related models have similar performances both in the USA and China, and better performances than that of EGM2008 in mainland China. Due to the contribution of GRACE data and the new marine gravity anomalies, SGG-UGM-2 is slightly better than SGG-UGM-1 both in mainland China and USA, see Tables 2 and 3.

Table 2: Statistics of comparison with GPS/levelling data in the USA (6169 points) in metres.

Model	Max	Min	Mean	STD	RMS
EGM2008	0.360	-1.396	-0.511	0.284	0.584
SGG-UGM1	0.317	-1.407	-0.511	0.280	0.583
SGG-UGM2	0.386	-1.394	-0.511	0.277	0.578
GECO	0.313	-1.391	-0.513	0.281	0.585
EIGEN-6C4	0.397	-1.392	-0.512	0.282	0.585

Table 3: Statistics of comparison with GPS/levelling data in mainland China (649 points) in metres.

Model	Max	Min	Mean	STD	RMS
EGM2008	1.729	-1.535	0.239	0.240	0.339
SGG-UGM1	0.744	-0.618	0.246	0.162	0.294
SGG-UGM2	0.744	-0.603	0.246	0.161	0.292
GECO	1.165	-0.847	0.244	0.180	0.303
EIGEN-6C4	0.729	-0.698	0.243	0.157	0.289

Işık et al. (2021) provides the investigation results that it was carried out in the 1-cm geoid experiment of the International Association of Geodesy Joint Working Group (IAG JWG) 2.2.2. In the content of the study, the least-squares modification of Stokes's and Hotine's integral formulas were applied with the terrestrial-only, airborne-only and combined gravity datasets in U.S. Colorado area, and the significant contribution of the airborne gravity measurements at the mountainous part of the study area was clarified. In the investigation results, it was reported the Hotine integral formula provided slightly improved geoid model accuracy in comparison with the Stokes integral formula. The article also includes a comprehensive comparison of the issued geoid model solutions with the solutions, which were submitted by the contributed institutions to the IAG JWG 2.2.2. Shortly saying this study aims to make a contribution to the applied researches regarding the clarifying the methodology differences and data contribution in local geoid modeling.

Varga et al. (2021) performed the spectral analysis of surface and airborne gravity anomaly grids across the mountainous area in Colorado, USA, which provided insights into specific wavelength bands in which airborne gravity data contributed and improved the power spectrum. It is shown that airborne gravity anomalies were significantly more powerful in the bandwidth of 200–1400 compared to only terrestrial gravity anomalies and combined gravity anomalies. The airborne gravity power decreased beyond the SH degree 1400, where parts of the medium- and high-frequency spectrum caused by the topographic gravity signal were not detected by the airborne gravity or were filtered out during data preprocessing.

Grigoriadis et al. (2021) applied LSC for combination of the airborne and terrestrial data for the Colorado 1-cm geoid experiment. The covariance model employed in the gridding procedure was the one of the residual surface gravity data. This model properly fits also the empirical covariance of the downward continued values (R2 = 0.93), as it is by definition, since these values have been obtained by LSC using this model covariance. When being compared to the GPS/levelling data along the GSVS17 line, the combined quasi-geoid models reach an accuracy of 2.4 cm and 2.8 cm for the FFT and LSC based methods, respectively. The airborne only solution shows the same level of accuracy as the one from tterrestrial data.

Identification of data requirements and gaps

In many regions in the world, the metadata of the terrestrial gravity observations, which are used in geoid modeling studies, are either incomplete or not well known. In some countries, terrestrial gravity measurements are not dense enough for the high accuracy geoid model calculation. Erol et al. (2020b) combine the terrestrial gravity datasets obtained by two different institutions in Turkey to calculate the local geoid model with higher accuracy by using combined gravity datasets in a denser grid. Within the scope of the research, the geoid model accuracies obtained by using the data before and after combining were compared. The least-squares collocation approach, where the stochastic information of the terrestrial datasets is employed, was applied in the calculation of the experimental local geoid models in the study area.

Downward continuation of high-altitude airborne gravity data

Li et al. (2021) characterized the ill-posedness of the downward continuation problem (DCP) by comparing six DC methods, which are spherical harmonic analysis (SHA) (NGS), LSC (DTU Space), Poisson and ADC (NRCan), RBF (DU Delft), and RLSC (TUM) using both simulated data and real data. The data were downward continued to both surface points and to the reference ellipsoid surface. The surface points are directly evaluated with the observed gravity data on the topography. The results show the LSC, RLSC and regularized RBF methods can effectively stabilize the DCP.

Grigoriadis et al. (2021) applied LSC for downward continuation of GRAV-D data for the Colorado 1-cm geoid experiment. The covariance function model employed in these LSC computations was the one of the reduced terrestrial free-air gravity anomaly residuals. Given the point-wise downward continued gravity anomaly residuals, a consistency check with the surface gravity anomaly residuals was performed. The mean and the standard deviation of the differences are 1.96 mGal and 5.42 mGal, respectively, while the minimum value is -30.44 mGal and the maximum value is 42.45 mGal. Varga et al. (2021) also applied LSC for the downward continuation of GRAV-D data over the same experiment region.

Modelling of topographic effects

The classical RTM technique is subject to approximation errors due to the harmonic correction and the spectral inconsistence. Bucha et al. (2019) have proposed and successfully applied a novel regional RTM approach that combines spatial- and spectral-domain gravity forward modelling techniques. This approach can be considered as a regional modification of the baseline global RTM solution of Hirt et al. (2019). The newly introduced regional feature avoids the global spatial-domain Newtonian integration (Hirt et al. 2019), which is too demanding computationally. A validation over two mountainous areas, Switzerland and Slovakia, reveals that this technique is at least comparable with two other common RTM variants (RMS agreement up to 0.1 mGal).

Estimation of data and geoid/quasi-geoid model errors

During the 2015-2017 period of ICCT's JSG on Regional Geoid/-Quasigeoid Modelling, Ophaug and Gerlach (2017) carried out a synthetic study on the equivalence of three commonly used geoid modelling techniques, namely Stokes integration, Least-Squares Collocation and modelling using radial basis functions. The methods were found to agree numerically on the millimeter level. In a follow-up study Ophaug and Gerlach (2020) investigated the agreement of formal error measures derived from the three methods. Comparing empirical and formal errors, it was found that the formal errors are realistic if the methods are tuned with respect to spectral band limitation and adaption of the covariance function. However, direct comparison of the error measures must also consider that integration and estimation methods not necessarily give identical results, because integration techniques may not take the signal properties into account, possibly leading to too optimistic results. Another important finding was that standard methods, like the L-curve method or generalized cross validation failed to provide an optimal regularization parameter – something that can only be investigated in a simulation scenario. Further investigations are necessary on how to use these findings in real-case scenarios.

Dynamic geoid/quasi-geoid modelling

CGVD2013 represents a modern vertical datum in Canada as it is compatible with today's positioning technique through Global Navigation Satellite System (GNSS). It was realized by the Canadian Gravimetric Geoid of 2013, an equipotential surface representing the best fit of mean sea level (MSL) for the North American region. Even though this geoid model is associated to an epoch (2011.0), NRCan considers currently the geoid model as static, i.e., the geoid heights do not change in time. However, the real-time geoid varies with time in response to mass redistributions associated with various processes in the Earth system. These processes include atmospheric, oceanic and hydrological circulations, glacial accumulation/ loss, glacial isostatic adjustment (GIA), solid earth and ocean tides, earthquakes and volcanic eruption, and other mass variations inside the Earth. Observations from space and ground based sensors are required to study these processes. To connect CGVD2013 to its defined equipotential surface in time, temporal change of the geoid needs to be determined from the observations and resulting models of these processes. Huang et al. (2019) aimed to define the data requirement for determining the geoid change greater than 1 cm and its corresponding spatial scale over a time scale of 10 years. The study primarily focuses on temporal geoid changes due to GIA, glacial/ice melt and terrestrial water storage variations, which are three dominant processes in Canada. It has used two GIA models (ICE-5G and ICE-6G models), and GPS-absolute-gravity derived gravity changes, the ice mass balance model of RACMO2.3, and GLDAS prediction to quantify spatial scales and amplitudes of the changes, and monthly GRACE models from three processing centers (CSR, GFZ, JPL) to determine the suitability of GRACE and GRACE FO for monitoring the geoid changes. Main conclusions are:

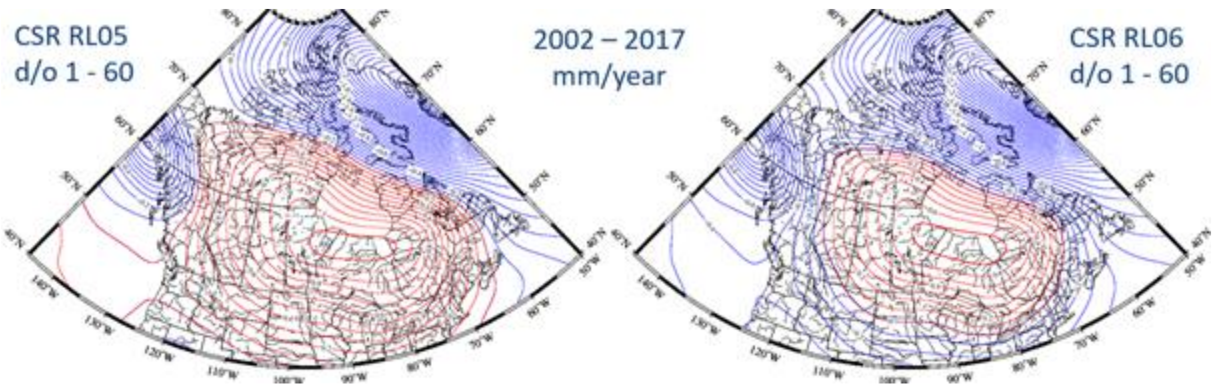


Figure 1: Dynamic geoid models derived from the monthly GRACE models. Degree-1 coefficient series are from JPL RL05 (Swenson et al. 2008) and RL06 (Sun et al. 2016), and C20 coefficient series from CSR RL05 and RL06 (Cheng et al. 2013; Cheng and Ries 2017).

- Significant difference is shown between dynamic geoid models derived from RL05's and RL06's monthly GRACE models as shown in Fig. 1, and is found largely due to degree-1 terms, to a less extent degree-2 terms.
- Geoid change components above degree/order 60 are dominated by glacial melt effect.
- ITSG Grace2018s and GOCO06s's time-variable models captured small scale of geoid change signal over mountain glaciers in western North America.

The geoid and quasi-geoid models for South America

For the last two years, Ana Cristina de Matos has collaborated in scientific projects with prof. Denizar Blitzkow at the University of São Paulo (USP) and the Center of Studies of Geodesy (CENEGEO), see, e.g., Hernandez et al. 2019, as:

- updating, analyzing the gravimetric database belonging to USP in order to compute the geoid and quasegeoid models for South America;
- teaching geoid computation at the Instituto Geografico Militar in Ecuador in July 2019;
- computing the Colorado geoid model;
- computing the quasi-geoid model for São Paulo State;
- contributing to the altimetric reference at the Funil Hydroelectric Plant;
- computing the geopotential number and potential for the absolute stations in São Paulo State and IHRF stations in Brazil;
- collaborating in the analysis of the absolute gravimetric network that was established in Costa Rica;
- evaluating the geoid model GEOID2015 and GPS/levelling in Colombia.

3. Interactions with the IAG Commissions and GGOS

- The JSG actively supports the implementation of the International Height Reference Frame (IHRF) under GOGOS Focus Area: Unified Height System in collaboration with IGFS, ISG, IAG SC 2.2, in particular, JWG 2.2.1: Error assessment of the 1-cm geoid experiment.
- Ana Cristina de Matos coordinates geoid models for the SIRGAS-GTIII (Vertical datum) and member of Joint Working Group on Implementation of the International Height Reference Frame (IHRF).

4. Refined plan for the period of 2021-2023

A refined plan is still under discussion. A JSG meeting was held in April 2021 discussing a study plan for the next two years. A splinter meeting is planed for the IAG 2021 Assembly to continue this discussion. Below are some ideas of activities for 2021-2023:

- Contribute to the first solution of IHRF: regional vs global approaches.
- Support continuation of the Colorado geoid experiment to reduce difference due to methodology.
- Organize a series of thematic workshops on topics of interest.
- Propose a session at the Hotine-Marussi Symposium 2022.
- Define Essential Geodetic Variables (EGVs) for geoid and quasi-geoid models.
- Develop the geoid model for South America.

5. Publications

Selected peer-reviewed publications

Bucha B, Hirt C, Yang M et al. (2019) Residual terrain modelling (RTM) in terms of the cap-modified spectral technique: RTM from a new perspective. *Journal of Geodesy* 93: 2089-2108, https://doi.org/10.1007/s00190-019-01303-4

Erol B, Işık MS, Erol S (2020a) An assessment of the GOCE high-level processing facility (HPF) released global geopotential models with regional test results in Turkey. *Remote Sensing* 12(3): 586

Erol B, Işık MS, Erol, S (2020b). Assessment of gridded gravity anomalies for precise geoid modeling in turkey. *Journal of Surveying Engineering* 146(3): 05020005.

Guimarães GN, Blitzkow D, Matos ACOC, Castro Junior CAC, Inoue MEB (2020) 30 Anos De Medições Gravimétricas Absolutas No Brasil. *Revista Brasileira De Cartografia* 72(1): 159-76, https://doi.org/10.14393/rbcv72n1-50229

Grigoriadis VN, Vergos GS, Barzaghi R et al. (2021) Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. *Journal of Geodesy* 95: 52, https://doi.org/10.1007/s00190-021-01507-7.

Hirt, C, Bucha B, Yang M et al. (2019) A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high-degree spectral gravity modelling. *Journal of Geodesy* 93: 1469-1486, https://doi.org/10.1007/s00190-019-01261-x.

Işık MS, Erol B, Erol S, Sakil FF (2021) High-resolution geoid modeling using least squares modification of Stokes and Hotine formulas in Colorado. *Journal of Geodesy* 95(5): 1-19

Liang W, Pail R, Xu X, Li J (2020a) A new method of improving global geopotential models regionally using gnss/leveling data. *Geophysical Journal Intetnational* 221: 542-549, https://doi.org/10.1093/gji/ggaa047.

Wei L, Li J, Xu X, Zhang S, Zhao Y (2020b) A high-resolution Earth's gravity field model SGG-UGM-2 from GOCE, GRACE, satellite altimetry and EGM2008. *Engineering* 6: 860-878, https://doi.org/10.1016/j.eng.2020.05.008

Ophaug V Gerlach C (2020) Error propagation in regional geoid computation using spherical splines, least-squares collocation, and Stokes's formula. *Journal of Geodesy* 94: 120, doi: 10.1007/s00190-020-01443-y.

Sánchez L, Ågren J, Huang J et al. (2021) Strategy for the realisation of the International Height Reference System (IHRS). *Journal of Geodesy* 95: 33, https://doi.org/10.1007/s00190-021-01481-0.

Silva VC, Blitzkow D, Almeida FGV, Matos ACOC, Bjorkstrom IM (2020) Atualização da Estrutura Gravimétrica do Estado de São Paulo: Vínculo ao Sistema Gravimétrico de Referência. Anuário do Instituto de Geociências 43: 212-226, https://doi.org/10.11137/2020_3_215_226.

Varga M, Pitoňák M, Novák P, Bašić T (2021) Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. *Journal of Geodesy* 95: 53, https://doi.org/10.1007/s00190-021-01494-9.

Wang Y, Sánchez L, Ågren J, Huang J, Forsberg R, Abd-Elmotaal H, Ahlgren K, Barzaghi R, Bašic T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koc O, Li X, Ahlgren K, Krcmaric J, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, PitoňákM, Schmidt M, Varga M, Vergos GS, Véronneau M, Willberg M, Zingerle P (2021) Colorado geoid computation experiment – overview and summary. *Journal of Geodesy* (submitted).

Presentations

Blitzkow D, Matos ACOC (2019) Colorado geoid model from Helmert anomaly. 27th IUGG General Assembly, Québec, Canada, July 8-18, 2019.

https://www.czechin.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737270

Guimarães GN, Blitzkow D, Matos ACOC, Mendonça L (2019) First efforts for the IHRF establishment in Brazil by least squares collocation and numerical integration. https://www.czech-in.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737100

Guimarães GN, Blitzkow D, Matos ACOC (2019) An analysis of the use of least squares collocation and the numerical integration to compute the disturbing potential at IHRF stations in Brazil. SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/89_Guaimaraes_et_al_2019_LSC_IHRF_Brazil.pdf

Guimarães GN, Blitzkow D, Matos ACOC, Castro Junior CAC, Inoue MEB (2019) 30 years of absolute gravity measurements in South America. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/45_Guaimaraes_et_al_2019_Absolute_gravimetry_SouthAmerica.pdf

Hernandez JN, Blitzkow D, Matos ACOC, Mora F (2019) Evaluación del modelo geoidal GEOID2015 en Colombia, 2019. SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/83_Hernandez_et_al_2019_Evaluacion_GEOI2015_Colombia.pdf

Huang J, Véronneau M, Pavlic G, Crowley JW (2019) Data requirement for determining temporal change of the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) and IHRF, AGU 100 Fall Meeting, 9-13 December 2019

Li X, Huang J, Willberg M, Pail R, Slobbe C, Klees R, Forsberg R, Hwang C, Hilla S (2021) On downward continuing airborne gravity data for local geoid modeling. EGU General Assembly, 19-30 April 2021, EGU21-2706, https://doi.org/10.5194/egusphere-egu21-2706, 2021

Lucke OH, Salvatierra JP, Leon JG, Fernandez AV, Blitzkow D, Bjorkstrom I, Silva VC, Matos ACOC (2019). Absolute gravity network in Costa Rica. 27th IUGG General Assembly, Québec, Canada, July 8-18, 2019, https://www.czech-in.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737560

Pacino MC, Blitzkow D, Matos ACOC (2019) Geoid modelling in South America, 2019. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/46_Pacino_et_al_Geoid_modelling_SouthAmerica.pdf

Sanchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Denker H, Ihde J, Abd-Elmotaa H, Ahlgren K, Amos M, Barzaghi R, Bašić T, Blitzkow D, Carrion D, Claessens S, Erol B, Filmerm M, Forsberg R, Grigoriadis VN, Serkan Işık M, Jiang T, Li X, Liu Q, Matos ACOC, Matsuo K, Novák P, Pail R, Pitoňák M, Roman D, Schmitd M, Sideris M, Varga M, Vergos G, Véronneau M, Willberg M, Zhang C, Zingerle P (2019) Advances in the realisation of the International Height Reference System. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/42_Sanchez_et_al_2019_IHRS_IHRF_advances.pdf

Silva VC, Blitzkow D, Almeida Filho FGV, Matos ACOC, Bjorkstrom IM (2019) Gravity and height references in the São Paulo state. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019,
http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/91_Silva_et_al_2019_Gravy_heights_SaoPaulo.pdf

Joint Study Group T.27: Coupling processes between magnetosphere, thermosphere, and ionosphere

***Chair**: Andres Calabia (China)*
Vice-Chair: Munawar Shah (Pakistan)
Research Coordinator: Binod Adhikari (Nepal)

Members
Christine Amory-Mazaudier (France, Italy)
Astrid Maute (USA)
Yury Yasyukevich (Russia)
Gang Lu (USA)
Anoruo Chukwuma (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Munawar Shah (Pakistan)
Binod Adhikari (Nepal)
Andres Calabia (China)
Piyush M. Mehta (USA)
LiangLiang Yuan (Germany)
Naomi Maruyama (USA)
Toyese Tunde Ayorinde (Brazil)
Charles Owolabi (Nigeria)
Emmanuel Abiodun Ariyibi (Nigeria)
Olawale S. Bolaji (Australia)

Note: A presentation introducing the magnetosphere-thermosphere-ionosphere (MTI) system with figures and details concerning the results summarized in this report is available at (Calabia et al. 2021) https://zenodo.org/record/4761386

1. Activities of the group

The activities of the Joint Study Group "Coupling processes between magnetosphere, thermosphere, and ionosphere" during the period 2019-2020 can be summarized as follows:

- Structuring the group with active members that can contribute as advisors and/or skilled participants (Ph.D. on relevant topic) that can promote and develop the planned activities in the ToR.
- Working effectively within the group members, creating a common platform to increase communication. JSG1 started a website-forum with information and updates concerning the coupled processes within the MTI, including bibliography, data, and models, instructions and examples on how to use the models, and other relevant information;
- Enhance international cooperation with developing countries by sharing knowledge and research tools, co-supervising thesis and helping to improve manuscripts, etc.
- Enhance and achieve successful interaction and cooperation along with the 3 Joint Working Groups of the IAG GGOS FA GSWR and other IAG Commissions, see Sect. 3.
- Elaboration and submission of scientific manuscripts co-authored by the group members, see Sects. 2 and 3.
- Elaboration of data and model products freely available for the scientific community, see Sect. 5.
- Elaboration and submission of a project at the International Space Intelligent Innovation and Entrepreneurship Competition, Nanjing, China. Funds were not granted, but the project draft is available for future submissions.

2. Achievements and results

- In Heelis and Maute (2020), the challenge to Understand the MTI System is addressed to advance in geodetic observations of plasma and mass density compositions and velocities, as well as the dynamics of energetic particles and field-aligned currents from magnetospheric energy inputs.
- In Calabia and Jin (2020b), Total Electron Content (TEC) and Thermospheric Mass Density (TMD) observables show a very similar response to solar flux. The annual cycle of TEC is approximately one order of magnitude larger. A hemispheric asymmetry is shown in TMD, with higher values in the southern hemisphere. The asymmetry is not visible in TEC.
- In Petadella et al (2018), the uncertainties in physics-based models are investigated by perturbing high-latitude electric potential and auroral energy flux. Specification of high-latitude electric fields is an important source of uncertainty when modelling the ionosphere response to geomagnetic storms.
- In Calabia and Jin (2019), a seasonal dependence in amplitude of TMD variability due to magnetospheric forcing is shown only in the southern high latitude.
- In Lu et al (2020), comparisons between physics-based models and TEC observations show storm phenomena driven by ionospheric convection, aurora precipitation, and SubAurora Plasma Stream field.
- In Zhang et al (2020), the TMD cooling due to only NO show not be sufficient to explain the observed variability.
- In Zhu et al (2019), physics-based model simulations show Joule heating is 27% globally enhanced by the small-scale and mesoscale electric field variation, but particle precipitation rerduce this enhancement in 5% globally, and up to 18% locally.
- In Forbes et al (2020), physics-based model simulations show the tide contributions to S0 TMD response at 325 km consists of planetary wave fluctuations of order ±4%, roughly equivalent to the day-to-day variability associated with low-level geomagnetic activity. The short periods TMD variability (< 9 days) correlates with temperature changes (hydrostatic origin). Over longer periods TMD is also controlled by composition and mean molecular mass.

3. Interactions with the IAG Commissions and GGOS

Iteraction with JWG1: Electron density modelling

- In Calabia and Jin (2020b), a new empirical TEC model from Global Ionosphere Maps is presented. Available at *http://doi.org/10.5281/zenodo.3563463*.
- In Yasyukevich et al (2020b), small-scale ionospheric irregularities caused by auroral oval expansion during geomagnetic storms results in large GNSS PPP errors.
- In Yasyukevich et al (2020a), SIMuRG is a new online service that provides high-rate ionospheric products including TEC, RPTI, AATR and vTEC. The service is available at https://simurg.iszf.irk.ru.

Interaction with JWG2: Improvement of thermosphere models

- In Yuan et al (2019), a new thermospheric mass density observable from SWARM-C GNSS is presented.
- In Calabia et al. (2019, 2020), a new empirical model of thermosphere mass density is validated and investigated. Available at *http://doi.org/10.5281/zenodo.3234582*.
- In Licata et al. (2021), the new HASDM dataset is validated against the JB2008 using the Principal Component Analysis (PCA). Comparisons of HASDM to GRACE and CHAMP densities during geomagnetic storms show better agreement than JB2008.

Interaction with FA Geohazards

- In Shah et al (2020a), the lithosphere-ionosphere coupling is investigated from TEC observables during earthquake events. Interaction with FA Geohazards.
- In Shah et al (2020b), the statistical analysis of 1182 earthquakes during 1998-2019 shows TEC anomalies within 5 days before the main shock.

4. Refined plans for the period of 2021-2023

- Working effectively within the group members, creating a common platform to increase communication.
- Advancement of MTI science in developing countries by organizing workshops, etc.
- Elaboration and submission of scientific manuscripts co-authored by the group members.
- Elaboration of data and model products freely available for the scientific community.
- Keep the Website-Forum active and updated.
- Organizing a session at the 2022 Hotine-Marussi Symposium.
- Improvement and submission of the existing project draft to request funds for publications fees, etc.
- Elaboration of proposal for International Workshop on MTI Coupling (IWMTIC2021): Prospects, Challenges, and Opportunities. Kathmandu, Nepal. June 2022?
- Participation in a blended mode of international conference at Nepal Physical Society.

5. Publications

Selected peer-reviewed publications

Calabia A, Jin SG (2019) Solar-flux and asymmetric dependencies of GRACE-derived thermospheric neutral density disturbances due to geomagnetic and solar wind forcing. *Annals of Geophysics* 37(5), 989-1003, doi: 10.5194/angeo-37-989-2019

Calabia A, Jin SG (2020a), Upper atmospheric characterization from neutral and electron density observations. Proceedings of International Association of Geodesy Symposia, IAGS-D-19-00063R2, doi:10.1007/1345_2020_123.

Calabia A, Jin SG (2020b) New modes and mechanisms of long-term ionospheric TEC variations from Global Ionosphere Maps. *Journal of Geophysical Research – Space Physics* 125(6), doi:10.1029/2019JA027703.

Calabia A, Tang G, Jin SG (2020) Assessment of new thermospheric mass density model using NRLMSISE-00 model, GRACE, Swarm-C, and APOD observations. *Journal of Atmospheric, Solar and Terrestrial Physics* 199: 105207, doi: 10.1016/j.jastp.2020.105207.

Forbes J, Zhang X, Maute A, Hagan ME (2018) Zonally symmetric oscillations of the thermosphere at planetarywave periods. *Journal of Geophysical Research – Space Physics* 123, 41104128, doi: 10.1002/2018JA025258.

Gao, C, Jin SG, Yuan LL (2020) Ionospheric responses to the June 2015 geomagnetic storm from ground and LEO GNSS observations. *Remote Sensing* 12(14), 2200, doi: 10.3390/rs12142200.

Heelis RA, Maute A (2020) challenges to understanding the Earth's ionosphere and thermosphere. *Journal of Geophysical Research – Space Physics* 125: e2019JA027497, doi:10.1029/2019JA027497.

Licata R, Mehta PM, Tobiska WK, Bowman BR, Pilinski MD (2021) Qualitative and quantitative assessment of the SET HASDM database. *Earth and Space Science Open Archive*, https://doi.org/10.1002/essoar.10506516.2.

Lu G, Zakharenkova I, Cherniak I, Dang T (2020) Large-scale ionospheric disturbances during the 17 March 2015 storm: A model-data comparative study. *Journal of Geophysical Research – Space Physics* 125: e2019JA027726, doi:10.1029/2019JA027726.

Pedatella NM, Lu G, Richmond AD (2018), Effects of high-latitude forcing uncertainty on the low-latitude and midlatitude ionosphere. *Journal of Geophysical Research – Space Physics* 123: 862-882, doi:10.1002/2017JA024683.

Shah M, Calabia A, Tariq MA, Ahmed J, Ahmed A (2020) Possible ionosphere and atmosphere precursory analysis related to Mw >6.0 earthquakes in Japan. *Remote Sensing of Environment* 239: 111620, doi: 10.1016/j.rse.2019.111620.

Shah M, Ahmed A, Ehsan M, Khan M, Tariq MA, Calabia A, Rahman ZU (2020) Total electron content anomalies associated with earthquakes occurred during 1998-2019. *Acta Astronautica*, doi: 10.1016/j.actaastro.2020.06.005.

Syrovatskiy SV, Yasyukevich Y, Edemskiy IK, AM Vesnin, Voeykov V, Zhivetiev IV (2019) Can we detect X/M/C-class solar flares from global navigation satellite system data? *Results in Physics* 12: 1004-1005, doi: 10.1016/j.rinp.2018.12.069.

Tang GS, Li X, Cao J, Liu S, Chen G, Haijun M, Zhang X, Shi S, Sun J, Li Y, Calabia A (2020) APOD mission status and preliminary results. *Sci. China Earth Sci.* 63: 257-266, doi:10.1007/s11430-018-9362-6.

Yasyukevich Y, Kiselev AV, Zhivetiev IV, Edemskiy IK, Syrovatskii SV, Maletckii BM, Vesnin AM (2020a) SIMuRG: System for Ionosphere Monitoring and Research from GNSS. *GPS Solutions* 24(69), doi:10.1007/s10291-020-00983-2.

Yasyukevich Y, Vasilyev R, Ratovsky K, Setov A, Globa M, Syrovatskii S, Yasyukevich A, Kiselev A, Vesnin A (2020b) Small-scale ionospheric irregularities of auroral origin at mid-latitudes during the 22 June 2015 magnetic storm and their effect on GPS positioning. *Remote Sensing* 12: 1579, doi:10.3390/rs12101579.

Yuan LL, Jin SG, Calabia A (2019) Distinct thermospheric mass density variations following the September 2017 geomagnetic storm from GRACE and SWARM precise orbits. *Journal of Atmospheric, Solar and Terrestral Physics* 184: 30-36, doi: 10.1016/j.jastp.2019.01.007.

Zhang Y, Paxton LJ, Lu G, Yee S (2019) Impact of nitric oxide, solar EUV and particle precipitation on thermospheric density decrease *Journal of Atmospheric, Solar and Terrestral Physics* 182: 147-154, doi: 10.1016/j.jastp.2018.11.016.

Zhu Q, Deng Y, Richmond A, McGranaghan RM, Maute A (2019), Impacts of multiscale field-aligned currents (FACs) on the ionosphere-thermosphere: GITM simulation. *Journal of Geophysical Research – Space Physics* 124: 3532 3542, doi:10.1029/2018JA026082.

Zhu Q, Deng Y, Richmond A, Maute A (2018) Small-scale and mesoscale variabilities in the electricfield and particle precipitation and their impacts on Joule heating. *Journal of Geophysical Research – Space Physics* 123: 9862-9872, doi:10.1029/2018JA025771.

Presentations at conferences

Calabia A, Jin SG (2019) Upper atmospheric characterization through neutral and electron density observables. oral presentation at IUGG 2019 General Assembly, Montreal, Canada, 8 to 18 July.

Calabia A, Jin SG (2019) Thermospheric mass density perturbations due to Space Weather from LEO GPS POD and accelerometer, oral presentation at *2019* Workshop on Smart Navigation and Applications and Annual Meeting of Jiangsu Engineering Center for Navigation, Nanjing, China, 11-13, January.

Shah M (2019) Low latitude ionospheric variations associated with geomagnetic storm in Pakistan from GNSS TEC, International Nithiagali Summer School, Islamabad, June 11-13.

Jin SG, Yuan LL (2019) Thermospheric variations from GNSS and accelerometer observations on GRACE and Swarm, The 4th COSPAR Symposium on Small Satellites for Sustainable Science and Development, Herzliya, Israel, 4-8 November.

Yasyukevich Y, et al. (2019) Ionosphere modeling and monitoring using GPS and GLONASS techniques. Invited talk at the 10th China satellite navigation conference. Beijin, China. May 22-25.

Other publications

Calabia A, Munawar S, Adhikari B, Amory-Mazaudier C, Maute A, Gang L, Yasyukevich Y (2021) IAG-FA-GSWR-JSG1 2019 Mid-term Report PPT. Zenodo. http://doi.org/10.5281/zenodo.4761386

Website & forum

- https://ggos.org/about/org/fa/geodetic-space-weather-research/groups/jsg1-coupling-processes/
- https://www.researchgate.net/project/IAG-JSG1-Coupling-processes-between-magnetosphere-thermosphere-and-ionosphere-MTI

Data & software products

Calabia A, Jin SG (2019) Supporting information for "Solar-cycle, seasonal, and asymmetric dependencies of thermospheric mass density disturbances due to magnetospheric forcing". Zenodo. http://doi.org/10.5281/zenodo.3234582

Calabia A, Jin SG (2019) Supporting Information for "New modes and mechanisms of long-term ionospheric TEC variations from Global Ionosphere Maps". Zenodo. http://doi.org/10.5281/zenodo.3563463

Calabia A, Jin SG (2020) Supporting Information for "Short-term ionospheric TEC variations from Global Ionosphere Maps" [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4280436
SIMuRG: System for Ionosphere Monitoring and Research from GNSS. https://simurg.iszf.irk.ru

Other relevant links

- Community Coordinated Modelling Center: https://ccmc.gsfc.nasa.gov/models/models_at_glance.php

Joint Study Group T.28: Forward gravity field modelling of known mass distributions

Chair: *Dimitrios Tsoulis (Greece)*

Members

Carla Braitenberg (Italy)
Christian Gerlach (Germany)
Ropesh Goyal (India)
Olivier Jamet (France)
Michael Kuhn (Australia)
Pavel Novák (Czech Republic)
Konstantinos Patlakis (Greece)
Daniele Sampietro (Italy)
Matej Varga (Croatia)
Jérôme Verdun (France)

1. Activities of the group

In the course of the previous two years the activities of the study group concentrated on two major objectives: (a) the performance of analytical and numerical computations of terrain effects over dense Digital Elevation Models and (b) the investigation of alternative and more stable computational strategies for the potential harmonic coefficients of a polyhedral source.

2. Achievements and results

The main achievements and results can be briefly outlined as follows:

- Development of a modified spatial-spectral combined methodology for efficient computation of local planar terrain corrections (TC) with demonstrated convergence (Goyal et al. 2020a).
- The spatial-spectral combination method has been utilized to calculate 1”x1” and 3”x3” local planar TC maps over India and adjacent regions using SRTM1” DSM and MERIT 3” DEM, respectively. These are the first high-resolution TC maps that i) are constructed in a region having varied topography consisting of the Himalayas, the Gangetic plain, the Thar desert, the Deccan plateaus, and various Hill ranges and ii) have guaranteed convergence of < 1μGal. However, with some more testing we found that the stripe effects that are present in the SRTM 1” DSM are propagated to the computed TC values. Considerations on the corresponding TC error grid are on the way.

  A 0.02˚ grid of TC constructed by block-averaging the 3” TC map from MERIT DEM has being utilized for computation of the first gravimetric geoid model for India (Goyal et al. 2020b, 2021c). TC computed using this strategy has been utilized in the geoid/quasigeoid computation over Colorado (Claessens and Filmer 2020) and Auvergne (Goyal et al. 2021b). The original and block-averaged TC grids are shown in Figs. 1 and 2. The scatter plot of block-averaged TC wrt to heights and the histogram are shown in Fig. 3.

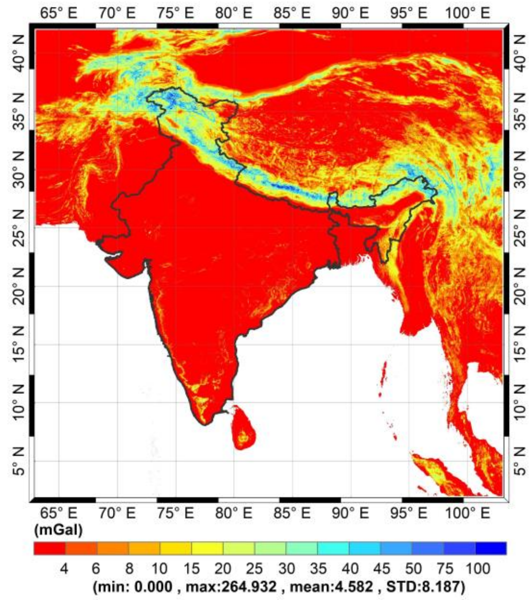


Figure 1: 3" TC from MERIT 3" DEM.

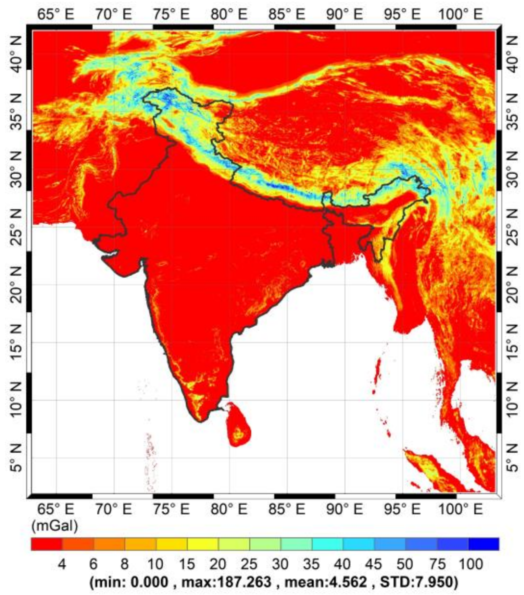


Figure 2: Block-averaged TC from MERIT 3" DEM.

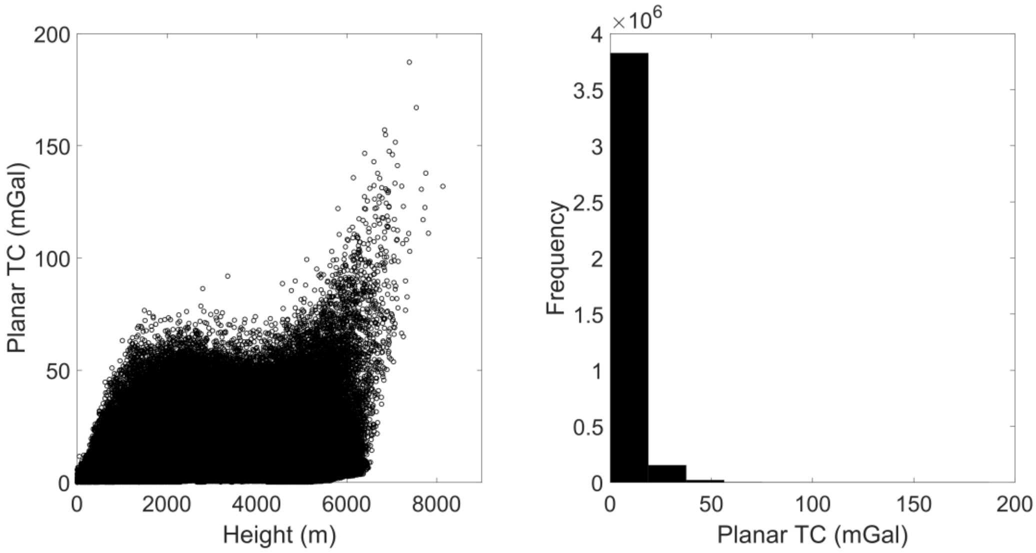


Figure 3: Scatter plot of block-averaged TC wrt heights and the corresponding histogram.

Larger values of TC are obtained in the regions with high peaks and rapidly undulating terrain. In the plateau regions where we have high elevation but relatively lesser undulating terrain, TC have smaller values. TC vary considerably (~1mGal to 50 mGal) for the areas having greater heights (~2000 m to 6500 m). Thus, TC vary noticeably in the regions with the undulating terrain compared to the regions only having higher elevations.

- The application of FFTs in these computations provided input for further investigations. With some random tests in extremely plain areas, i.e., regions with no emerging condition of divergence, FFTs are providing somewhat unexpected results. Moreover, on further derivations of TC errors up to higher order binomial expansion it is observed that the FFT based TC errors are divergent. Thus, the stability of FFT in different topographical features should be examined.
- Another important observation is the substantial difference in TC for various regions (especially mountainous regions) computed with different DEMs/DSMs. This is due to the horizontal shifts among various freely available global DEMs/DSMs. Moreover, the freely

available DSM/DEM are not in agreement at various topographical features, especially in the undulating mountainous hills (cf. Goyal et al. 2021a). Therefore, a study on the minimization of geolocation errors and their effect on terrain effects will be undertaken.

- Explicit introduction of ‘dynamic’ or ‘floating’ integration radius may be introduced in the computation of topographical/terrain effects involving numerical integration with cascading grid. It may be possible that researchers might be already using the floating integration radius as it is required to avoid the effects from overlapping or missing DEM elements, especially at the transition zones. This has been followed to compute the topographical effect in the gravimetric geoid model of India using the UNB method. A numerical test will be undertaken to quantify this effect.
- A new approach for the computation of the spherical harmonic coefficients induced by a constant density polyhedral source has been presented. Unlike previous computational algorithms the coefficients emerge directly from the evaluation of the corresponding line integrals. The derived algorithm is also numerically much more stable with respect to its predecessors, with stable computed coefficients up to degree 360 (Jamet and Tsoulis 2020), see Fig. 4.

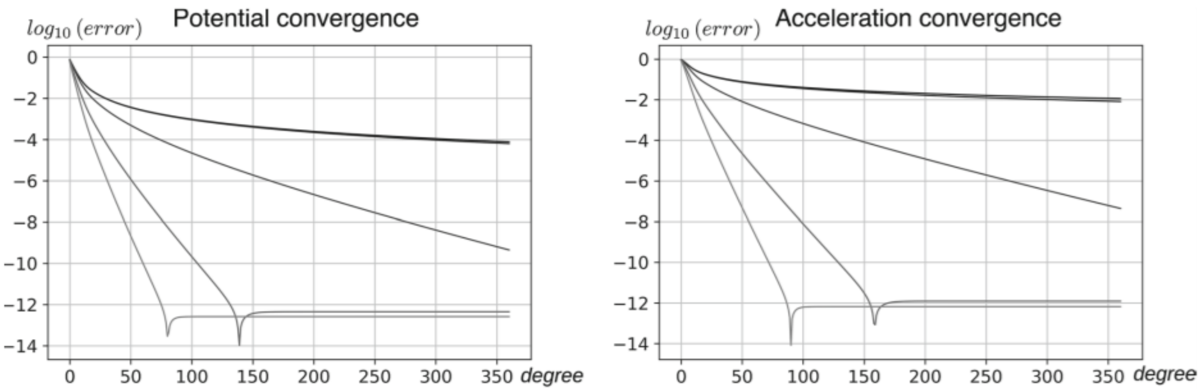


Figure 4: Convergence rate in line integral coefficient algorithm (Jamet and Tsoulis 2020).

- The spherical harmonic expansion of topography and the implied gravity signal has been considered in terms of its convergence behavior especially for very high degrees (Bucha and Kuhn 2020). Numerical considerations and technical definitions regarding these expansions, such as the definition of the integration cap, were investigated in the frame of Residual Terrain Modelling computations and spectral forward gravity modelling (Bucha et al. 2019a-d, Hirt et al. 2019a).
- A global computation of terrain corrections has been carried out using SRTM terrain information at a 3’’ spatial resolution. The obtained computational volume was tackled by a combination of spatial and spectral techniques in a parallel computing environment (Hirt et al. 2019b).

3. Interactions with the IAG Commissions and GGOS

- Gravity and geoid in the Asia-Pacific: Sub-Commission 2.4e.

4. Refined plans for the period of 2021-2023

It is envisaged to continue the investigation of different forward modelling techniques in terms of their mathematical and computational properties when applied to ideal and real distributions, as those defined by a digital elevation model. Main scientific event for presenting case studies as well as review computations is the forthcoming Hotine Marussi Symposium in 2022.

5. Publications

Bucha B, Hirt C, Yang M, Kuhn M, Rexer M (2019a) Residual terrain modelling (RTM) in terms of the cap-modified spectral technique: RTM from a new perspective. *Journal of Geodesy* 93(10): 2089-2108

Bucha B, Hirt C, Kuhn M (2019b) Cap integration in spectral gravity forward modelling up to the full gravity tensor. *Journal of Geodesy* 93(9): 1707-1737

Bucha B, Hirt C, Kuhn M (2019c) Divergence-free spherical harmonic gravity field modelling based on the Runge-Krarup theorem: a case study for the Moon. *Journal of Geodesy* 93(4): 489-513

Bucha B, Hirt C, Kuhn M (2019d) Cap integration in spectral gravity forward modelling: near- and far-zone gravity effects via Molodensky's truncation coefficients. *Journal of Geodesy* 93(1): 65-83

Bucha B, Kuhn M (2020) A numerical study on the integration radius separating convergent and divergent spherical harmonic series of topography-implied gravity. *Journal of Geodesy* 94(12): 112

Claessens SJ, Filmer MS (2020) Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. *Journal of Geodesy* 94(52), doi:10.1007/s00190-020-01379-3

Goyal R, Featherstone WE, Tsoulis D, Dikshit O (2020a) Efficient spatial-spectral computation of local planar gravimetric terrain corrections from high-resolution digital elevation models. *Geophysical Journal International* 221(3): 1820-1831

Goyal R, Featherstone WE, Claessens SJ, Dikshit O, Balasubramanian N (2020b) Indian gravimetric geoid model: data, methods and a preliminary test using Curtin University's approach. In: First Asia-Pacific geoid workshop for IAG Sub-Commission 2.4e.

Goyal R, Featherstone WE, Dikshit O, Nagarajan B (2021a) Comparison and validation of satellite-derived digital elevation/surface models over India. *Journal of Indian Society of Remote Sensing* 49: 971-986, doi:10.1007/s12524-020-01273-7.

Goyal R, Ågren J, Featherstone WE, Sjöberg LE, Dikshit O, Balasubramania N (2021b) Empirical comparison between stochastic and deterministic modifiers over the French Auvergne geoid computation test-bed. *Survey Review*, online first.
doi: 10.1080/00396265.2021.1871821.

Goyal R, Featherstone WE, Claessens SJ, Dikshit O, Balasubramanian N (2021c) Indian gravimetric geoid modelling using Curtin University's approach. *Terrestrial, Atmospheric and Oceanic Sciences*, under-review.

Hirt C, Yang M, Bucha B, Kuhn M (2019a) A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high-degree spectral gravity modelling. *Journal of Geodesy* 93(9): 1469-1486

Hirt C, Yang M, Kuhn M, Bucha B, Kurzman A, Pail R (2019b) SRTM2gravity: An ultra high resolution global model of gravimetric terrain corrections. *Geophysical Research Letters* 46(9): 4618-4627

Jamet O, Tsoulis D (2020) A line integral approach for the computation of the potential harmonic coefficients of a constant density polyhedron. *Journal of Geodesy* 94(3): 30

Joint Study Group T.29: Machine learning in geodesy

***Chair**: Benedikt Soja (Switzerland)*

Members

Kyriakos Balidakis (Germany)
Clayton Brengman (USA)
Jingyi Chen (USA)
Maria Kaselimi (Greece)
Ryan McGranaghan (USA)
Randa Natras (Germany)
Bertrand Rouet-Leduc (USA)
Simone Scardapane (Italy)
Ashutosh Tiwari (India)

1. Activities of the group

Since the establishment of the JSG T.29 “Machine learning in geodesy” (from here on, simply “JSG”), two meetings have been organized to coordinate the activities of the JSG and promote cooperation and interactions of the group members. In the context of the JSG, several activities – as envisioned in the Terms of Reference – have been pursued as highlighted below.

Scientific session organization

A new session at the European Geosciences Union (EGU) General Assembly *vEGU21* was established by some of the JSG members: “G1.4 Data science and machine learning in geodesy”. It is the first time this session is part of the Geodesy Division program at EGU General Assemblies. 12 abstracts were submitted, covering a diverse range of geodetic applications. In terms of geodetic observation techniques, the presentations focused in particular on GNSS and InSAR. Concerning the type of machine learning algorithm, most authors utilized some form of deep artificial neural networks. With more than 150 participants, the session was very well attended and one of the most popular sessions in the program of the EGU Geodesy Division.

Editorial activities

A Special Issue in the Journal *Remote Sensing* has been organized by members of the JSG. The title of the Special Issue is “Data Science and Machine Learning for Geodetic Earth Observation” and submissions will be accepted from mid-2021 to mid-2022. A call for papers is intended to be sent out before the IAG Scientific Assembly 2021. Papers published as part of the Special Issue will be fully open access.

Website:

A website with a description of the JSG has been created:
https://space.igp.ethz.ch/icct-study-group.html
Currently, it includes the Terms of Reference and member list, but will be further populated with information on machine learning applications in geodesy and the activities of the JSG.

2. Achievements and results

The members have been actively researching topics related to the JSG. Related publications and presentations are listed in the last section of this report. The publications can be grouped into:

- InSAR-related investigations, mostly utilizing deep convolutional neural networks (Devara et al., submitted, Tiwari et al., 2020, 2021).
- Time series modeling and prediction. While mostly based on GNSS data, very different types of parameters are investigated, including station positions, tropospheric and ionospheric parameters as well as Earth orientation (Gou et al. 2021, Halbheer 2021, Kaselimi et al. 2020a, 2020b, 2021, Kiani and Soja, 2021a, 2021b, submitted, Natras and Schmidt 2020, 2021, Ruttner 2021).
- Other topics include the use of artificial intelligence for improved VLBI scheduling (Schartner et al. 2021a, 2021b, Wicki 2021) as well as the application of machine learning for Earthquake classification (Crocetti et al. 2021) and seismology (Shujian 2021).

A variety of machine learning algorithms were utilized, from decision tree ensembles (random forest, boosting trees, ...) to artificial neural networks (convolutional, recurrent, graph, transformers, …).

3. Interactions with the IAG Commissions and GGOS

The JSG is affiliated with IAG Commissions 2, 3, 4, as well as GGOS. In particular, synergies with a certain GGOS component are highlighted below. Additional engagements by the JSG with other entities are mentioned as well.

GGOS Focus Area on Geodetic Space Weather Research

It has been identified that several members of the JSG work on the topics related to the ionosphere and space weather (M. Kaselimi, R. McGranaghan, and R. Natras). Machine learning has become an important tool for the prediction of ionospheric parameters, typically utilizing not only geodetic measurements, but also solar data as features. This fits well to the scope of the GGOS Focus Area about the relationships between ionosphere/thermosphere and space weather. B. Soja, chair of the ICCT JSG, is vice-chair of the JWG "Improved understanding of space weather events and their monitoring by satellite missions". Synergies between these groups are fostered.

IERS Earth Orientation Parameter Prediction Comparison Campaign (EOP PCC)

The chair of the JSG is involved in the committee for the organization of the second EOP PCC and is representing the interests of the JSG in this context. The goal of the EOP PCC is to compare operational EOP prediction products provided by various institutions. The first EOP PCC finished more than ten years ago and was considered a success. A repetition is important due to the significant changes in data quality and availability as well as the developments in prediction algorithms since then. In particular, this includes the increase in popularity of machine learning/deep learning for parameter prediction, making the EOP PCC very relevant to the JSG. Furthermore, an initiative has been started by the JSG that participants of the EOP PCC provide their code – if possible – as open source, reflecting common practice in the domain of data science and machine learning.

ITU-T Focus Group on Artificial Intelligence for Natural Disaster Management

Contact has been established to the chairs of the ITU-T Focus Group on "Artificial Intelligence for Natural Disaster Management" (FG-AI4NDM), in particular to the Topic Group on "AI for Tsunami data monitoring" that heavily relies on GNSS data. Potential collaborations in this context will be explored.

4. Refined plans for the period of 2021-2023

During the half-term 2019-2021, reasonable progress has been made toward the objectives formulated in the Terms of Reference as mentioned above. The remaining goals will be addressed until the end of the term of the JSG in 2023. A meeting of the JSG members has been scheduled for June 2021 to coordinate the next steps.

Website

An initial website of the JSG has already been set up. In addition to the current content, it will be populated with:

- an inventory of machine learning algorithms,
- benchmark datasets to test the performance of these algorithms,
- a comprehensive record of previous activities/publications related to machine learning in geodesy,
- a description of ongoing activities by the JSG members.

The application of certain machine learning algorithms to geodetic data sets could for example be presented in the form of user-friendly Jupyter Notebooks, to be made available on a repository of the JSG.

Review paper

Work on a state-of-the-art review paper about machine learning in geodesy, co-authored by the JSG members, is planned for the last year of the term (from mid-2022 to mid-2023). The collection of suitable references is already ongoing, also in view of listing them on the website of the JSG. The work on the review paper will follow the conclusion of the Special Issue in *Remote Sensing*, which should happen in mid-2022.

Scientific sessions

The promotion of sessions related to the topics of the JSG is an ongoing process. Motivated by the success of the first machine learning-related geodesy session at the EGU General Assembly, the aim is to continue these activities for subsequent EGU General Assemblies as well as to expand to other conferences. Furthermore, as soon as the significant progress has been made related to the goals of the JSG (e.g., improved website offering machine learning examples), the presentations on the JSG activities will be held at scientific meetings.

5. Publications

Crocetti L, Schartner M, Soja B (2021) Detecting earthquakes in GNSS station coordinate time series using machine learning algorithms. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1975, https://doi.org/10.5194/egusphere-egu21-1975.

Devara M, Vipin Kumar M, Ashutosh T, Ramji D (2021) A multi-criteria landslide susceptibility mapping using deep neural networks. *Advances in Space Research* (submitted).

Gou J, Kiani Shahvandi M, Hohensinn R, Soja B (2021) Ultra-short-term prediction of LOD using LSTM neural networks, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-2308, https://doi.org/10.5194/egusphere-egu21-2308.

Halbheer M (2021) Prediction of atmospheric parameters from GNSS observations and weather models with machine learning. Bachelor Thesis, ETH Zurich, 2021.

Kaselimi M, Doulamis N, Doulamis A, Delikaraoglou D (2020) a sequence-to-sequence temporal convolutional neural network for ionosphere prediction using GNSS observations. The International Archives of Photogrammetry. *Remote Sensing and Spatial Information Sciences* 43: 813-820

Kaselimi M, Voulodimos A, Doulamis N, Doulamis A, Delikaraoglou D (2020) A causal long short-term memory sequence to sequence model for tec prediction using GNSS observations. *Remote Sensing* 12(9): 1354.

Kaselimi M, Voulodimos A, Doulamis N, Doulamis A, Delikaraoglou (2021) Deep recurrent neural networks for ionospheric variations estimation using GNSS measurements. *IEEE Transactions on Geoscience and Remote Sensing* [accepted].

Kiani Shahvandi M, Soja B (2021) A new spatio-temporal graph neural network method for the analysis of GNSS geodetic data. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-545, https://doi.org/10.5194/egusphere-egu21-545.

Kiani Shahvandi M, Soja B (2021) modified deep transformers for GNSS time series prediction. *IEEE International Geoscience and Remote Sensing Symposium*, accepted.

Kiani Shahvandi M, Soja, B (2021) Small datasets and deep networks: A new deeplearning method for time series prediction, withapplication to geodetic data science. The 7th International Conference on Machine Learning, Optimization, Data Science, submitted.

Natras R, Schmidt M (2021) Relationship between ionosphere VTEC and space weather indices for machine learning-based model development EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-18978, https://doi.org/10.5194/egusphere-egu2020-18978.

Natras R, Schmidt M (2021) Ionospheric VTEC Forecasting using machine learning. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-8907, https://doi.org/10.5194/egusphere-egu21-8907.

Natras R, Schmidt M (2021) Ensemble machine learning for geodetic space weather forecasting. Scientific Assembly of the International Association of Geodesy 2021, June 28 – July 2, 2021.

Ruttner P (2021) Analysis and prediction of long term GNSS height time series and environmental loading effects. Master Thesis, ETH Zurich.

Schartner M, Plötz C, Soja B (2021) Automated VLBI scheduling using AI-based parameter optimization. *Journal of Geodesy* 95: 58, https://doi.org/10.1007/s00190-021-01512-w

Schartner M, Plötz C, Soja B (2021) Improved VLBI scheduling through evolutionary strategies, EGU General Assembly 2021, 19–30 Apr 2021, EGU21-1250, https://doi.org/10.5194/egusphere-egu21-1250.

Shujian S (2021) Inversion of rock properties using the fully connected neural network. Master Thesis, The University of Tulsa.

Tiwari A, Avadh Bihari N, Onkar D (2020) Deep learning networks for selection of measurement pixels in multi-temporal SAR interferometric processing, *ISPRS Journal of Photogrammetry and Remote Sensing* 166: 169-182. https://doi.org/10.1016/ j.isprsjprs.2020.06.005.

Tiwari A, Avadh Bihari N, Onkar D (2021) A deep learning approach for efficient multi-temporal interferometric synthetic aperture radar (MT-InSAR) processing. EGU General Assembly 2021, 19–30 Apr 2021, EGU21-12784, https://doi.org/10.5194/egusphere-egu21-12784.

Wicki J (2021) Optimizing geodetic VLBI simulation parameters based on swarm intelligence. Bachelor Thesis, ETH Zurich.

Joint Study Group T.30: Dynamic modeling of deformation, rotation and gravity field variations

Chair: *Y. Tanaka (Japan)*

Members

Shin-Chan Han (Australia)
Guangyu Fu (China)
Anthony Mémin (France)
Volker Klemann (Germany)
Zdeněk Martinec (Ireland)
Daniel Melini (Italy)
Giorgio Spada (Italy)
Jun'ichi Okuno (Japan)
Yoshiyuki Tanaka (Japan), chair
Taco Broerse (Netherlands)
Riccardo Riva (Netherlands)
Wouter van der Wal (Netherlands)
Craig Miller (New Zealand)
Peter Vajda (Slovakia)
José Fernández (Spain)
Pablo J. González (Spain)
Cheinway Hwang (Taiwan)
Hom Nath Gharti (USA)
Jeanne Sauber (USA)

1. Activities of the group

This group consists of members working on dynamic modelling using diverse approaches for a better interpretation and a deeper understanding of the various geophysical phenomena, which have been revealed by the GGOS and the related geophysical observations and experiments. The targets of the modelling include local, regional and global variations. In the following, only selected studies are summarized, due to the limited space.

<u>*Theories on surface loading, co- and post-seismic deformation*</u>

Liu et al. (2020) introduced a new method to compute the post-seismic crustal internal deformations in a layered earth model. This method does not require a combination of the general solution and particular solution when calculating internal deformation above the seismic source, thus avoids the loss of precision. Chen et al. (2020) revealed the effect of earth curvature on the co-seismic Coulomb failure stress changes due to the Tohoku-Oki MW9.0 earthquake. Liu et al. (2020) deduced a set of formulae for the co-seismic internal deformation in a spherically symmetric Earth model, taking simultaneously the self-gravitation, compressibility and realistically stratified structure of the Earth into account. Liu et al. (2019) drrived a complete set of Green's functions for the post-seismic surface strain changes for a spherically symmetric, self-gravitating viscoelastic Earth model.

Tanaka et al. (2019) developed a spectral finite-element method to include the effects of laterally heterogeneous elastic constants in the computation of surface loading. This method was expanded for the 3D case and applied to ocean loading of a heterogeneous Earth model in collaboration with oceanographers (Huang et al., submitted). This algorithm was applied to a point dislocation (Tanaka et al, 2020).

Gharti et al. (2019) implemented a spectral-infinite-element method to efficiently simulate earthquake-induced gravity perturbations for a heterogeneous earth model, using moment-density tensor and split-node approaches for the source implementation, which allows complex faults in various settings to be considered. Gharti and Tromp (2019) applied this method to magnetic anomalies. Langer et al. (2019) showed that the presence of topography causes changes in the shape of observed surface displacement patterns, while material heterogeneities primarily affect the magnitude of observed displacements.

Han et al. (2019) modeled viscoelastic relaxation after the 2009 Samoa-Tonga earthquake and estimated a long-term sea level rise in the Samoan Islands. Nijholt et al. (2021) employed a Bayesian approach to identify the cause of postseismic displacements due to the 2018 Mw7.5 Palu earthquake from three candidate mechanisms (afterslip, viscoelastic relaxation and poroelastic rebound and showed that deep afterslip on and below the coseismic rupture plane was dominant.

Inversion methods using topography, gravity, magnetic and heat flow data

Vajda et al. (2019; 2020a; 2020b; 2021) developed inversion approaches based on model exploration and growing source bodies for interpretation of sparse noisy 4D microgravity and evaluated gravitational effect of surface deformation in interpretation of residual spatiotemporal gravity changes in a volcanic field, which provided best practice for the gravitational effect.

Miller et al. (2020) combined 3-D inversion of high-resolution aeromagnetic data with airborne hyperspectral imaging to create a new method to map buried structure and hydrothermal alteration for Mt. Ruapehu volcano.

Camacho and Fernández (2019) and Camacho et al. (2020) presented a methodology for the simultaneous, nonlinear inversion of gravity changes and/or surface deformation observed by different techniques to determine 3D bodies, without any a priori assumption about their geometries, embedded into an elastic or poroelastic medium.

Fullea et al. (2021) presented a new global thermochemical model of the lithosphere and underlying upper mantle constrained by state of the art seismic waveform inversion, satellite gravity (geoid and gravity anomalies and gradiometric measurements from ESA’s GOCE mission), surface elevation and heat flow data.

Volcanic & tectonic deformation (analysis method, multidisplinary data)

Miguelsanz et al. (2021) provided direct evidence of tidal modulation of seismicity during a volcanic unrest. The modulation was correlated with periods of uplift, which helps understand magmatic overpressure systems. Rodriguez-Molina et al. (2021) presented evidence of long-lasting uplift signals affecting an active volcano during its long repose interruptive period.

Wallace et al. (2020) reported on a multidisplinary observation effort of volcanic activity during a shift from effusive to explosive behavior at an active volcano. The change is accompanied by significant variations in petrological and geophysical observations. Fernández et al. (2021) detected the onset of volcanic unrest on La Palma island, most likely decades before a potential eruption. The employed geodetic techniques allow tracking of the fluid migration and identifying the existence of dislocation sources which could be associated with a future flank failure. Advanced InSAR analysis methods and geodetic applications were presented by Lazecký et al. (2020a, b), Weiss et al. (2020), Jiang and González (2020), Sparacino et al. (2020), and Escayo et al. (2020). Leonard et al. (2021) summarized current understanding of Ruapehu and Tongariro stratovolcanoes in New Zealand.

Glacial Isostatic Adjustment

Spada and Melini (2019a) studied some of the physical and geometrical features of the GIA fingerprints, their symmetries and intercorrelations, also illustrating how they stem from the Sea Level Equation. Melini and Spada (2019) considered GIA modelling uncertainties either associated with limited knowledge of input parameters or associated with structural differences in GIA models. Sun and Riva (2020) presented a global empirical model of present-day GIA, solely based on GRACE data and on geoid fingerprints of mass redistribution.

Rovira-Navarro et al. (2020) studied the anomaly in the static gravity field in Canada. Using a model of the crust and the lithosphere and models for GIA and mantle convection, it was found that the anomaly is mostly due to GIA, and that the viscosity in the lower mantle has to be below 10^{22} Pas. Reusen et al. (2020) used GRACE data to constrain GIA in the Barents Sea and Scandinavia. From comparing the best fit range of models, they concluded that the upper mantle viscosity in the Barents Sea is lower than in Scandinavia, which agrees with lower seismic velocity anomalies that in the Barents Sea region.

Pappa et al. (2019) combined ssatellite gravity gradient data with seismic data and rock properties to create a new model for the lithosphere of Antarctica. The result shows lower temperatures and somewhat higher viscosity estimates than other studies. Goto-Azuma et al. (2021) reivewed scientific results obtained by the Arctic Challenge for Sustainability (ArCS) project for the variability of the Greenland Ice Sheet and climate.

Sauber et al. (2021) and Rollins et al. (2021) investigated stress transfer due to large earthquakes and recent GIA and reported that the post-1770 GIA likely increased seismicity in Southeast Alaska since 1920.

Non-tidal atmospheric, oceanic and hydrological mass redistributions

Mémin et al. (2020a) showed that vertical land motions variability is reduced on average by more than 20% when correcting the series for non-tidal atmospheric, oceanic and hydrological loading. Mémin et al. (2020b) estimated the isostatic response of the lithosphere due to Megalake Chad for the first and presented its impact on the elevation of these paleo-shorelines, using the TABOO software. Yin et al. (2020) and Tangdamrongsub et al. (2020) developed a method to assimilate multivariate data including GRACE data and significantly improved groundwater storage estimates. Yang et al. (2020) identified land subsidence due to seasonal hydrological loading in Taiwan, using InSAR combined with GNSS.

Earth rotation and global deformation

Razeghi et al. (2019) developed a technique for co-estimation of geocenter motion and gravitational potential field seamlessly from degree 1 to 90 by simultaneously inverting a set of globally-distributed GPS displacement time series and the GRACE data.

Xu and Chao (2019) and Kuang et al. (2019) studied effects of earthquakes and electromagnetic core-mantle coupling on polar motion, respectively. The inner core libration and changes in oblatness related to the 6-year LOD fluctuation were discussed in Chen et al, (2019), Chao and Yu (2020), Chao et al. (2020) and Shih and Chao (2020).

Ghobadi-Far et al. (2019) revealed the existence of a significant transient signal after the 2004 Sumatra earthquake in the GRACE KBR data that could be potentially associated with the largest excitation due to the “football” mode of the Earth's free oscillation.

2. Achievements and results

In addition to the development of the theories, analysis methods and applications to real data, freely available software for various purposes has also been released by members:

Broerse et al. (2021) developed a strain analysis method that can deal with large deformation to properly discriminate extension, shortening and strike-slip. This method allows us to retrieve deformation information of laboratory models of tectonics and results from numerical models, optical or SAR displacement fields and to create high resolution maps of finite strain and the type of strain. The developed software to compute deformation is freely available at https://doi.org/10.5281/zenodo.4529475.

Camacho et al. (2021) developed a software package GROWTH 3.0 to determine the subsurface 3D density distribution from gravity anomaly data. The software uses very general assumptions and automatically determines the 3D density structures described by the aggregation of thousands of small rectangular prisms. This can be downloaded free.

Nagy et al. (2019) released a new tool to automatically process Sentinel-2 optical images to obtain surface glacier ice flow. The tool is open source and can be downloaded from https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/glacier-velocity/.

Spada and Melini (2019b) presented an open source program (SELEN version 4.0) that simulates the glacial isostatic adjustment (GIA) process in response to the melting of the Late Pleistocene ice sheets.

The package by Gharti et al. (2019) is available via the Computational Infrastructure for Geodynamics (geodynamics.org).

3. Interactions with the IAG Commissions and GGOS

Because of the multidisciplinary targets of our modeling and applications, many studies have been carried out with collaborators from the other IAG components, not only commissions 2 and 3 and GGOS but also newly established joint commissions. As an example, Jose Fernández is a member of the Steering Committee of the Joint Commission on Volcano Geodesy between the IAG and the IAVCEI from 2017, who organized the following EGU session:

- Fernandez J et al., Interpretation of volcanic surface deformation using a 3D multi-source approach. EGU General Assembly 2021 (online), 19-30/April/2021.
- A workshop on GIA was held in September 2019: https://www.scar.org/scar-news/serce-news/gia-workshop-2019/.

4. Refined plans for the period of 2021-2023

We will continue our activities as planned.

5. Publications

Broerse et al. (2021) Mapping and classifying large deformation from digital imagery: application to analogue models of lithosphere deformation. *Geophysical Journal Internationl* 226: 984-1017

Camacho AG, Fernández J (2019) Modeling 3D free-geometry volumetric sources associated to geological and anthropogenic hazards from space and terrestrial geodetic data. *Remote Senseing* 11(17): 2042, doi:10.3390/rs11172042.

Camacho AG, Fernández J, Samsonov SV, Tiampo KF, Palano M (2020) Multisource 3D modelling of elastic volcanic ground deformations. *Earth and Planetary Science Letters* 547C, 116445, https://doi.org/10.1016/j.epsl.2020.116445.

Camacho AG, Prieto JF, Aparicio A, Ancochea E, Fernández J (2021) Upgraded GROWTH 3.0 software for structural gravity inversion and application to El Hierro (Canary Islands). *Computers & Geosciences* 150, 104720, https://doi.org/10.1016/j.cageo.2021.104720.

Chao BF, Yu Y (2020) Variation of the equatorial moments of inertia associated with a 6-year Westward rotary motion in the Earth. *Earth and Planetary Science Letters*, https://doi.org/ 10.1016/j.epsl.2020.116316

Chao BF, Yu Y, Chung CH (2020) Variation of Earth's oblateness J2 on interannual-to-decadal timescales. *Journal of Geophysical Research* 125, doi: 10.1029/2020JB019421.

Chen F, Liu T, She Y, Huang X, Fu G (2020) Co-seismic Coulomb stress changes on the northern Tanlu fault zone caused by the Tohoku-Oki Mw9.0 earthquake. *Earthquake Science* 33: 11-22

Chen JL, Wilson C, Kuang W, Chao BF (2019) Interannual oscillations in Earth rotation. *Journal of Geophysical Research*, https://doi.org/10.1029/2019JB018541.

Escayo J, Fernández J, Prieto JF, Camacho AG, Palano M, Aparicio A, Rodríguez-Velasco G, Ancochea E (2020) Geodetic study of the 2006-2010 ground deformation in La Palma (Canary Islands): observational results. *Remote Sensing* 12: 2566; doi:10.3390/rs12162566.

Fernández J, Escayo J, Hu Z, Camacho AG, Samsonov SV, Prieto JF, Tiampo KF, Palano M, Mallorquí JJ, Ancochea E (2021) Detection of volcanic unrest onset in La Palma, Canary Islands, evolution and implications. *Scientific Reports* 11: 2540, https://doi.org/10.1038/s41598-021-82292-3.

Fullea J, Lebedev S, Martinec Z, Celli NL (2021) WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical–petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data. *Geophysical Journal International* 226: 146-191, https://doi.org/10.1093/gji/ggab094.

Gharti HN, Langer L, Tromp J (2019) Spectral-infinite-element simulations of earthquake-induced gravity perturbations. *Geophysical Journal International* 217: 451-468

Gharti HN, Tromp J (2019) Spectral-infinite-element simulations of magnetic anomalies, *Geophysical Journal International* 217: 1656-1667

Goto-Azuma K, Homma T, Saruya T, Nakazawa F, Komuro Y, Nagatsuka N, Hirabayashi M, Kondo Y, Koike M, Aoki T, Greve R, Okuno J (2021) Studies on the variability of the Greenland Ice Sheet and climate. *Polar Science* 27, https://doi.org/10.1016/j.polar.2020.100557.

Ghobadi-Far K, Han SC, Sauber JM et al. (2019) Gravitational changes of the Earth's free oscillation from earthquakes: Theory and feasibility study using GRACE inter-satellite tracking. *Journal of Geophysical Research – Solid Earth* 2019JB017530, doi: 10.1029/2019jb017530.

Han SC, Sauber J, Pollitz F, Ray R (2019) Sea level rise in the Samoan Islands escalated by viscoelastic relaxation after the 2009 Samoa-Tonga earthquake. *Journal of Geophysical Research – Solid Earth*, 124, 4142-4156, doi: 10.1029/2018jb017110.

Huang P, Sulzbach RL, Tanaka Y, Klemann V, Dobslaw H, Martinec Z, Thomas M (2021) Anelasticity and lateral heterogeneities in Earth's upper mantle af-fecting ocean tides: surface displacement, self-attraction and load-ing, feedback to ocean dynamics. Submitted.

Jiang Y, González PJ (2020) Bayesian inversion of wrapped satellite interferometric phase to estimate fault and volcano surface ground deformation models. *Journal of Geophysical Research – Solid Earth* 125(5): 1-23 doi:10.1029/2019JB018313.

Kuang W, Chao BF, Chen J (2019) Reassessment of electromagnetic core-mantle coupling and its implications to decadal polar motion. *Journal of Geodynamics*, https://doi.org/10.1016/j.geog.2019.06.003.

Langer L, Gharti HN, Tromp J (2019) Impact of topography and three-dimensional heterogeneity on coseismic deformation. *Geophysical Journal International* 217: 866-878

Lazecký M, Hatton E, González PJ, Hlaváčová I, Jiránková E, Dvořák F, Šustr Z, Martinovič J (2020a) Displacements monitoring over Czechia by IT4S1 system for automatised interferometric measurements using Sentinel-1 data. *Remote Sensing* 12(18): 2960, doi:10.3390/rs12182960.

Lazecký M, Spaans K, González PJ, Maghsoudi Y, Morishita Y, Albino F, Elliot J, Greenall N, Hatton E, Hooper A, Juncu D, McDougall A, Walters R, Watson S, Weiss JR, Wright T (2020b) LiCSAR: An automatic InSAR tool for measuring and monitoring tectonic and volcanic activity. *Remote Sensing* 12(15): 2430, doi:10.3390/rs12152430.

Leonard GS, Cole RP, Christenson BW, Conway CE, Cronin SJ, Gamble JA, Hurst T, Kennedy BM, Miller CA, Procter JN, Pure LR, Townsend DB, White JDL, Wilson CJN (2021) Ruapehu and Tongariro stratovolcanoes: a review of current understanding. *New Zealand Journal of Geology and Geophysics*, https://doi.org/10.1080/00288306.2021.1909080.

Liu T, Fu G, She Y (2021) Post-seismic crustal internal deformations in a layered Earth model. *Geophysical Journal International:* ggab156, https://doi: 10.1093/gji/ggab156.

Liu T, Fu G, She Y, Zhao C (2020) Co-seismic internal deformations in a spherical layered Earth model. *Geophysical Journal International* 221(3): 1515-1531

Liu T, Fu G, She Y, Zhao C (2019) Green's function of post-seismic strain changes in a realistic Earth model and its application to the Tohoku-Oki Mw9.0 earthquake. *Pure and Applied Geophysics* 176(9): 3929-3949

Melini D, Spada G (2019) Some remarks on Glacial Isostatic Adjustment modelling uncertainties. *Geophysical Journal International* 218: 401-413, https://doi.org/10.1093/gji/ggz158.

Mémin A, Boy JP, Santamaria-Gomez A (2020a) Correcting GPS measurements for non-tidal loading. *GPS Solutions* 24: 1-13

Mémin A, Ghienne JF, Hinderer J, Roquin C, Schuster M (2020b) The Hydro-Isostatic Rebound Related to Megalake Chad (Holocene, Africa): First Numerical Modelling and Significance for Paleo-Shorelines Elevation. *Water* 12: 3180, https://doi.org/10.3390/w12113180.

Miguelsanz L, González PJ, Tiampo KF, Fernández J (2021) Tidal influence on seismic activity during the 2011–2013 El Hierro volcanic unrest. *Tectonics* 40(2), doi:10.1029/2020TC006201.

Miller CA, Schaefer LN, Kereszturi G, Fournier D (2020) Three-dimensional mapping of Mt. Ruapehu Volcano, New Zealand, from aeromagnetic data inversion and hyperspectral imaging. *Journal of Geophysical Research – Solid Earth* 125, https://doi.org/10.1029/2019JB018247.

Nagy T, Andreassen LM, Duller R, González PJ (2019) SenDiT: The Sentinel-2 displacement toolbox with application to glacier surface velocities. *Remote Sensing* 11(10): 1151, doi:10.3390/rs11101151.

Nijholt N, Simons WJF, Efendi J, Sarsito DA, Riva REM (2021) A transient in surface motions dominated by deep afterslip subsequent to a shallow supershear earthquake: The 2018 Mw7.5 Palu case. *Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2020GC009491.

Pappa F, Ebbing J, Ferracioli F, van der Wal W (2019) Modeling satellite gravity gradient data to derive density, temperature, and viscosity structure of the Antarctic lithosphere. *Journal of Geophysical Research – Solid Earth,* doi: 10.1029/2019JB017997.

Razeghi M, Han SC, McClusky S, Sauber JM (2019) A joint analysis of GPS displacement and GRACE geopotential data for simultaneous estimation of geocenter motion and gravitational field. *Journal of Geophysical Research – Solid Earth* 124: 12,241-12,263, doi: 10.1029/2019jb018289.

Reusen JM, Root BC, Szwillus W, Fullea J, van der Wal W (2020) Long-wavelength gravity field constraint on the lower mantle viscosity in North America. *Journal of Geophysical Research – Solid Earth:* e2020JB020484

Rollins C, Freymueller J, Sauber JM (2021) Stress promotion of the 1958 Mw7.8 Fairweather Fault earthquake and others in southeast Alaska by glacial isostatic adjustment and inter-earthquake stress transfer. *Journal of Geophysical Research – Solid Earth* 126, doi: 10.1029/ 2020JB020411.

Rovira-Navarro M, van der Wal W, Barletta VR, Root BC, Sandberg-Sørensen L (2020) GRACE constraints on Earth rheology of the Barents Sea and Scandinavia (open access). accepted in *Solid Earth Discussions*, doi: 10.5194/se-2019-105.

Rodriguez-Molina S, Gonzalez PJ, Charco M, Negredo AM, Schmidt DA (2021) Time-scales of inter-eruptive volcano uplift signals: Three Sisters Volcanic Center, Oregon (United States). *Frontiers in Earth Science* 8, doi: 10.3389/feart.2020.577588.

Sauber JM, Rollins C, Freymueller JT, Ruppert NA (2021) Glacially induced faulting in Alaska, glacially triggered faulting. https://ntrs.nasa.gov/citations/20205006654.

Shih SA, Chao BF (2020) Inner core and its libration under gravitational equilibrium: implications to lower-mantle density anomaly. *Journal of Geophysical Research – Solid Earth,* doi: 10.1029/2020JB020541.

Spada G, Melini D (2019a) On some properties of the glacial isostatic adjustment fingerprints. *Water* 11(9): 1844, https://doi.org/10.3390/w11091844

Spada G, Melini D (2019b) SELEN^4 (SELEN version 4.0): a Fortran program for solving the gravitationally and topographically self-consistent sea-level equation in glacial isostatic adjustment modeling. *Geosci. Model Dev.* 12: 5055–5075, https://doi.org/10.5194/gmd-12-5055-2019.

Sparacino F, Palano M, Peláez JA, Fernández J (2020) Geodetic deformation versus seismic crustal moment-rates: insights from the Ibero-Maghrebian region. *Remote Sensing* 12: 952, doi: 10.3390/rs12060952.

Sun Y, Riva REM (2020) A global semi-empirical glacial isostatic adjustment (GIA) model based on Gravity Recovery and Climate Experiment (GRACE) data. *Earth System Dynamics* 11: 129-137, https://doi.org/10.5194/esd-11-129-2020.

Tangdamrongsub N, Han SC et al. (2020) Multivariate data assimilation of GRACE, SMOS, SMAP measurements for improved regional soil moisture and groundwater storage estimates. *Advances in Water Resources* 135, https://doi.org/10.1016/j.advwatres.2019.103477.

Tanaka Y, Klemann V, Martinec Z (2019) Surface loading of a self-gravitating, laterally heterogeneous elastic sphere: preliminary result for the 2D case. IX Hotine-Marussi Symposium on Mathematical Geodesy: 57-163, doi: 10.1007/1345_2019_62.

Tanaka Y, Klemann V, Martinec Z (2020) Estimating the effects of laterally heterogeneous elasticity on coseismic deformation -a rotationally symmetric case. AGU FM G003-0003.

Vajda P, Zahorec P, Miller CA, Le Mével H, Papčo J, Camacho AG (2021) Novel treatment of the deformation–induced topographic effect for interpretation of spatiotemporal gravity changes: Laguna del Maule (Chile). *Journal of Volcanology and Geothermal Research* 414: 107230, https://doi.org/10.1016/j.jvolgeores.2021.107230.

Vajda P, Foroughi I, Vaníček P, Kingdon R, Santos M, Sheng M, Goli M (2020a) Topographic gravimetric effects in earth sciences: Review of origin, significance and implications. *Earth-Science Reviews* 211: 103428, https://doi.org/10.1016/j.earscirev.2020.103428

Vajda P, Zahorec P, Papčo J, Carbone D, Greco F, Cantarero M (2020b) Topographically predicted vertical gravity gradient field and its applicability in 3D and 4D microgravimetry: Etna (Italy) case study. *Pure and Applied Geophysics* 177(7): 3315-3333, https://doi.org/10.1007/s00024-020-02435-x.

Vajda P, Zahorec P, Bilčík D, Papčo J (2019) Deformation–induced topographic effects in interpretation of spatiotemporal gravity changes: Review of approaches and new insights, *Surveys in Geophysics* 40: 1095-1127, https://doi.org/10.1007/s10712-019-09547-7.

Wallace PA, Lamb OD, De Angelis S, Kendrick JE, Hornby AJ, Díaz-Moreno A, González PJ, von Aulock FW, Lamur A, Utley JEP, Rietbrock A, Chigna G, Lavallée Y (2020) Integrated constraints on explosive eruption intensification at Santiaguito dome complex, Guatemala. *Earth and Planetary Science Letters* 536: 116-139, doi:10.1016/j.epsl.2020.116139.

Weiss JR, Walters RJ, Morishita Y, Wright TJ, Lazecký M, Wang H, Hussain E, Hooper AJ, Elliot JR, Rollins C, Yu C, González PJ, Spaans K, Li Z, Parsons B, (2020) High-resolution surface velocities and strain for anatolia from Sentinel-1 InSAR and GNSS data. *Geophysical Research Letters* 47(17): 1-12, doi:10.1029/2020GL087376.

Xu CY, Chao BF (2019) Seismic effects on the secular drift of the Earth's rotational pole. *Journal of Geophysical Research – Solid Earth* 124, https://doi.org/10.1029/2018JB017164.

Yang YJ, Hwang C, Hung WC, Fuhrmann T, Chen YA, Wei SH (2019) Surface deformation from Sentinel-1A InSAR: relation to seasonal groundwater extraction and rainfall in central Taiwan. *Remote Sensing* 11: 2817, doi:10.3390/rs11232817.

Yin W, Han SC et al. (2020) Improved water storage estimates within the North China Plain by assimilating GRACE data into the CABLE model. *Journal of Hydrology* 590, https://doi.org/10.1016/j.jhydrol.2020.125348.

Joint Study Group T.31: Multi-GNSS theory and algorithms

***Chair**: Amir Khodabandeh (Australia)*

Members

Peter J.G. Teunissen (The Netherlands)
Jean-Marie Sleewagen (Belgium)
Bofeng Li (China)
Jacek Paziewski (Poland)
Robert Odolinski (New Zealand)
Baocheng Zhang (China)
Ali Reza Amiri-Simkooei (Iran)
Dimitrios Psychas (The Netherlands)
Gabriele Giorgi (Germany)

1. Activities of the group

Due to the pandemic, the planned group's activities have been delayed. However, during the period of 2021-2023, the group aims to establish continuous online meetings to discuss and address research challenges on the topic of multi-GNSS and to hopefully achieve the main objectives of this study group.

2. Achievements and results

Some of the multi-GNSS research outcomes of the group members are listed below:

- A new Frequency Division Multiple Access (FDMA) GLONASS model: Teunissen and Khodabandeh (2019) and Hou et al. (2020) studied and applied the new GLONASS FDMA ambiguity resolution model, as developed by Teunissen (2019), for short- and long-baseline data. This FDMA model is also applicable to low-cost GNSS receivers able to track FDMA GLONASS signals, such as the ublox ZED-F9P receivers, as explicitly demonstrated in Teunissen and Khodabandeh (2019). Zaminpardaz et al. (2021) performed a Code Division Multiple Access (CDMA) and FDMA combination of GLONASS-only satellites for real-time kinematic (RTK) positioning, and analyzed its performance using the future GLONASS constellation.
- Next Generation GNSS constellations: Giorgi et al. (2019) reviewed recent progress in optical frequency references and optical communication systems and discussed their utilizations in global satellite navigation systems and satellite geodesy. The study concerned a *revised* GNSS architecture, discussing a novel architecture which enables a more clear-cut separation between the space and time domains—which hinders current satellite navigation and geodesy applications—with a strong impact on orbit determination and time dissemination capabilities.
- E1/E5b rovers receiving E1/E5a RTK corrections: Sleewaegen and De Wilde (2019) presented a patent-pending technique addressing the situation where an E1/E5b rover receives RTK corrections of E1/E5a signals. Accordingly, the rover can recreate the missing E5b corrections by modifying his RTK-based observation equations, thus achieving RTK positioning without significant loss of positioning accuracy.
- Best Integer Equivariant Estimation applied to mass-market multi-GNSS receivers: Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency (SF) multi-GNSS RTK positioning. Odolinski and Teunissen (2020b) analyzed subsequently also the corresponding BIE performance for

low-cost dual-frequency (DF) long baseline multi-GNSS RTK positioning. It was shown that the BIE estimator outperforms ILS and the float solutions in terms of their positioning mean squared errors (MSEs).

- Role of multi-GNSS integration on the phase-only ambiguity resolution performance: Khodabandeh et al. (2021) studied the role played by the multi-GNSS integration in improving the ambiguity resolution performance of a dual-epoch phase-only model. It was shown that multi-GNSS integration makes near real-time centimetre-level phase-only positioning possible. The applicability of the presented phase-only model has the potential to be extended for LEO-based positioning applications through communication signals that are *not* necessarily accompanied by pseudo-range measurements.
- LEO enhanced Global Navigation Satellite System (LeGNSS): Ge et al. (2020) studied several aspects of LEO constellations in terms of number of LEO orbital planes, number of LEO satellites, and the selection of orbital inclinations to find out a suitable LEO constellation for LeGNSS. It was shown that the combination of several LEO constellations with different inclinations can lead to a more uniform distribution of the number of visible LEO satellites along the latitude for global fast convergent PPP.
- Smartphone positioning: Paziewski et al. (2021) assessed the quality of multi-GNSS observations of recent Android smartphones. It was shown that show that the higher the elevation of the satellite, the larger discrepancy in C/N0 between the geodetic receivers and smartphones. Through positioning experiments, it was demonstrated that it is feasible to obtain a precise cm-level solution of a smartphone to smartphone relative positioning with fixed integer ambiguities.

3. Interactions with the IAG Commissions and GGOS

The IUGG General Assembly was held in Montreal, Canada in July 2019 in which a number of the group members met and discussed potential research topics. There are also common research interests with WG 4.2.2: "Ambiguity resolution for low-cost GNSS positioning".

4. Refined plans for the period of 2021-2023

The study group members will arrange a series of online meetings so as to identify and investigate challenges that are posed by the integration of multi-GNSS and LEO observations. These meetings are aimed to base collaborative research activities among members, leading to publishable results. In particular, it is envisaged that many members can present the outcomes of such research activities at the Hotine-Marussi Symposium in June 2022.

5. Publications

Teunissen PJG (2019) A new GLONASS FDMA model. *GPS Solutions* 23: 100. https://doi.org/10.1007/s10291-019-0889-0.

Teunissen PJG, Khodabandeh A (2019) "GLONASS ambiguity resolution". *GPS Solutions* 23: 101. https://doi.org/10.1007/s10291-019-0890-7.

Hou P, Zhang B, Liu T (2020) Integer-estimable GLONASS FDMA model as applied to Kalman-filter-based short-to long-baseline RTK positioning. *GPS Solutions* 24(4): 1-14

Zaminpardaz S, Teunissen PJG, Khodabandeh A (2021) GLONASS-Only FDMA+CDMA RTK: performance and outlook. *GPS Solutions*, https://doi.org/10.1007/s10291-021-01132-z.

Giorgi G, Schmidt TD, Trainotti C et al. (2019) Advanced technologies for satellite navigation and geodesy. *Advances in Space Research* 64: 1256-1273

Sleewaegen J-M, De Wilde W (2019) Galileo E5b rover receiving E5a corrections? No problem! Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019).

Odolinski R, Teunissen PJG (2020a) On the best integer equivariant estimator for low-cost single-frequency multi-GNSS RTK positioning. Proceedings of the International Technical Meeting of the Institute of Navigation (ION), pp. 499-508. Institute of Navigation. doi: 10.33012/2020.17158

Odolinski R, Teunissen PJG (2020b) "Best integer equivariant estimation: Performance analysis using real data collected by low-cost, single- and dual- frequency, multi-GNSS receivers for short- to long-baseline RTK positioning. *Journal of Geodesy* 94: 91. http://dx.doi.org/10.1007/s00190-020-01423-2.

Khodabandeh A, Zaminpardaz S, Nadarajah N (2021) A study on multi-GNSS phase-only positioning. *Measurement Science and Technology* 32(9): 095005

Ge H, Li B, Nie L, Ge M, Schuh H (2020) LEO constellation optimization for LEO enhanced global navigation satellite system (LeGNSS). *Advances in Space Research* 66(3): 520-532

Paziewski J, Fortunato M, Mazzoni A, Odolinski R (2021) An analysis of multi-GNSS observations tracked by recent Android smartphones and smartphone-only relative positioning results. *Measurement* 175: 109162

Joint Study Group T.32: High-rate GNSS for geoscience and mobility

Chair: *Mattia Crespi (Italy)*

Members

Elisa Benedetti (United Kingdom)
Mara Branzanti (Switzerland)
Liang Chen (China)
Gabriele Colosimo (Switzerland)
Elisabetta D'Anastasio (New Zealand)
Roberto Devoti (Italy)
Rui Fernandes (Portugal)
Marco Fortunato (Italy)
Athanassios Ganas (Greece)
Pan Li (Germany)
Alain Geiger (Switzerland)
Jianghui Geng (China)
Dara Goldberg (USA)
Kathleen Hodgkinson (USA)
Roland Hohensinn (Switzerland)
Shuanggen Jin (China)
Iwona Kudlacik (Poland)
Jan Kaplon (Poland)
Augusto Mazzoni (Italy)
Joao Francisco Galera Monico (Brazil)
Héctor Mora Páez (Colombia)
Michela Ravanelli (Italy)
Giorgio Savastano (Luxembourg)
Sebastian Riquelme (Chile)
Peiliang Xu (Japan)

1. Activities of the group

In the framework of JSG T.32 activities the following topics were investigated, in agreement with the original plans and goals:

- high-rate GNSS for real-time and post-processing earthquake seismology and ionosphere seismology,
- high-rate GNSS for real-time estimation of ground-motions induced by natural causes and anthropogenic activities (special attention to mining),
- high-rate GNSS for structural health monitoring (SHM),
- high-rate GNSS as a resource for improving seismological networks and tsunami early warning services,
- high-rate GNSS and other sensors integration for kinematic parameters estimation and vehicle trajectory determination,
- high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones (EU GSA Task Force).

2. Achievements and results

The activities of the group members developed both within the group and in cooperation with other Colleagues/research groups; the main results are listed hereafter:

- comprehensive inventory of the available and applied methodologies for high-rate GNSS (Shen et al. 2019),
- real-time earthquake seismology: earthquake magnitude estimation from peak ground displacements (PGDs),
- the first initialization of GNSS rotational seismology demonstrated to be feasible,
- high-rate GNSS as a resource for improving seismological networks and tsunami early warning services (GGOS Geohazards Focus Area GATEW Working Group),
- real-time estimation of ground-motions induced by natural causes and anthropogenic activities (special attention to mining - EU H2020 GATHERS project),
- high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones (EU GSA Task Force).
- comparison of velocity and acceleration from very high-rate GNSS and from current velocimeters and accelerometers, demonstrated to fail to output physically correct instant velocity and acceleration; patent pending for a technological innovation of velocimeters and accelerometers.

3. Interactions with the IAG Commissions and GGOS

The interactions with other IAG components were mainly related to the following topics of shared interest:

- Commission 1 – accuracy and reliability of PPP kinematic positioning based on real-time data stream service.
- Commission 3 (SC 3.5: Seismogeodesy (joint with IASPEI)) – GNSS seismology.
- Commission 4 (SC 4.1: Emerging Positioning Technologies and GNSS Augmentations) – high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones.
- GGOS (Geohazards Focus Area) – high-rate GNSS as a resource for improving seismological networks and tsunami early warning services.

4. Refined plans for the period of 2021-2023

The activities of the group in the period 2021-2023 will develop mainly according to the original plans, hopefully benefiting of the improved pandemic situation in order to perform real experiments too. The main topics which will be focused are:

- improved Kalman filtering, stochastic models and multipath characterization and mitigation for high accuracy static and kinematic positioning with multi-frequency and multi-GNSS low-cost receivers and Android smartphones,
- accuracy and reliability achievable with PPP kinematic positioning and monitoring based on real-time data stream service,
- further investigations on integration approaches of multi-GNSS and multi-frequencies low-cost receivers and other sensors,
- improvement of earthquake magnitude estimation from peak ground displacements (PGDs)
- investigations and real experiments using high-rate GNSS as a resource for improving seismological networks and tsunami early warning services (GGOS Geohazards Focus Area GATEW Working Group).

It is also planned to change group memberships, inviting colleagues who recently developed investigation on topics close or included in the research interests of the group.

5. Publications

Peer-review publications

Fortunato M, Critchley-Marrows J, Siutkowska M, Ivanovici ML, Benedetti E, Roberts W (2019) Enabling high accuracy dynamic applications in urban environments using PPP and RTK on Android multi-frequency and multi-GNSS smartphones. European Navigation Conference, doi: 10.1109/EURONAV.2019.8714140.

Shen N, Chen L, Liu J, Wang L, Tao T, Wu D, Chen R (2019) A review of Global Navigation Satellite System (GNSS)-based dynamic monitoring technologies for structural health monitoring. *Remote Sensing* 11 (9): 1001, doi: 10.3390/rs11091001.

Ravanelli M, Occhipinti G, Savastano G, Komjathy A, Shume EB, Crespi M (2021) GNSS total variometric approach: first demonstration of a tool for real-time tsunami genesis estimation. *Scientific Reports* 11(1): 3114, doi: 10.1038/s41598-021-82532-6.

De Girolamo P, Crespi M, Romano A, Mazzoni A, Di Risio M, Pasquali D, Bellotti G, Castellino M, Sammarco P (2019) Estimation of wave characteristics based on global navigation satellite system data installed on board sailboats. *Sensors* 19(10): 2295, doi: 10.3390/s19102295.

Tesolin F, Vitti A, Mazzoni A, Crespi M (2019) Impact of Galileo data on the solutions of the variometric approach for displacement analysis. *Advances in Space Research* 63(9): 3053-3061, doi: 10.1016/j.asr.2019.01.048.

Meng X, Komjathy A, Verkhoglyadova OP, Savastano G, Crespi M, Ravanelli M (2019) Modeling the near-field ionospheric disturbances during earthquakes. Proceedings of the Institute of Navigation Pacific Positioning, Navigation and Timing Meeting, Pacific PNT, pp. 854-861. doi: 10.33012/2019.16844.

Ruhl CJ, Melgar D, Allen RM, Geng J, Goldberg DE, Bock Y, Crowell BW, Barrientos S, Riquelme S, Baez JC, Cabral-Cano E, Pérez-Campos X, Hill EM, Protti M, Ganas A, Ruiz M, Mothes P, Jarrín P, Nocquet J-M, Avouac J-P, D'Anastasio E (2019) A global database of strong-motion displacement GNSS recordings and an example application to PGD scaling. *Seismological Research Letters* 90 (1): 271-279, doi: 10.1785/0220180177.

Paziewski J, Fortunato M, Mazzoni A, Odolinski R (2021) An analysis of multi-GNSS observations tracked by recent Android smartphones and smartphone-only relative positioning results. *Measurement* 175: 109162, doi: 10.1016/j.measurement.2021.109162.

Fortunato M, Mazzoni A (2020) New opportunities for mass-market applications of real-time variometric velocity estimated using android GNSS raw measurements. European Navigation Conference, doi: 10.23919/ENC48637.2020.9317397.

Massarweh L, Fortunato M, Gioia C (2020) Assessment of real-time multipath detection with Android raw GNSS measurements by using a Xiaomi Mi 8 smartphone. 2020 IEEE/ION Position, Location and Navigation Symposium, doi: 10.1109/PLANS46316. 2020.9110169.

Fortunato M, Mazzoni A (2020) Towards a plug&play solution for real-time precise positioning on mass-market devices. Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+ 2020, pp. 1837-1849. doi: 10.33012/2020.17623.

Massarweh L, Fortunato M, Gioia C (2020) Assessment of real-time multipath detection with android raw gnss measurements by using a Xiaomi Mi 8 smartphone. 2020 IEEE/ION Position, Location and Navigation Symposium, PLANS 2020, art. no. 9110169, pp. 1111-1122, doi: 10.1109/PLANS46316.2020.9110169.

Fortunato M, Mazzoni A (2020) Towards a plug&play solution for real-time precise positioning on mass-market devices. Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+ 2020, pp. 1837-1849. doi: 10.33012/2020.17623

Fortunato M, Ravanelli M, Mazzoni A (2019) Real-time geophysical applications with Android GNSS raw measurements. *Remote Sensing* 11(18): 2113, doi: 10.3390/rs11182113.

Xin S, Geng J, Zeng R, Zhang Q, Ortega-Culaciati F, Wang T (2021) In-situ real-time seismogeodesy by integrating multi-GNSS and accelerometers. *Measurement* 179: 109453, doi: 10.1016/j.measurement.2021.109453.

Fang R, Zheng J, Geng J, Shu Y, Shi C, Liu J (2020) Earthquake magnitude scaling using peak ground velocity derived from high-rate gnss observations. *Seismological Research Letters* 92(1): 227-237, doi: 10.1785/0220190347.

Melgar D, Melbourne TI, Crowell BW, Geng J, Szeliga W, Scrivner C, Santillan M, Goldberg DE (2020) Real-time high-rate GNSS displacements: Performance demonstration during the 2019 ridgecrest, California, earthquakes. *Seismological Research Letters* 91(4): 1943-1951, doi: 10.1785/0220190223

Geng J, Wen Q, Zhang T, Li C (2020) Strong-motion seismogeodesy by deeply coupling GNSS receivers with inertial measurement units. *Geophysical Research Letters* 47(8): e2020GL087161, doi: 10.1029/2020GL087161.

Li G, Geng J (2019) Characteristics of raw multi-GNSS measurement error from Google Android smart devices. *GPS Solutions* 23(3): 90, doi: 10.1007/s10291-019-0885-4.

Geng J, Wen Q, Chen Q, Chang H (2019) Six-degree-of-freedom broadband seismogeodesy by combining collocated high-rate GNSS, accelerometers, and gyroscopes. *Geophysical Research Letters* 46(2): 708-716, doi: 10.1029/2018GL081398.

Hohensinn R, Häberling S, Geiger A (2020) Dynamic displacements from high-rate GNSS: Error modeling and vibration detection. *Measurement* 157: 107655, doi: 10.1016/ j.measurement.2020.107655

Hohensinn R, Geiger A, Willi D, Meindl M (2019) Movement detection based on high-precision estimates of instantaneous GNSS station velocity. *Journal of Surveying Engineering* 145(3): 04019005, doi: 10.1061/(ASCE)SU.1943-5428.0000276.

Hongcai Z, Melgar D, Goldberg DE (2021) Magnitude calculation without saturation from strong-motion waveforms. *Bulletin of the Seismological Society of America* 111(1): 50-60. doi: 10.1785/0120200133.

Hodgkinson KM, Mencin DJ, Feaux K, Sievers C, Mattioli GS (2020) Evaluation of earthquake magnitude estimation and event detection thresholds for real-time GNSS networks: Examples from recent events captured by the network of the Americas. *Seismological Research Letters* 91(3): 1628-1645. doi: 10.1785/0220190269.

Dahmen N, Hohensinn R, Clinton J (2020) Comparison and combination of gnss and strong-motion observations: A case study of the 2016 mw 7.0 kumamoto earthquake. *Bulletin of the Seismological Society of America* 110(6): 2647-2660. doi: 10.1785/0120200135.

Su K, Jin S, Ge Y (2019) Rapid displacement determination with a stand-alone multi-GNSS receiver: GPS, Beidou, GLONASS, and Galileo. *GPS Solutions* 23(2): 54, doi: 10.1007/ s10291-019-0840-4.

Jin SG, Su K (2019) Co-seismic displacement and waveforms of the 2018 Alaska earthquake from high-rate GPS PPP velocity estimation. *Journal of Geodesy* 93(9): 1559-1569, doi: 10.1007/s00190-019-01269-3.

Su K, Jin SG (2021) Analytical performance and validations of the Galileo five-frequency precise point positioning models. *Measurement* 172: 108890, DOI: 10.1016/j.measurement. 2020.108890.

Hu H, Zhou F, Jin SG (2021) Improved stochastic modeling of multi-GNSS single point positioning with additional BDS-3 observations. *Measur. Sci. Tech.* 32(4): 045105, doi: 10.1088/1361-6501/abd1fd.

Shen N, Chen L, Wang L, Hu H, Lu X, Qian C, Liu J, Jin SG, Chen R (2021) Short-term landslide displacement detection based on GNSS real-time kinematic positioning. *IEEE Trans. Instrum. Measur.* 70: 1004714, doi: 10.1109/TIM.2021.3055278.

Jin SG, Su K (2020) PPP models and performances from single- to quad-frequency BDS observations. *Satell. Navig.* 1(1): 16, doi: 10.1186/s43020-020-00014-y.

Su K, Jin SG, Jiao G (2020) Assessment of multi-frequency GNSS PPP models using GPS, Beidou, GLONASS, Galileo and QZSS. *Measur. Sci. Tech.* 31(6): 064008, doi: 10.1088/1361-6501/ab69d5.

Gurbuz G, Aktug B, Jin SG, Kutoglu SH (2020) A GNSS-based near real time automatic Earth crust and atmosphere monitoring service for Turkey. *Advances in Space Research* 66(12): 2854-2864, doi: 10.1016/j.asr.2020.07.026.

Zhao D, Hancock C, Roberts G, Jin SG (2019) Cycle slip detection during high ionospheric activities based on three-frequency combined GNSS signals. *Remote Sensing* 11(3): 250, doi: 10.3390/rs11030250.

Su K, Jin SG, Hoque MM (2019) Evaluation of ionospheric delay effects on multi-GNSS positioning performance. *Remote Sensing* 11(2): 171, doi: 10.3390/rs11020171.

Su K, Jin SG (2019) Triple-frequency carrier phase precise time and frequency transfer models for BDS-3. *GPS Solutions* 23(3): 86, doi: 10.1007/s10291-019-0879-2.

Kudłacik I, Kapłon J, Lizurek G, Crespi M, Kurpiński G (2021) High-rate GPS positioning for tracing anthropogenic seismic activity: The 29 January 2019 mining tremor in Legnica-Głogów Copper District, Poland. *Measurement* 168: 108396, doi: 10.1016/j.measurement. 2020.108396.

Ilieva M, Rudziński L, Pawłuszek-Filipiak K, Lizurek G, Kudłacik I, Tondaś D, Olszewska D (2021) Combined study of a significant mine collapse based on seismological and geodetic data – 29 January 2019, Rudna Mine, Poland. *Remote Sensing* 12(10): 1570, doi: 10.3390/ rs12101570.

Kudlacik I, Kaplon J, Bosy J, Lizurek G (2019) Seismic phenomena in the light of high-rate gps precise point positioning results. *Acta Geodynamica et Geomaterialia* 16(1): 99-112, doi: 10.13168/AGG.2019.0008.

Zheng K, Xiaohong Zhang X, Li X, Li P, Sang J, Ma T, Schuh H (2019) Capturing coseismic displacement in real time with mixed single- and dual-frequency receivers: application to the 2018 Mw7.9 Alaska earthquake. *GPS Solutions* 23(9), doi: 10.1007/s10291-018-0794-y.

Zheng K, Xiaohong Zhang X, Li P, Li X, Ge M, Guo F, Sang J, Schuh H (2019) Multipath extraction and mitigation for high-rate multi-GNSS precise point positioning. *Journal of Geodesy* 93(10): 2037-2051, doi: 10.1007/s00190-019-01300-7.

de Oliveira PS Jr, Monico JFG, Morel L (2020) Mitigation of receiver biases in ionospheric observables from PPP with ambiguity resolution. *Advances in Space Research* 65(8): 1941-1950, doi: 10.1016/j.asr.2020.01.037.

Monico JFG, Marques HA, Tsuchiya Í, Oyama RT, Queiroz WRS, Souza MC, Wentz JP (2019) Real time ppp applied to airplane fligtht tests. *Boletim de Ciencias Geodesicas* 25(2): e2019007, doi: 10.1590/s1982-21702019000200009.

Barrientos SE, Riquelme S (2020) CSN Team Operational capabilities during crisis: The Chilean seismographic network. *Seismological Research Letters* 92(1): 119-126

Xu P, Du F, Shu Y, Zhang H, Shi Y (2021) Regularized reconstruction of peak ground velocity and acceleration from very high-rate GNSS precise point positioning with applications to the 2013 Lushan Mw6.6 Earthquake. *Journal of Geodesy* 95(1): 17, doi: 10.1007/s00190-020-01449-6.

Xu P, Shu Y, Liu J, Nishimura T, Shi Y, Freymueller JT (2019) A large scale of apparent sudden movements in Japan detected by high-rate GPS after the 2011 Tohoku Mw9.0 earthquake: Physical signals or unidentified artifacts? *Earth, Planets and Space* 71(1): 43, doi: 10.1186/s40623-019-1023-9.

Xu P, Shu Y, Niu X, Liu J, Yao W, Chen Q (2019) High-rate multi-GNSS attitude determination: Experiments, comparisons with inertial measurement units and applications of GNSS rotational seismology to the 2011 Tohoku Mw9.0 earthquake. *Measurement Science and Technology* 30(2): 024003, doi: 10.1088/1361-6501/aaf987.

Joint Study Group T.33: Time series in geodesy and geodynamics

Chair: *Kosek Wiesław (Poland)*

Members

Orhan Akyilmaz (Turkey)
Johannes Boehm (Austria)
Xavier Collilieux (France)
Olivier de Viron (France)
Laura Fernandez (Argentina)
Richard Gross (USA)
Mahmut O. Karslioglu (Turkey)
Anna Kłos (Poland)
Hans Neuner (Germany)
Tomasz Niedzielski (Poland)
Sergei Petrov (Russia)
Waldemar Popiński (Poland)
Michael Schmidt (Germany)
Michel Van Camp (Belgium)
Jan Vondrák (Czech Republic)
Dawei Zheng (China)
Yonghong Zhou (China)

1. Activities of the group

Main activity of the group is a co-organization of the PICO sessions "Mathematical methods for the analysis of potential field data and geodetic time series" at the European Geosciences Union General Assemblies in Vienna, Austria in 2020 and 2021. Due to pandemic, both meetings were held on-line, but the session has still been a great success, due to a number of presentations submitted and the interest shown by the geodetic community.

2. Achievements and results

Members of the group were very active in the past two years. Below is a list of major results they obtained:

The problem of discrete Fourier analysis of complex valued function observations at equidistant or non-equidistant time moments using the standard set of complex harmonics and least squares method is studied. Observation model considered includes correlated complex valued random errors with zero mean value and finite variance. Uniqueness and finite sample properties of the observed function Fourier coefficients estimators obtained by the least squares method are examined and compared with those of the standard Discrete Fourier Transform (Popiński 2020).

The study of Keleş et al. (2021) aims to fill the 11-months of gap between GRACE and GRACE-FO missions where there are no observations. GRACE-like monthly terrestrial water storage anomalies (TWSA) for this 11-months period using data driven, state of the art deep machine learning algorithms/models were produced. The time series of the observed GRACE/GRACE-FO derived TWSA have been used along with series of hydro-meteorological observations to retrieve spatio-temporal interconnections/relationships between the two by adjusting the deep neural network parameters through advanced machine learning algorithms.

Global seismic tomography has been compared using the varimax Principal Component Analysis (PCA). It was found that such rotated version of the PCA which compresses the large amount of information is a useful tool for the quantitative comparison and interpretation of tomography models (De Viron et al. 2021).

The capability of time-series clustering to retrieve such features on real time-lapse ERT datasets considering three aspects: (1) the comparison between three clustering algorithms k-means, hierarchical agglomerative clustering (HAC), and Gaussian Mixture Model (GMM), including the question of the optimal choice of cluster number and the identification of resistivity series whose classification is uncertain, (2) the effect of adding a spatial constraint in clustering, and (3) the robustness of the approaches to various representations of resistivity values and the number of time-steps involved in the clustering (Delforge et al. 2021).

A parsimonious data-driven model, EDM-Simplex, with two objectives: forecasting recession and characterizing its nonlinear behaviour was proposed. The new model through a global sensitivity analysis applied to three distinctive hydrograph series from a heterogeneous karstic catchment was evaluated (Delforge et al. 2020).

The weighted wavelet transform was used to study naked-eye observations series of sunspots from 200 BC to 1918 AD from historical documents. The results show the Suess/de Vries cycle with a period from 195- to 235-year existing in the discontinuous sunspot series. Meanwhile, the cycle signal changes with time (Lihua Ma and Vaquero 2020).

With wavelet analysis, possible connection between average temperature series in the contiguous United States during the period from January 1895 to July 2018 and solar activity was investigated. The results show modulation action from solar activity plays an important role in the oscillation of the contiguous United States average temperature, especially on decade time scales (Lihua Ma 2021a).

The Lomb-Scargle periodogram was used to study long-term slowdown trend, periodic and irregular fluctuations in the LOD series in the past 4000 years. The significant quasi-1500 years cycle signal was found. Furthermore, with weighted wavelet Z-transform, time-varying characteristics of the cycle in the LOD change were obtained (Lihua Ma 2021b).

The Lomb-Scarle periodogram was also employed by Klos et al. (2021b) to provide a comprehensive assessment of noise present in daily GPS height time series after seasonal signals were subtracted by using conventional harmonic function approach and GRACE-assimilating hydrological model. Analysis was also supported by Maximum Likelihood Estimation (MLE) approach. They concluded that the GRACE-assimilated model output removes the effect of high-frequency hydrological deformations, producing less correlated residuals of GPS height time series.

Hydrology-induced interannual displacements derived from GRACE (Gravity Recovery and Climate Experiment) observations and hydrological models were studied by Lenczuk et al. (2020). Authors used Singular Spectrum Analysis (SSA) to model the interannual variations of displacements in eastern European river basins. They noted a large interannual displacements observed by GRACE between 2004 and 2009, but mismodelled by both GLDAS (Global Land Data Assimilation System) and WGHM (Water GAP Global Hydrological Model) hydrological models.

Richter et al. (2021) addressed a problem of a gap between two consecutive GRACE missions, namely GRACE and GRACE Follow-On, which is 11 months long. They filled the gap by combining low-resolution gravity field models derived from European Space Agency’s Swarm satellites with the dominating spatial modes of mass variability obtained from GRACE by using Empirical Orthogonal Function (EOF) analysis. In this way, they reduced noise present in Swarm gravity fields and obtained sufficient gravity changes for a few global basins.

GPS (Global Positioning System) tropospheric products were used for the first time to monitor and predict hurricane tracks by Eijgu et al. (2021). Authors employed GPS-derived integrated water vapour (IWV) derived for stations situated at the east coast of North America and constructed spaghetti plot lines during hurricane season with two major hurricanes Harvey and Irma, both occurred in 2017.

Klos et al. (2021a) provided a comprehensive assessment of sensitivity of GPS displacements for non-tidal environmental loadings for stations in Eurasia. They examined various frequency bands from the lowest frequencies, i.e. 2 days, up to long-term trends, by retrieving them using wavelet decomposition. They concluded that non-tidal atmospheric loading is a main contributor to GPS displacements in the highest frequencies, while hydrological loading contributes to seasonal band only.

The atmospheric surface pressure time series of Madras, Darwin, and Tahiti together with non-tidal length-of-day (LODR) variations and axial component of atmospheric angular momentum (AAM) were analyzed by wavelet transform as well as the combination of the Fourier transform band pass filter with the Hilbert transform (FTBPF+HT) to detect interannual and intra-seasonal oscillations in them. Variable characteristics of annual and semi-annual oscillations in the atmospheric surface pressure variations, LODR and AAM were found (Lihua Ma et al. 2021).

The integrated Length-of-Day (LoD) values from GNSS were compared against UT1-UTC values from VLBI. Special focus was put on the numerical integration itself, as well as on the calibration of the biases which are inherent in the LoD series from GNSS (Mikschi et al. 2019).

The common geocenter signal in the the geocenter coordinates based on four independent techniques: Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite System (GNSS), Gravity Recovery and Climate Experiment with the ocean bottom pressure model, and Satellite Laser Ranging, was found using the wavelet-based semblance filtering (WBSF) method. Variable amplitudes and phases of the annual and semi-annual oscillations in the geocenter coordinates of these techniques by the combination of the Fourier Transform Band Pass Filter (FTBPF) with the Hilbert Transform (FTBPF+HT) and to compare their mean values with those obtained by other authors (Kosek et al. 2020).

Similar amplitude variations of 3-4 year oscillations caused by ENSO were found in LOD, axial component of atmospheric angular momentum, global mean surface temperature, southern oscillation index, Nino3.4 index and global mean see level based on the tide gauge and satellite altimetry data using FTBPF+HT (Kosek 2020).

At Jet Propulsion Laboratory (JPL) a time series approach to determining ITRF-like combined reference frames using sequential estimation was developed. The main concepts underlying the determination of terrestrial reference frames (TRFs) through a recursive algorithm based on Kalman Filtering and Rauch-Tung-Striebel (RTS) smoothing which is currently adopted to compute sub-secular frame products (JTRFs) were reviewed. Comparisons of JTRF solutions to standard products such as the International Terrestrial Reference Frame (ITRF) suggest high-level consistency in a long term sense with time derivatives of the Helmert transformation parameters connecting the two TRFs below 0.18 mm/yr (Abbondanza et al, 2020).

3. Interactions with the IAG Commissions and GGOS

There are several interactions with other IAG components. The papers of Lenczuk et al. (2020) and Keleş et al. (2021) are relevant to the goals/tasks of IAG Commission 2 (Gravity Field) as well as those of GGOS where monitoring and prediction of extreme weather events and consequent hazards (floods/droughts) are crucial. Research activities of Lihua Ma (2021a, b) as well as Lihua Ma and Vaquero (2020) involve Earth rotation and geodynamics (IAG Comissions 3), space reference frame (IAG Comissions 1) and positioning and application (IAG Comissions 4 and GGOS). Research activities of Eijgu et al. (2021), Klos et al. (2021a,b), Richter et al. (2021) and Kosek (2020) closely inherent with the objectives of ICCC (Inter-Commission Committee on Geodesy for Climate Research). Dr. Anna Klos was the convener of the session G3.2 “Observing geophysical signals in the Climate and Earth System through Geodesy” at the EGU 2020 and 2021.

4. Refined plans for the period of 2021-2023

There are several activities planned within JSG T.33 group for the period of 2021-2023. First is organization of a session on time series analysis in geodesy at the Hotine-Marussi Symposium in 2022. Then, PICO sessions on “Mathematical methods for the analysis of potential field data and geodetic time series” will be organized again at the European Geosciences Union General Assemblies in 2022 and 2023 in Vienna, Austria.

5. Publications

Abbondanza C, Chin TM, Gross RS, Heflin MB, Parker JW, Soja BS, Wu X (2020) A sequential estimation approach to terrestrial reference frame determination. *Advances in Space Research* 65(4): 1235-1249, doi:10.1016/j.asr.2019.11.016.

Delforge D, Vanclooster M, van Camp M, Muñoz-Carpena R (2020) A parsimonious empirical approach to streamflow recession analysis and forecasting. *Water Resources Research*, doi:10.1029/2019WR025771.

Delforge D, Watlet A, Kaufmann O, van Camp M, Vanclooster M (2021) Time-series clustering approaches for subsurface zonation and hydrofacies detection using a real time-lapse electrical resistivity dataset. *Journal of Applied Geophysics*, doi: 10.1016/j.jappgeo. 2020.104203.

Ejigu YG, Teferle FN, Klos A, Bogusz J, Hunegnaw A (2021) Monitoring and prediction of hurricane tracks using GPS tropospheric products. *GPS Solutions* 25: 76, https://doi.org/ 10.1007/s10291-021-01104-3.

Keleş M, Ay T, Tandoğdu B, Uz M, Zhang Y, Akyilmaz O, Shum CK, Atman KG (2021) Bridging the gap between GRACE and GRACE-FO by simulating GRACE-like terrestrial water storage anomalies using deep machine learning tools. Submitted to IAG 2021 Scientific Assembly of the International Association of Geodesy, Beijing, China, June 28-July 2, 2021.

Klos A, Dobslaw H, Dill R, Bogusz J (2021a) Identifying the sensitivity of GPS to non-tidal loadings at various time resolutions: examining vertical displacements from continental Eurasia. *GPS Solutions* 25: 89, https://doi.org/10.1007/s10291-021-01135-w.

Klos A, Karegar MA, Kusche J, Springer A (2021b) Quantifying noise in daily GPS height time series: harmonic function versus GRACE-assimilating modeling approaches. *IEEE Geoscience and Remote Sensing Letters* 18(4): 627-631, doi: 10.1109/LGRS.2020.2983045.

Kosek W, Popiński W, Wnęk A et al. (2020) Analysis of systematic errors in geocenter coordinates determined from GNSS, SLR, DORIS, and GRACE. *Pure and Applied Geophysics* 177: 867-888, https://doi.org/10.1007/s00024-019-02355-5.

Kosek W (2020) Application of spectra-temporal analysis methods to detect common signals in length of day, global mean sea level, global mean surface temperature data, and ENSO indices, 22nd EGU General Assembly, 4-8 May 2020, id.8196, 2020EGUGA.22.8196K.

Lenczuk A, Leszczuk G, Klos A, Kosek W, Bogusz J (2020) Study on the inter-annual hydrology-induced deformations in Europe using GRACE and hydrological models. *Journal of Applied Geodesy* 14(4): 393-403, https://doi.org/10.1515/jag-2020-0017.

Lihua M, Vaquero JM (2020) New evidence of the Suess/de Vries cycle existing in historical naked-eye observations of sunspots. *Open Astronomy* 29(1): 28-31

Lihua M (2021a) Possible solar modulation of average temperature in the contiguous United States during 1895-2018. *Geomagnetism and Aeronomy* 61(2): 272-276

Lihua Ma (2021b) Quasi-1500 year cycle signal in length-of-day change. *Artificial Satellites* (in review).

Lihua M, Kosek W, Han Y (2021) Comparison of length of day, atmospheric angular momentum and atmospheric surface pressure observed at chosen meteorological stations near equator. *Studia Geophysica et Geodaetica* (submitted).

Mikschi M, Böhm J, Böhm S, Horozovic D (2019) Comparison of Integrated GNSS LOD to dUT1. Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, pp. 247-251.

Popiński W (2020) On least squares discrete fourier analysis of unequally spaced data. *Applicationes Mathematicae* 47(2): 207-224

Richter HMP, Lück C, Klos A, Sideris MG, Rangelova E, Kusche J (2021) Reconstructing GRACE-type time-variable gravity from the Swarm satellites. *Scientific Reports* 11: 1117, https://doi.org/10.1038/s41598-020-80752-w.

de Viron O, van Camp M, Grabkowiak A, Ferreira AMG (2021) Comparing global seismic tomography models using the varimax Principal Component Analysis. *Solid Earth Discussions.* [preprint], https://doi.org/10.5194/se-2021-16.

Joint Study Group T.34: High resolution harmonic analysis and synthesis of potential fields

Chair: *Sten Claessens (Australia)*

Members

Sten Claessens (Australia), chair
Hussein Abd-Elmotaal (Egypt)
Blažej Bucha (Slovakia)
Christoph Förste (Germany)
Toshio Fukushima (Japan)
Ropesh Goyal (India)
Christian Hirt (Germany)
Elmas Sinem Ince (Germany)
Norbert Kühtreiber (Austria)
Kurt Seitz (Germany)
Michal Šprlák (Czechia)
Philipp Zingerle (Germany)

1. Activities of the group

Research by members of the group into high-resolution harmonic analysis and synthesis of potential fields has made good progress over the period 2019-2021.

New methods have been developed for the computation of high-resolution harmonic potential models using ellipsoidal geometry. A major component of any high-resolution harmonic model is forward gravity modelling to generate a topographic gravity model. Ince et al. (2020) derive a mass layer concept that makes use of a sequence of thin ellipsoidal shells. Their model agrees with older models up to d/o 2190 at the sub-mm level in the high-frequency components of the gravity field (n>180). Abd-Elmotaal and Kühtreiber (2021) derive a direct technique suitable for computation of the topographic or topographic-isostatic potential for a certain data-window as well as globally, which also shows a good agreement to earlier models. Šprlák et al. (2020a) derive a novel, explicit, and efficient method for spectral forward modelling in the spheroidal domain and apply this to the Moon and 1 Ceres. Šprlák et al. (2020b) also study spectral forward gravity modelling using lateral and spatial 3D density variations and show the significance of density variations for modelling of the topographic gravity field of the Moon.

The combination of different data sources requires special attention in the creation of a high-resolution global gravity model. Ince et al. (2020) combine a topographic gravity model with a satellite-only or combined model using a weighted combination of the harmonic coefficients in a dedicated degree transition range. Zingerle et al. (2019a) describe a different strategy for the combination of topographic gravity and satellite gravity data and Zingerle et al. (2021) present a method for the smooth integration of terrestrial and airborne gravity observations into high-resolution global models. Their method relies on a combination of terrestrial data grids with a satellite-only model on the normal equation level, thus far up to degree and order 5400.

High-resolution residual terrain modelling (RTM) also has an application in the development of combined global gravity models. Hirt et al. (2019) apply spectral forward modelling to investigate RTM approximation errors including the harmonic correction problem. Bucha et al. (2019a, 2019b) present a method for the spectral forward modelling of data within a spherical cap that can be used to mitigate the spectral filter problem. Bucha et al. (2019c) provide a new perspective on RTM, showing that both these problems are caused by filtering in the topography domain and can be avoided by filtering in the gravity domain.

Possible divergence of spherical and spheroidal harmonic series near the Earth's surface is an ongoing challenge, but recent studies on the Moon and other celestial bodies have provided interesting insights. Šprlák et al. (2020a) quantify divergence of both spherical and spheroidal series on the Moon and 1 Ceres. Bucha et al. (2019d) and Bucha and Kuhn (2020) study the divergence effect on the Moon. They show that a Runge-Krarup type harmonic series can be created that does not diverge near the surface like a harmonic series derived by spectral forward modelling, and that harmonic series derived only from far-zone topography do not significantly diverge. Bucha and Sansò (2021) further study the divergence effect for the irregularly shaped asteroid Bennu, revealing conceptual differences between spherical harmonic coefficients from satellite data and from surface gravity data.

Validation of high-resolution harmonic analysis methods for topographic gravity modelling is routinely performed through comparison with gravity forward modelling in the spatial domain. This has proved very successful in spherical approximation but is still a challenge for modelling of the ellipsoidal topographic potential (Claessens and Kuhn 2019). Members of the group have also worked on forward gravity modelling in the spatial domain, which can be of use for these validations among other applications (e.g., Fukushima 2020a, 2020b; Goyal et al. 2020; Marotta et al. 2019; Yang et al. 2019, 2020).

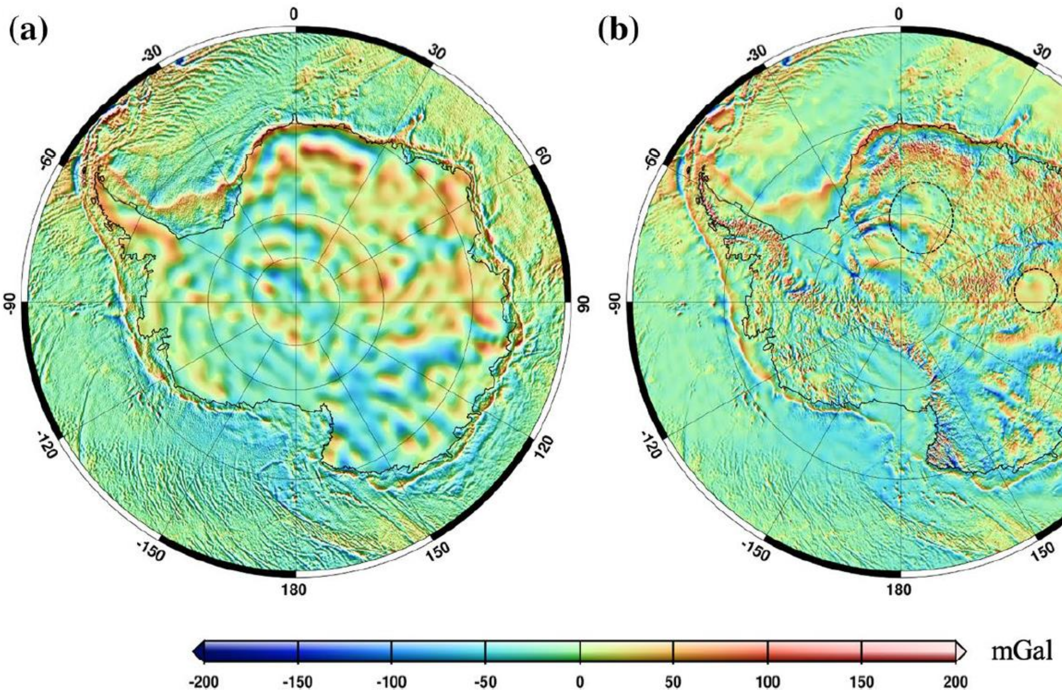


Figure 1: Spherically approximated gravity anomalies synthesised from a) EIGEN-6C4 and b) GOCE-DIR6 combined with forward-modelled topography, showing the enhancement due to the contribution of the forward model over Antarctica (Ince et al. 2020).

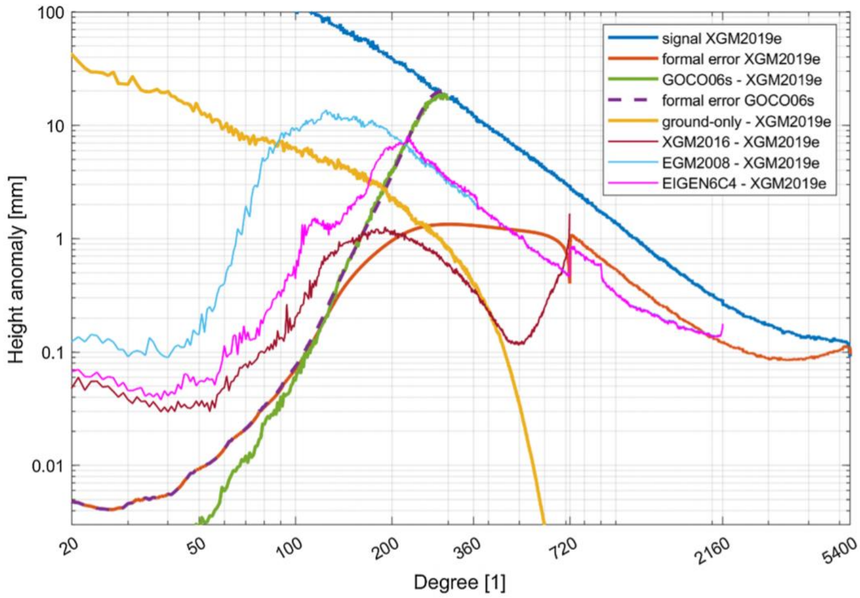


Figure 2: XGM2019e degree signals and errors in terms of height anomalies and the degree signal differences with other models (Zingerle et al. 2020a).

2. Achievements and results

Apart from the many theoretical advances described in the previous section, research by members of the group has also resulted in the generation of many high-resolution gravity models. Many of these are published by the International Centre for Earth Gravity Models (ICGEM; Ince et al. 2019; Förste et al. 2020) and are freely available to the wider scientific community.

A highlight is the creation of XGM2019e (Zingerle et al. 2019b, 2020a), the first static global gravity model (GGM) beyond degree and order 2190 listed by ICGEM. This model is complete to spheroidal harmonic degree and order 5400, and available as a spherical harmonic model to degree and order 5540. Work on a future version of this model is underway and ongoing (Zingerle et al. 2020b). Another high-resolution global model published in this time period is the topographic gravity model ROLI_EllApprox_SphN_3660 to degree and order 3660 (Abrykosov et al. 2019; Ince et al. 2020). Finally, high-resolution topographic gravity models for the Moon have been published by Bucha et al. (2019d) and Šprlák et al. (2020a) and for 1 Ceres by Šprlák et al. (2020a), and these are also listed by ICGEM.

3. Interactions with the IAG Commissions and GGOS

Two conference sessions related to the topic of this study group have been organised in interaction with IAG Commission 2. At the IUGG General Assembly, Montreal, Canada, July 2019, a joint session was held in collaboration between IAG and IAGA: JG02 Theory and methods of potential fields (conveners: D. Tsoulis, S. Claessens and M. Fedi). At the IAG Scientific Assembly, Beijing, China, June/July 2021, a session is held in Symposium 2a organised jointly by IAG Commission 2 and ICCT: 2a.7 Topography and bathymetry gravity modelling (conveners: R. Forsberg, S. Claessens and B. Ke).

4. Refined plans for the period of 2021-2023

Members of the group will continue to pursue the objectives stipulated in the terms of reference. No changes have been made to the group’s objectives and membership. Unfortunately, due to the COVID-19 pandemic most of the group’s members have not been able to meet in person in 2020 and 2021. It is hoped that many can attend the Hotine-Marussi Symposium in June 2022.

5. Publications

Abd-Elmotaal HA, Kühtreiber N (2021) Direct harmonic analysis for the ellipsoidal topographic potential with global and local validation. *Surveys in Geophysics* 42: 159-176, https://doi.org/10.1007/s10712-020-09614-4.

Abrykosov O, Ince ES, Förste C, Flechtner F, Reißland S (2019): Rock-Ocean-Lake-Ice topographic gravity field model (ROLI model) expanded up to degree 3660. https://doi.org/10.5880/ICGEM.2019.011.

Bucha B, Hirt C, Kuhn M (2019a) Cap integration in spectral gravity forward modelling: near- and far-zone gravity effects via Molodensky's truncation coefficients. *Journal of Geodesy* 93: 65-83, https://doi.org/10.1007/s00190-018-1139-x.

Bucha B, Hirt C, Kuhn M (2019b) Cap integration in spectral gravity forward modelling up to the full gravity tensor. *Journal of Geodesy* 93: 1707-1737, https://doi.org/10.1007/s00190-019-01277-3.

Bucha B, Hirt C, Yang M, Kuhn M, Rexer M (2019c) Residual terrain modelling (RTM) in terms of the cap-modified spectral technique: RTM from a new perspective. *Journal of Geodesy* 93: 2089-2108, https://doi.org/10.1007/s00190-019-01303-4.

Bucha B, Hirt C, Kuhn M (2019d) Divergence-free spherical harmonic gravity field modelling based on the Runge–Krarup theorem: a case study for the Moon. *Journal of Geodesy* 93: 489-513, https://doi.org/10.1007/s00190-018-1177-4.

Bucha B, Kuhn M (2020) A numerical study on the integration radius separating convergent and divergent spherical harmonic series of topography-implied gravity. *Journal of Geodesy* 94: 112, https://doi.org/10.1007/s00190-020-01442-z.

Bucha B, Sansò F (2021) Gravitational field modelling near irregularly shaped bodies using spherical harmonics: a case study for the asteroid (101955) Bennu. *Journal of Geodesy* 95: 56. https://doi.org/10.1007/s00190-021-01493-w.

Claessens SJ, Kuhn M, Hirt C (2019) Comparison between ellipsoidal topographic potential modelling in the space and spectral domains. 27th General Assembly of the International Union of Geodesy and Geophysics (IUGG), Montreal, Canada, July 2019.

Förste C, Ince SE, Reißland S, Elger K, Flechtner F, Barthelmes F (2020) The International Centre for Global Earth Models (ICGEM), EGU General Assembly Conference Abstracts, May 2020, 3511.

Fukushima T (2020a) Taylor series expansion of prismatic gravitational field. *Geophysical Journal International* 220(1): 610-660, https://doi.org/10.1093/gji/ggz449.

Fukushima T (2020b) Speed and accuracy improvements in standard algorithm for prismatic gravitational field. *Geophysical Journal International* 222(3): 1898-1908, https://doi.org/10.1093/gji/ggaa240.

Goyal R, Featherstone WE, Tsoulis D, Dikshit O (2020) Efficient spatial-spectral computation of local planar gravimetric terrain corrections from high-resolution digital elevation models. *Geophysical Journal International* 221(3): 1820-1831, https://doi.org/10.1093/gji/ggaa107.

Hirt C, Bucha B, Yang M, Kuhn M (2019) A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high-degree spectral gravity modelling. *Journal of Geodesy* 93: 1469-1486, https://doi.org/10.1007/s00190-019-01261-x.

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F, Schuh H (2019) ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services, and future plans. Earth Syst. Sci. Data 11, 647-674, https://doi.org/10.5194/essd-11-647-2019.

Ince ES, Abrykosov O, Förste C, Flechtner F (2020) Forward gravity modelling to augment high-resolution combined gravity field models. *Surveys in Geophysics* 41: 767-804, https://doi.org/10.1007/s10712-020-09590-9.

Marotta AM, Seitz K, Barzaghi R, Grombein T, Heck B (2019) Comparison of two different approaches for computing the gravitational effect of a tesseroid. *Studia Geophysica et Geodaetica* 63: 321-344. https://doi.org/10.1007/s11200-018-0454-2.

Šprlák M, Han SC, Featherstone WE (2020a) Spheroidal forward modelling of the gravitational fields of 1 Ceres and the Moon. *Icarus* 335: 113412, https://doi.org/10.1016/j.icarus.2019.113412.

Šprlák M, Han SC, Featherstone WE (2020b) Crustal density and global gravitational field estimation of the Moon from GRAIL and LOLA satellite data. *Planetary and Space Science* 192: 105032.

Yang M, Hirt C, Rexer M, Pail R, Yamazaki D (2019) The tree-canopy effect in gravity forward modelling. *Geophysical Journal International* 219(1): 271-289, https://doi.org/10.1093/gji/ggz264.

Yang M, Hirt C, Pail R. (2020) TGF: A New MATLAB-based Software for Terrain-related Gravity Field Calculations. *Remote Sensing* 12(7): 1063, https://doi.org/10.3390/rs12071063.

Zingerle P, Pail R, Scheinert M, Schaller T (2019a) Evaluation of terrestrial and airborne gravity data over Antarctica: a generic approach. *Journal of Geodetic Science* 9: 29-40, https://doi.org/10.1515.jogs-2019-0004.

Zingerle P, Pail R, Gruber T, Oikonomidou X (2019b) The experimental gravity field model XGM2019e. https://doi.org/10.5880/ICGEM.2019.007.

Zingerle P, Pail R, Gruber T. Oikonomidou X (2020a) The combined global gravity field model XGM2019e. *Journal of Geodesy* 94: 66, https://doi.org/10.1007/s00190-020-01398-0.

Zingerle P, Pail R, Gruber T (2020b) High-resolution combined global gravity field modelling – The d/o 5,400 XGM2020 model, EGU General Assembly Conference Abstracts, May 2020, 16447.

Zingerle P, Li X, Willberg M, Pail R, Roman D (2021) Integrating NGS GRAV-D gravity observations into high-resolution global models. EGU General Assembly Conference Abstracts, April 2021, 7955.

Joint Study Group T.35: Advanced numerical methods in physical geodesy

Chair: *R. Čunderlík (Slovakia)*

Members

Róbert Čunderlík (Slovakia), chair
Jérôme Droniou (Australia)
Petr Holota (Czechia)
Michal Kollár (Slovakia)
Marek Macák (Slovakia)
Matej Medľa (Slovakia)
Karol Mikula (Slovakia)
Zuzana Minarechová (Slovakia)
Otakar Nesvadba (Czechia)
Robert Tenzer (Hong Kong)
Zhi Yin (Germany)

1. Activities of the group

Activities of JSG-T.35 during the period 2019‒2021 have been focused on further development of the advanced numerical methods used in physical geodesy, mainly for high-resolution gravity field modelling in spatial domain. To obtain numerical solutions of the geodetic boundary value problems directly on the Earth's surface, the oblique derivative problem has to be treated. For this purpose, there have been developed numerical approaches based on the finite volume method (FVM) (Droniou et al. 2019) and finite element method (FEM) (Macák et al. 2020, Minarechová et al. 2021) that have been applied for high-resolution local gravity field modelling (Čunderlík et al. 2020, Minarechová et al. 2021). In the case of boundary integral methods like the boundary element method (BEM) or method of fundamental solution (MFS), we have focused on an elimination of far zones interactions using the Hierarchical matrices, namely the Adaptive Cross Approximation (ACA) algorithm (Bejdák 2021). It has efficiently reduced numerical complexity of the BEM or MFS approaches while allowing more detailed global modelling. For the FVM approaches, the domain decomposition (DD) methods based on the Additive Schwarz Method have been implemented in order to reduce large memory requirements (Macák et al. 2021).

2. Achievements and results

In the case of FVM, the oblique derivative boundary condition (BC) has been treated in the way that its tangential component is considered as an advection along the Earth's topography regularized by a carefully designed surface diffusion term. For this approach, the theoretical rates of convergence have been illustrated by several numerical tests (Droniou et al. 2019). Later on, this approach has been applied for local gravity field modelling in Slovakia using terrestrial gravimetric measurements (Čunderlík et al. 2020).

In the case of FEM, two different approaches have been developed. In the first one, the oblique derivative BC is considered as an average value on the bottom side of finite elements (Macák et al. 2020). In the second one, the oblique derivative is incorporated directly into the computational nodes using two tangential vectors for each node (Minarechová et al. 2021). This has led to more stable and the second order accurate numerical scheme which has been afterwards applied for local gravity field modelling in Slovakia.

Reducing of numerical complexity of the BEM or MFS approaches using the Hierarchical matrices has shown that the ACA algorithm is able to save almost 99% of memory requirements in the case of a detailed discretization of the Earths' surface (Bejdák 2021). Such an elimination of far zones interactions is very effective and enables us to use BEM or MFS for high-resolution global gravity filed modelling in spatial domain.

For the FEM or FVM approaches, the DD methods can be used to reduce large memory requirements. An implementation of the overlapping DD methods for the FVM approach based on the Additive Schwarz Method has demonstrated how to optimize large-scale parallel computations. It has resulted in a reduction of memory requirements by the factor 4.5 while reaching a significant speed-up of the computation time (Macák et al. 2021).

3. Interactions with the IAG Commissions and GGOS

Majority of activities of JSG-T.35 are focused on high-resolution global or local gravity field modelling in spatial domain, so they directly interact with *Commission 2* of IAG. The obtained gravity field models can also contribute in the process of establishing and realization of the IHRS, and thus can interact with particular objectives of *GGOS*.

4. Refined plans for the period of 2021-2023

Activities of JSG-T.35 during the second period 2021-2023 will continue according to the original plan while interacting to new findings and results. The members of JSG-T.35 intend to organize a session in the following Hotine-Marusi Symposium in 2022.

5. Publications

The achieved results have been published in several papers (see below) and they were presented at the major geodetic conferences like the EGU General Assemblies in Vienna (EGU-2020, EGU-2021) within the session "Recent Developments in Geodetic Theory".

Droniou J, Medľa M, Mikula K (2019) Design and analysis of finite volume methods for elliptic equations with oblique derivatives; application to Earth gravity field modelling. *Journal of Computational Physics* 398: 108876, doi: 10.1016/j.jcp.2019.108876.

Yin Z, Sneeuw N (2019) Modeling the gravitational field by Using CFD techniques. In: *IAG Symposia Series* 151, https://doi.org/10.1007/1345_2019_72.

Tanaka Y, Klemann V, Martinec Z (2019) Surface loading of a self-gravitating, laterally heterogeneous elastic sphere: preliminary result for the 2D case. In: *IAG Symposia Series* 151, https://doi.org/10.1007/1345_2019_62.

Čunderlík R, Medľa M, Mikula K (2020) Local quasigeoid modelling in Slovakia using the finite volume method on the discretized Earth's topography. *Contributions to Geophysics and Geodesy* 50 (3): 287-302

Macák M, Minarechová Z, Čunderlík R, Mikula K (2020) The finite element method as a tool to solve the oblique derivative boundary value problem in geodesy. *Tatra Mountains Mathematical Publications* 75 (1): 63-80

Minarechová Z, Macák M, Čunderlík R, Mikula K (2021) On the finite element method for solving the oblique derivative boundary value problems and its application in local gravity field modelling. *Journal of Geodesy* (accepted in May 2021).

Bejdák M (2021) Boundary methods for gravity field modeling using the Hierarchical matrices. Diploma thesis. Slovak University of Technology in Bratislava (in Slovak).

Macák M, Čunderlík R, Minarechová Z, Mikula K (2021) Computational optimization in solving the geodetic boundary value problems. *Discrete & Continuous Dynamical Systems – S* 14(3): 987-999, doi: 10.3934/dcdss.2020381.

Joint Study Group T.36: Dense troposphere and ionosphere sounding

***Chair**: Giorgio Savastano (Luxembourg)*

Members

Matthew Angling (UK)
Elvira Astafyeva (France)
Riccardo Biondi (Italy)
Mattia Crespi (Italy)
Kosuke Heki (Japan)
Addisu Hunegnaw (Luxembourg)
Alessandra Mascitelli (Italy)
Giovanni Occhipinti (France)
Michela Ravanelli (Italy)
Eugenio Realini (Italy)
Lucie Rolland (France)
Felix Norman Teferle (Luxembourg)
Jens Wickert (Germany)

1. Activities of the group

This mid-term report describes the activities carried out by the JGR T.36 during the 2019-2021 period. We divided the report into 2 main research areas: troposphere and ionosphere sounding; and a third more operational topic which deals with the enhancement the data infrastructure for dealing with extremely large datasets.

Due to the global COVID-19 pandemic, this study group was unable to hold meetings and convene conference sessions during the 2019-2021 period.

Troposphere sounding

The main topic we have dealt with is the analysis of the impact that GNSS and InSAR technologies can have in the field of meteorology and for weather forecasts.

In our studies, ground based GNSS and InSAR are used as complementary tools to obtain tropospheric delay data to study of water vapor variations and their relationship with weather forecasts and – to some extent – with climate analyses. To this end, tests conducted on data provided by both geodetic and mass-market GNSS receivers have contributed to improved data processing, leading to a more accurate comparison with products from different atmosphere measurement techniques, as well as to a better understanding of the atmospheric water vapor behavior in relation with various types of rain events. The impact of using GNSS- and InSAR-derived tropospheric delay information to produce/improve rain forecasts was studied in terms of both physics-based numerical weather prediction models and machine learning-based neural networks.

Ionosphere sounding

The main topics we have dealt with are:

- Classification of perturbations (i.e., sporadic E layers, TIDs) in the lower ionosphere using GNSS radio occultation (RO) observations collected using Spire's constellation of CubeSats. In our study, we extract sTEC information with a very high vertical resolution (better than 100 m) directly from high-rate (50 Hz) GNSS-RO profiles

- Development of Total Variometric Approach (TVA) methodology to contribute to the understanding of the physics and detectability of tsunami genesis by real-time GNSS ionospheric monitoring and to support tsunami warning systems
- Investigate the possibility to densify the GNSS information using GNSS ionospheric observations coming from dual-frequency smartphones, geostationary satellites and ship-based GNSS receivers

Some of the ongoing activities are:
- Implementation of an onboard detection algorithm of ionospheric scintillations via ionospheric indexes (e.g., ROTI and sigmaPhi) collected from Spire’s GNSS- POD and RO antennas.
- Climatological- and cross- validation studies of Spire's scintillation measurements collected from GNSS- POD and RO antennas.
- Development of an innovative methodology to estimate the correct altitude of the ionospheric perturbation detection.
- Investigation of machine learning approaches for ionospheric perturbation detection.

Enhancement of current data infrastructure for extremely large datasets

Many atmospheric remote sensing datasets consist of multi-dimensional arrays of numerical data, such as sTEC point measurements scattered irregularly in latitude, longitude, altitude, and time dimensions. The traditional workflow to analyze this data is to download datasets to a personal laptop or workstation and perform all analysis there. As sensor technology and computer power continue to develop, the volume of our datasets is growing exponentially. This workflow is not feasible or efficient with multi-terabyte datasets, and it is impossible with petabyte-scale datasets. For this reason, part of our time went toward the enhancement of our current data infrastructure to handle extremely large datasets and enable effective exploratory data analysis.

2. Achievements and results

The activities carried out have led to:

Troposphere sounding

The definition of an effective method for processing data from single-frequency receivers (Mascitelli et al. 2019a) for meteorological purposes, to the continuation of tests aimed at assimilating GNSS data into numerical weather prediction models (Mascitelli et al. 2020, Mascitelli et al. 2019b, Lagasio et al. 2019a, b) and at using them for neural networks (Sangiorgio et al. 2019a, b), to the successful validation of products obtained using different techniques (Mascitelli et al. 2019c, Tiberia et al. 2021, D’Adderio et al. 2020, Meroni et al. 2020, Pierdicca et al. 2020, Manzoni et al. 2020, Tagliaferro et al. 2019) and to the contribution of GNSS-derived data to climatological studies (Ssenyunzi et al. 2019, 2020).

Ionosphere sounding

The definition of a new methodology to automatically classify perturbations in the lower ionosphere using GNSS radio occultation observations collected using Spire’s constellation of CubeSats (Savastano et al. 2019, 2020).

The definition of the Total Variometric Approach methodology for real-time tsunami genesis estimation (Ravanelli et al. 2020a), to the integration of ionospheric observations coming dual-frequency smartphones, geostationary satellites and ship-based GNSS receivers (Ravanelli et al. 2020b, Savastano et al. 2020, Fortunato et al. 2019, Rolland et al. 2021) into the VARION algorithm and to the validation of inverse modeling to reproduce ionospheric perturbation from GNSS ground motion data (Meng et al. 2019).

The development of numerical models to rapidly retrieve the main characteristics of the driver source (tsunami waveform or seismic deformation) from the ionospheric perturbation (Rolland et al. 2021, Zedek et al. 2021, Mikesell et al. 2019).

Data infrastructure for extremely large datasets

The implementation of a DataCube infrastructure by indexing the data into grids of target resolutions (see EASE grids at https://nsidc.org/ease/ease-grid-projection-gt). We used Xarray and Dask technology that allows us to load data lazily and perform analysis inside Jupyter notebooks. We use Zarr format extensively for storage on the cloud (i.e., AWS S3 buckets).

5. Publications

D'Adderio LP, Pazienza L, Mascitelli A, Tiberia A, Dietrich S (2020) A combined IR-GPS satellite analysis for potential applications in detecting and predicting lightning activity. *Remote Sensing* 12(6): 1031

Brenot H, Rohm W, Kačmařík M, Möller G, Sá A, Tondaś D, Rapant L, Biondi R, Manning T, Champollion C (2020) Cross-comparison and methodological improvement in GPS tomography. *Remote Sensing* 12(1): 30

Cigala V, Biondi R, Prata AJ, Steiner AK, Kirchengast, G, Brenot H (2019) GNSS radio occultation advances the monitoring of volcanic clouds: The case of the 2008 Kasatochi eruption. *Remote Sensing* 11(19): 2199

Fortunato M, Ravanelli M, Mazzoni A (2019) Real-time geophysical applications with android GNSS raw measurements. *Remote Sensing* 11(18): 2113

Lagasio M, Parodi A, Pulvirenti L, Meroni AN, Boni G, Pierdicca N, Rommen B (2019a) A synergistic use of a high-resolution numerical weather prediction model and high-resolution earth observation products to improve precipitation forecast. *Remote Sensing* 11(20): 2387

Lagasio, M, Pulvirenti, L, Parodi, A, Boni, G, Pierdicca, N, Venuti, G, Rommen B (2019b) Effect of the ingestion in the WRF model of different Sentinel-derived and GNSS-derived products: Analysis of the forecasts of a high impact weather event. *European Journal of Remote Sensing* 52(sup4): 16-33

Lasota E, Steiner AK, Kirchengast G, Biondi R (2020) Tropical cyclones vertical structure from GNSS radio occultation: an archive covering the period 2001-2018. *Earth System Science Data* 12(4): 2679-2693

Manzoni M, Monti-Guarnieri AV, Realini E, Venuti G (2020) Joint exploitation of SAR and GNSS for atmospheric phase screens retrieval aimed at numerical weather prediction model ingestion. *Remote Sensing* 12(4): 654

Mascitelli A, Gatti A, Realini E, Venuti G (2019a) Statistical comparison between different approaches to GNSS single-frequency data processing for meteorological applications. In: International Workshop on R3 in Geomatics: Research, Results and Review, pp. 16-26, Springer, Cham.

Mascitelli A, Barindelli S, Realini E, Luini L, Venuti G (2019b) Precipitable water vapor content from GNSS/GPS: Validation against radiometric retrievals, atmospheric sounding and ECMWF model outputs over a test area in Milan. In: International Workshop on R3 in Geomatics: Research, Results and Review, pp. 27-34, Springer, Cham.

Mascitelli A, Federico S, Fortunato M, Avolio E, Torcasio RC, Realini E, Dietrich S (2019c) Data assimilation of GPS-ZTD into the RAMS model through 3D-Var: preliminary results at the regional scale. *Measurement Science and Technology* 30(5): 055801

Mascitelli A, Federico S, Torcasio RC, Dietrich S (2020) Assimilation of GPS zenith total delay estimates in RAMS NWP model: Impact studies over central Italy. *Advances in Space Research*.

Meng X, Komjathy A, Verkhoglyadova O, Savastano G, Crespi M, Ravanelli M (2019) Modeling the near-field ionospheric disturbances during earthquakes. Proceedings of the ION 2019 Pacific PNT Meeting, Honolulu, Hawaii, April 2019, 854-861.

Meroni AN, Montrasio M, Venuti G, Barindelli S, Mascitelli A, Manzoni M, Monti Guarnieri AV, Gatti A, Lagasio M, Parodi A, Realini E, Tagliaferro G (2020) On the definition of the strategy to obtain absolute InSAR Zenith Total Delay maps for meteorological applications. *Front. Earth Sci* 8: 359

Mikesell TD, Rolland LM, Lee RF, Zedek F, Coïsson P, Dessa JX (2019) IonoSeis: A package to model coseismic ionospheric disturbances. *Atmosphere*, doi: 10.3390/ atmos10080443

Pierdicca N, Maiello I, Sansosti, E, Venuti G, Barindelli S, Ferretti R, Verde S (2020). Excess path delays from Sentinel interferometry to improve weather forecasts. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13: 3213-3228

Prata AT, Folch A, Prata AJ, Biondi R, Brenot H, Cimarelli C, Corradini S, Lapierre J, Costa, A (2020) Anak Krakatau triggers volcanic freezer in the upper troposphere. *Scientific Reports* 10(1): 1-13

Ravanelli M, Occhipinti G, Savastano G, Komjathy A, Shume E, Crespi M (2020a) Real-time detection of tsunami ionospheric disturbances with a stand-alone GNSS receiver: A preliminary feasibility demonstration. *Scientific Reports* 11(1): 1-12

Ravanelli M, Foster J, Crespi M (2020b) TIDs detection from ship-based GNSS receiver: First Test On 2010 Maule Tsunami. *IEEE International Geoscience and Remote Sensing Symposium*. IEEE.

Rolland L, Munaibari E, Zedek F, Sakic P, Sladen A, Larmat C, Mikesell TD, Delouis B (2021) Worldwide GNSS ionospheric response of the magnitude 8.8 2010 Chilean earthquake and tsunami: a revisit, EGU General Assembly 2021, 19-30 April 2021, EGU21-10958, https://doi.org/10.5194/egusphere-egu21-10958, 2021.

Sangiorgio M, Barindelli S, Biondi R, Solazzo E, Realini E, Venuti G, Guariso G (2019a) Improved extreme rainfall events forecasting using neural networks and water vapor measures. In: 6th International conference on Time Series and Forecasting, pp. 820-826.

Sangiorgio M, Barindelli S Guglieri V, Biondi R, Solazzo E, Realini E, Guariso G (2019b) A comparative study on machine learning techniques for intense convective rainfall events forecasting. In International Conference on Time Series and Forecasting, pp. 305-317, Springer, Cham.

Savastano G, Nordström K, Angling M, Masters D (submitted) Semi-supervised Classification of Lower-Ionospheric Perturbations using GNSS Radio Occultation Observations from Spire's Cubesat Constellation.

Savastano G, Komjathy A, Shume E, Vergados P, Ravanelli M, Verkhoglyadova O, Meng X, Crespi M (2019a) Advantages of geostationary satellites for ionospheric anomaly studies: ionospheric plasma depletion following a rocket launch. *Remote Sensing* 11(14): 1734

Savastano G, Ravanelli M (2019b) Real-time monitoring of ionospheric irregularities and TEC Perturbations. Satellites Missions and Technologies for Geosciences, IntechOpen.

Savastano G, Nordström K, Angling M, Nguyen V, Duly T, Yuasa T, Masters D (2020) Monitoring perturbations in the lower-ionosphere using GNSS radio occultation observed from Spire's Cubesat Constellation. EGU General Assembly 2020, 4-8 May 2020, EGU2020-7390, https://doi.org/10.5194/egusphere-egu2020-7390.

Scherllin-Pirscher B, Steiner AK, Anthes RA, Alexander MJ, Alexander SP, Biondi R, Birner T, Kim J, Randel WJ, Son SW, Tsuda T (2021) Tropical temperature variability in the UTLS: New insights from GPS radio occultation observations. *Journal of Climate* 34(8): 2813-2838

Ssenyunzi RC, Oruru B, D'ujanga FM, Realini E, Barindelli S, Tagliaferro G, van de Giesen, N (2019) Variability and accuracy of Zenith Total Delay over the East African tropical region. *Advances in Space Research* 64(4): 900-920

Ssenyunzi RC, Oruru B, D'ujanga FM, Realini E, Barindelli S, Tagliaferro G, van de Giesen N (2020) Performance of ERA5 data in retrieving Precipitable Water Vapour over East African tropical region. *Advances in Space Research* 65(8): 1877-1893

Tagliaferro G, Gatti A, Realini E (2019) Assessment of GNSS zenith total delay estimation using smart devices. In Proceedings of the 32nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2019), pp. 3879-3891.

Tiberia A, Mascitelli A, D'Adderio LP, Federico S, Marisaldi M, Porcù F, Realini E, Gatti A, Ursi A, Fuschino F, Tavani M, Dietrich S (2021) Time evolution of storms producing terrestrial gamma-ray flashes using ERA5 reanalysis data. GPS, Lightning and Geo-Stationary Satellite Observations. *Remote Sensing* 13(4): 784

Tournigand PY, Cigala V, Prata AJ, Steiner AK, Kirchengast G, Brenot H, Clarisse L, Biondi R (2020a) Yhe 2015 Calbuco volcanic cloud detection using GNSS radio occultation and satellite lidar. 2020 IEEE International Geoscience and Remote Sensing Symposium, 2020, pp. 6834-6837.

Tournigand PY, Cigala V, Lasota E, Hammouti M, Clarisse L, Brenot H, Prata F, Kirchengast G, Steiner AK, Biondi R (2020b) A multi-sensor satellite-based archive of the largest SO 2 volcanic eruptions since 2006. *Earth System Science Data* 12(4): 3139-3159.

Zedek F, Rolland LM, Mikesell TD, Sladen A, Delouis B, Twardzik C, Coïsson P (2021) Locating surface deformation induced by earthquakes using GPS, GLONASS and Galileo ionospheric sounding from a single station. *Advances in Space Research* (submitted).

Joint Study Group T.37: Theory and methods related to the combination of high-resolution topographic/bathymetric models in geodesy

***Chair**: Daniela Carrion (Italy)*

Members

Daniela Carrion (Italy), Chair
Riccardo Barzaghi (Italy)
Mattia Crespi (Italy)
Vassilios Grigoriadis (Greece)
Karsten Jacobsen (Germany)
Kevin Kelly (US)
Michael Kuhn (Australia)
Rajinder Nagi (US)
Dan Palcu (Brazil)
Cornelis Slobbe (Netherlands)

1. Activities of the group

The activities of the Study Group focused on the exploration of critical transitions from land to sea in order to select one or more test areas to perform further analyses.

In particular, the assessments raised from ongoing computation activities for the GEOMED2 project, for the geoid of Cameroun computation as well as for the preliminary activities for the computation of the new release of the official Italian geoid. These activities involved sub groups of the commission membership.

The land-sea height transition has been explored, where data come different sources of information and with different resolutions for land and sea respectively. In view of the selection of a test case, two available Digital Terrain and Bathymetry Models (DTM/DBM) have been considered. The first is SRTM+, see Fig. 1, which efficiently integrates global SRTM on land and available bathymetric data, and the second is the Italian DTM, which was obtained by combining SRTM on land, bathymetric data coming from international databases, as well as data coming from digitized local maps. The second DTM/DBM was used for the computation of the last official release of the Italian geoid. The differences between the two models are significant in the sea, see Fig. 2. When displayed, in particular when the gradient of height is computed, both height models show discontinuities due to the inconsistent combination of the different sources of information contributing to the bathymetry: in Fig. 3 it is possible to see that the gradient shows some sharp boundaries, a sort of squared pattern due to the data sources and to the different resolutions, these differences appear also close to the coastline. One limitation in exploring the quality of bathymetry is represented by the lack of reference data. In most cases, only inter-comparison can be performed. For the Italian case, the availability of GPS/levelling data close to the coastline allows for the analysis of the indirect effects of the quality of bathymetry to sea/land transition on the geoid undulation.

In the next steps of the activities of the group, it is planned to further explore the impact (if any) of these discontinuities and of the lack of accuracy in bathymetry data on geodetic functionals.

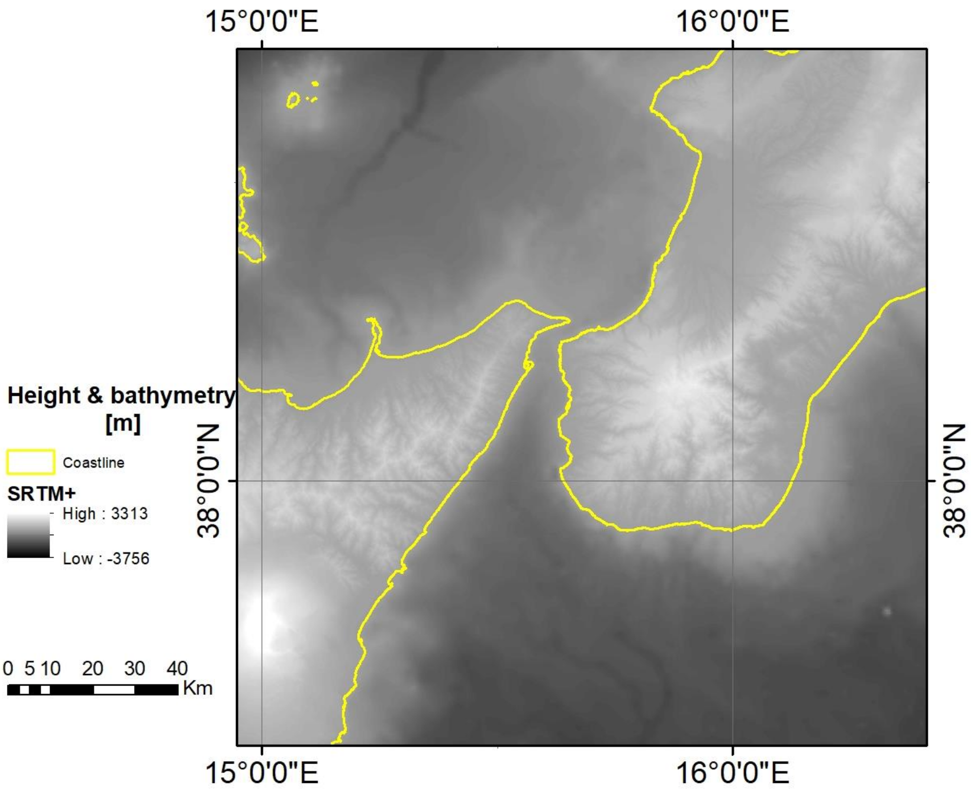


Figure 1: SRTM+ in Southern Italy, around the Strait of Messina.

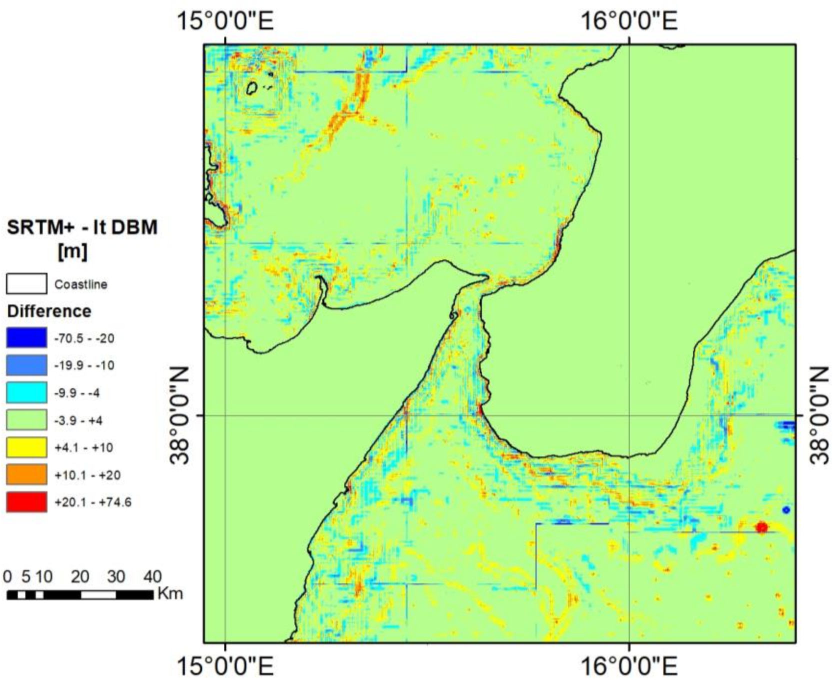


Figure 2: Difference between SRTM+ and the height model used for Italian geoid computation.

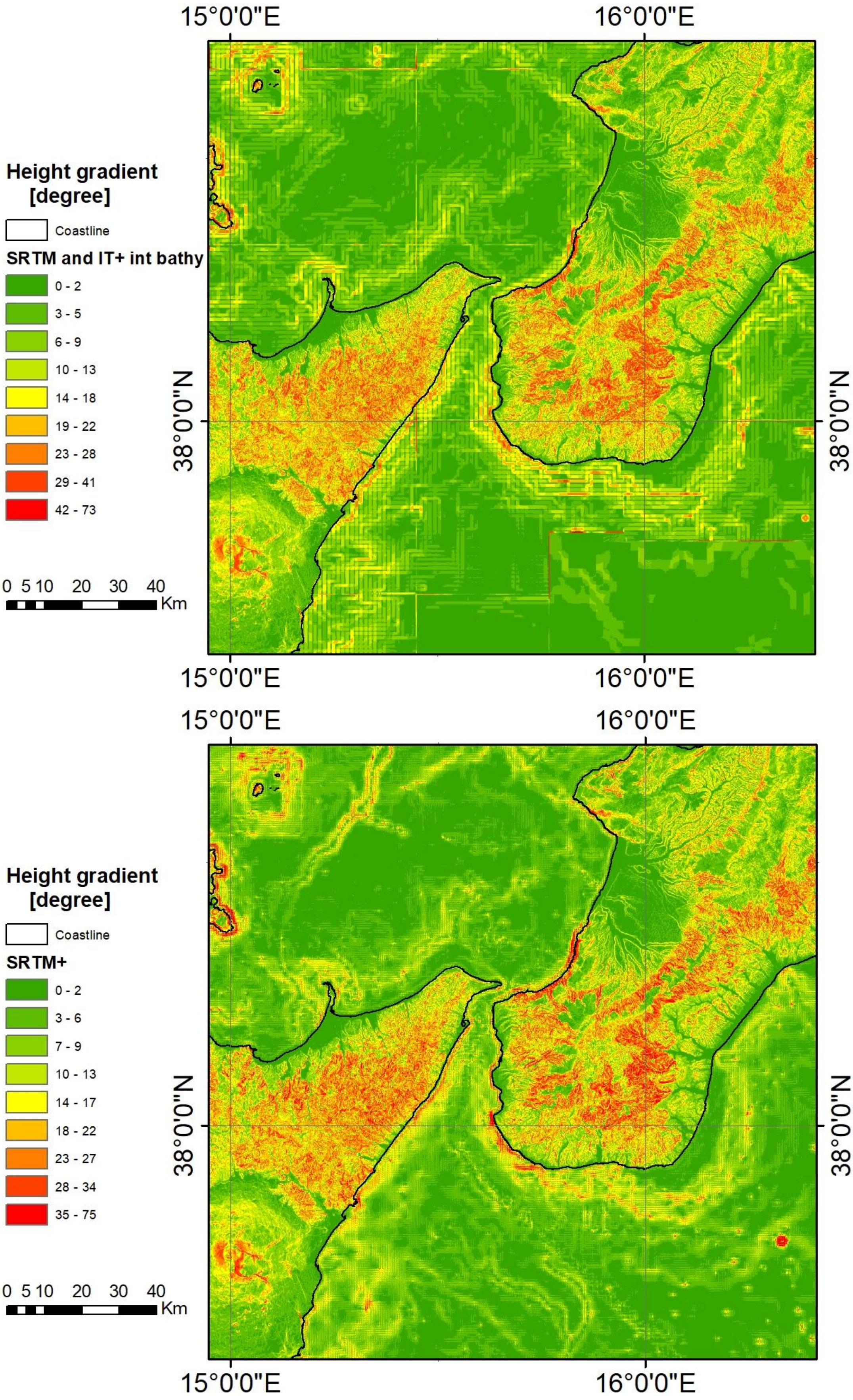


Figure 3: Height gradients in Southern Italy, around the Strait of Messina for the height model used for Italian geoid computation (top) and for SRTM+ (bottom).

2. Achievements and results

The first test area selected is in southern Italy, around the Strait of Messina. This is a very interesting area because it has steep coastline and deep sea with steep transition. It is a volcanic area, with active volcanoes and it corresponds to the boundaries between the Eurasian and the African tectonic plates. The Italian test site allows for the comparison between the SRTM+ integrated topography/bathymetry model and the Italian DTM/DBM which was obtained from the digitizing of bathymetry maps close to the coastlines, integrated with international bathymetry data and SRTM heights on land.

3. Interactions with the IAG Commissions and GGOS

So far, the commission interacted with IGFS and the OGC working group on the discussion about developing a standardized Gridded Geodetic data eXchange Format (GGXF). The definition of a standard for grid data sharing is essential, considering the variety of available formats, which are very similar one to the other and that with lack of metadata could lead to misinterpretations. It is evident that the choice of such a standard is strongly related to the use of DTM/DBM-models.

It is also planned to interact with International Height Reference System JWG GGOS 0.1.3, as the consistency of DTM/DBM with the tide gauges, which are positioned along the coast, is essential.

4. Refined plans for the period of 2021-2023

COVID-19 pandemic had an indirect effect on the commission activities. The additional burden provided to everyday family life and the pressure of other activities which have changed modality has slowed down the work with respect to the original plans.

The upcoming activities regard parallel tests performed by the group members on the study areas to verify criticalities in the height transition from land to sea. In particular, the impact will be verified with respect to the geoid modelling computation and, more in general, the geodetic functionals, exploiting the remove-compute-restore technique. In particular, the computation of the new release of the official Italian geoid model is foreseen for the next period of the study group activities. Italy has very long coastlines and the accuracy of the knowledge of the land-sea transition can affect the geoid computation accuracy, in particular, before the computation of the last release of the official Italian geoid it was verified that the DBM information is crucial to improve the accuracy of the local geoid computation (Borghi et al, 2007). Particular attention will be dedicated to the data quality with respect to DTM and bathymetry data and to the impact of the transition on the geoid computation. If the inconsistent patching of different sources of information as well as if an impact of the DTM/DBM combination on the accuracy of geoid computation are confirmed, the possibility to apply smoothing algorithms to the problematic areas of the DBM will be explored in order to verify if they can provide improvement.

On land, the performance of the AW3D30 model will be also considered with respect to SRTM.

In addition, the next steps of the GEOMED2 project for the geoid of the Mediterranean will take place within 2021. In this case, as already anticipated with respect to the results, the quality of bathymetry, as well as the transition from land to sea, will be explored and the results will be shared in the framework of the JSG.

It is planned also to explore the coastal bathymetric mapping possibilities of the ICESat-2 mission.

In 2022 the X Hotine Marussi Symposium will be held in Milan and part of the commission members are as well members of the organizing committee. It is planned to propose one or more presentations regarding the impact of topographic/bathymetric models in geodesy.

5. Publications

Barzaghi R, Carrion D, Kamguia J, Kande LH, Yap L, Betti B (submitted), Estimating gravity field and quasi-geoid in Cameroon (CGM20). *Journal of African Earth Sciences.*

Barzaghi R et al. (2018) GEOMED2: High-resolution geoid of the Mediterranean. In: Freymueller J, Sánchez L. (eds) International Symposium on Advancing Geodesy in a Changing World. *International Association of Geodesy Symposia* 149. Springer, Cham, https://doi.org/10.1007/1345_2018_33.

Borghi A, Carrion D, Sona G (2007) Validation and fusion of different databases in preparation of high resolution geoid determination. *Geophysical Journal International* 171: 539-549

Inter-Commission Committee on Geodesy for Climate Research (ICCC)

https://iccc.iag-aig.org/

President: Annette Eicker (Germany)
Vice President: Carmen Boening (USA)

Structure

Joint Working Group C.1:	Climate Signatures in Earth Orientation Parameters
Joint Working Group C.2:	Quality control methods for climate applications of geodetic tropospheric parameters
Joint Working Group C.3:	Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling
Joint Working Group C.4:	Sea level and vertical land motion
Joint Working Group C.5:	Understanding the monsoon phenomenon from a geodetic perspective
Joint Working Group C.6:	Numerical Simulations for Recovering Climate-Related Mass Transport Signals
Joint Working Group C.7:	Satellite geodetic data assimilation for climate research
Joint Working Group C.8:	Methodology of comparing/validating climate simulations with geodetic data

Overview

The new Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) was officially established during the IUGG General Assembly in Montreal (July 2019) to enhance the use of geodetic observations for climate studies. The aim is to enable a systematic and comprehensive approach among the various geodetic communities, but also to establish and foster links to climate science.

ICCC Steering Committee (2019-2021):

President:	Annette Eicker (Germany)
Vice-President:	Carmen Boening (USA)
Representative of Comm.1:	Christopher Kotsakis (Greece)
Representative of Comm.2:	Wei Feng (China)
Representative of Comm.3:	Michael Schindelegger (Germany)
Representative of Comm.4:	Anna Klos (Poland)
Representative of GGOS:	Mayra Oyola (USA)
Representative of IAMAS:	Vincent Humphrey (USA)
Member at Large:	Felipe Nievinski (Brazil)

The following specific goals were identified for the ICCC:

- to deepen the understanding of the potential (and limitations) of geodetic measurements for the observation, analysis and identification of climate signals.
- to advance the development of geodetic observing systems, analysis techniques and data products regarding their sensitivity to and impact on Essential Climate Variables.

- to advance the improvement of numerical climate models, climate monitoring systems, and climate reanalysis efforts through incorporating geodetic observations.
- to stimulate scientific exchange and collaboration between the geodetic and the climate science communities.
- to make geodetic variables more user-friendly by sharing them publicly and explaining their usefulness.

Outreach and communication:

An important focus in the starting phase of the ICCC was the set-up of **outreach activities** to enhance the visibility of the ICCC:

- The new ICCC website (https://iccc.iag-aig.org/) was established within the framework of the IAG web pages.
- An ICCC Twitter account (@IAG_climate) was set up and has actively started tweeting (520 followers & 135 tweets as of May 2021).
- An overview article was published in GIM International and in the IAG Newsletter.
- An ICCC representative (A. Eicker) has become member of the IUGG Union Commission on Climatic and Environmental Change (CCEC).
- Emails were sent to contact persons at various climate organizations (IAMAS, WCRP/GEWEX, GCOS,…) to connect the ICCC with the climate science community.

Fig. 1: ICCC Twitter account

Furthermore, facilitating efficient **communication** means has been considered an important basis for starting a successful cooperation. Therefore, both an internal mailing list was set up for everyone actively involved in the ICCC and an open mailing list has recently been established to which everyone interested in the ICCC can subscribe. To enable more rapid communication, e.g. during the workshop planning phase, an ICCC workspace was established on the chat platform Slack. Additionally, personal communication was achieved during regular video conferences, such as the ICCC Kick-Off meeting (May 2020) and various meetings of the workshop planning team over the months leading up to the workshop.

1. ICCC Workshop

The most important ICCC event during the reporting period was the successful implementation of the first ICCC workshop as the beginning of a regular ICCC workshop series. It took place on March 29-30, 2021 as an online event and was planned as a mixture of live sessions (held on Zoom) and additional online content to be viewed and discussed at any time to accommodate time zone conflicts. All presentations (orals and posters) were be available for download before the beginning of the workshop to allow asynchronous viewing. The live sessions were held in 2x2h blocks each day, one in the morning (CEST) and one in the late afternoon to enable participation from all time zones. The live meetings consisted of invited overview lectures and short 12-minutes oral presentations. Additionally, two poster sessions were carried out in which each presenter had the opportunity to discuss the poster and to show additional content in their own Zoom breakout room. The chat platform Slack was applied to enable communication between all workshop participants and to discuss the science presentations and posters. No financial budget was anticipated for the workshop. As only free tools (or tools freely available to the organizers) were used, it was possible to offer the workshop free of charge to all participants. This resulted in more than 400 registered participants from over 50 countries and a strong participation of between 100-160 people in each live session. More than half of both participants and speakers identified themselves as early career researchers. In addition to individual scientific presentations, overarching discussions were encouraged on topics such as possible geodetic contributions to observing Essential Climate Variables and on best ways to increase visibility of geodesy in in the public and in neighboring disciplines. The outcome of these discussions will be a good starting point for future ICCC activities.

CEST (UTC+2)	Monday (29.03.21)	Tuesday (30.03.21)	Wednesday (31.03.21)
« Morning » block (2 hours)			
8:00	Welcome	Session 04 : Cryosphere	Keynote : Sea level & cryo
8:15	Keynote : ECVs		Session 07 : Sea level
8:30	Session 01 : Hydrology and data processing (Hydrology I)		
8:45			
9:00			
9:15		Session 05 : Poster breakout II	
9:30			
9:45	Discussion		Discussion
« Afternoon » block (2 hours)			
17 :00	Keynote : Climate models	Keynote : Troposphere	Session 08 : Hydrology II
17 :15	Session 02 : Climate model evaluation	Session 06 : Atmosphere	
17 :30			
17 :45			
18 :00			
18 :15	Session 03 : Poster breakout I		
18 :30			
18 :45		Discussion	
			Closing and next steps

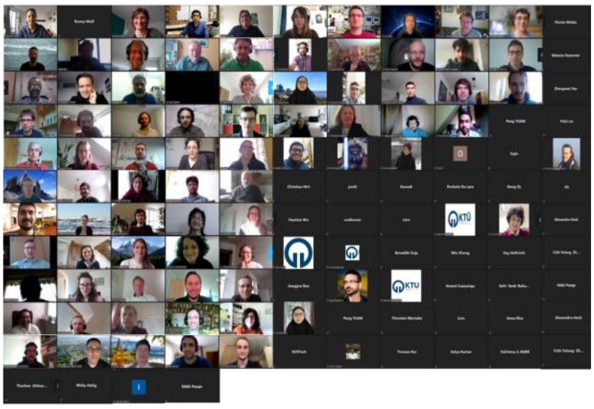


Fig. 2: 1. ICCC Workshop: Program and participants

Scientific sessions

To further promote ICCC activities, dedicated sessions have been proposed and carried out under the umbrella of the ICCC at major international conferences (e.g. EGU 2021&2020, IAG Scientific Assembly 2021, AGU 2020 & 2021). Additionally, various JWGs have organized specific sessions on their JWG topics.

JWG C.1: Climate Signatures in Earth Orientation Parameters

Chair: *Jolanta Nastula (Poland)*
Vice-Chair: *Henryk Dobslaw (Germany)*

Members

- *Christian Bizouard (France)*
- *Sigrid Boehm (Austria)*
- *Aleksander Brzezinski (Poland)*
- *Benjamin Fong Chao (Taiwan)*
- *Yavor Chapanov (Bulgaria)*
- *Jianli Chen (USA)*
- *Alexandre Couhert (France)*
- *Robert Dill (Germany)*
- *Alberto Escapa (Spain)*
- *José Manuel Ferrandiz (Spain)*
- *Laura Fernandez (Argentina)*
- *Franziska Goettl (Germany)*
- *Richard Gross (USA)*
- *Robert Heinkelmann (Germany)*
- *Sébastien Lambert (France)*
- *Vladimir Pashkevich (Russia)*
- *Elena Podladchikova (Belgium)*
- *Cyril Ron (Czech Republic)*
- *David Salstein (USA)*
- *Michael Schindelegger (Germany)*
- *Nikolay Sidorenkov (Russia)*
- *Leonid Zotov (Russia)*

Activities and publications during the period 2019-2021

During the reporting period, Working Group C.1 has organized six virtual meetings on the topics *EOP and Climate* (May 6th, 2020), *Polar Motion from CMIP6 models* (June 11th, 2020), *Pole Tide Signatures in GRACE Data* (August 28th, 2020), *EOP Prediction* (November 12th, 2020), *Atmospheric and Oceanic Excitation Functions* (January 14th, 2021), and *Consistent Combination of EOP and Geophysical Excitation Functions* (March 18th, 2021). All meetings were held online via zoom and have attracted between 25 and 45 members of the working group and other interested scientists. JWG C.1 also contributed actively to the organization of the first Workshop of the ICCC via participation in the Organizing Committee, by chairing a Session, and by contributing several oral presentations and posters.

To further expedite the scientific work, a new website (https://syrte.obspm.fr/~bizouard/ipercc/index.html) provides structured access to data sets and literature that is relevant to the work of JWG C.1. A number of scientific publications have been already completed on topics like terrestrial water storage contributions to observed EOP (Sliwinska et al., 2020), the accurate representation of the effects of the oceanic pole tide in EOP and satellite gravimetry (Chen et al., 2021), and on the ability of numerical oceans to accurately simulate high-frequency ocean mass transports (Schindelegger et al., 2021).

The topic of the fourth meeting of the JWG C.1, *EOP Prediction*, has met with particularly high interest by the scientific community. In a total of five talks from scientists representing different international research centers active in the field of EOP prediction have been presented. Following the discussion, it has been decided to rigorously compare the accuracy of present-day methods and algorithms applied in EOP prediction by means of a dedicated international comparison campaign. This campaign will be organized under the auspices of the IERS within a newly established working group (https://www.iers.org/WGEOPPCC2), but cooperation with JWG C.1 on this topic will be maintained also in the future.

References

Chen, J., Ries, J. C., & Tapley, B. D. (2021). Assessment of degree-2 order-1 gravitational changes from GRACE and GRACE Follow-on, Earth rotation, satellite laser ranging, and models. *Journal of Geodesy*, *95*(4), 38. https://doi.org/10.1007/s00190-021-01492-x

Schindelegger, M., Harker, A. A., Ponte, R. M., Dobslaw, H., & Salstein, D. A. (2021). Convergence of Daily GRACE Solutions and Models of Submonthly Ocean Bottom Pressure Variability. *Journal of Geophysical Research: Oceans*, *126*(2). https://doi.org/10.1029/2020JC017031

Śliwińska, J., Nastula, J., Dobslaw, H., & Dill, R. (2020). Evaluating Gravimetric Polar Motion Excitation Estimates from the RL06 GRACE Monthly-Mean Gravity Field Models. *Remote Sensing*, *12*(6), 930. https://doi.org/10.3390/rs12060930

JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters

Chair: Rosa Pacione (Italy)
Vice-Chair: Marcelo Santos (Canada)

Affiliation: Commission 4, IGS, IVS

Members

- *Fadwa Alshawaf (Germany)*
- *Kyriakos Balidakis (Germany)*
- *Sharyl Byram (USA)*
- *Galina Dick (Germany)*
- *Gunnar Elgered (Sweden)*
- *Olalekan Isioye (South Africa)*
- *Jonathan Jones (UK)*
- *Michal Kačmařík (Czech Republic)*
- *Anna Klos (Poland)*
- *Haroldo Marques (Brazil)*
- *Thalia Nikolaidou (Canada)*
- *Tong Ning (Sweden)*
- *Mayra Oyola (USA)*
- *Eric Pottiaux (Belgium)*
- *Paul Rebischung (France)*
- *Roeland Van Malderen (Belgium)*
- *Yibin Yao (China)*

Activities and publications during the period 2019-2021

For the sake of this report, let us restate some of the scientific questions JWG C.2 procures to address. They include (a) are there advantages of combining ZTD estimates over not combining them? Is there any 'loss of information' in performing combinations? (b) Would there be difference in trends derived from them? If so, how much implication for feeding information to climate? (c) Can we trust in a combined ZTD as we trust any combined products (e.g., orbits, clock, site coordinates) (d) What the best combination strategy can be done (not necessarily to combined exactly the same way as other products)? (e) Under what criteria can we use spectral analysis to demonstrate that a 'good' combined product has the same properties of the contributing solutions? (f) What metrics should be used to ascertain that the optimal set of ZTD estimates, gradients and their trends, are provided to the climate community?

A desired investigation of this JWG dealing with quality control depends on the release of REPRO3, more specifically, their tropospheric estimates. The huge and careful effort required for REPRO3 by the IGS Analysis Centres demanded an appropriate amount of time, which overlapped with some of the term of the JWG C.2. REPRO3 has just recently been made available. This obviously created an undesirable delay in the numerical aspect of assessing quality control methods, and, as such, addressing some of the questions previously mentioned. Nonetheless, several discussions on various topics took place and activities carried out. A summary is presented in the sequel.

Two meetings involving the members of the JGW took place during the period, both virtual meetings. The second meeting had the participation of a few invited guests from the climate community. Their participation helped to clarify a few points as well as to open important insights from their perspective. If we, as geodetic community, want to provide a product, being tropospheric parameters or trends, to the climate community, we need to understand their needs and demands. From the other side of the equation, they should understand the different ways these products can be generated so that they can point to the most useful one depending on their needs.

One such discussions was around what type of solution the climate community would prefer, a combined or an individual solution. A combined product may provide a more consistent climatic trend, but is that what is wanted, or would it be preferable several good quality individual solutions? How could we ascertain that those individual solutions are of similar quality? A combined solution could have added extra layers of uncertainty because of the combination process. Would the climate community prefer to have delivered trends or just estimates (i.e., ZTD time series) and they would derive the trends? In case they prefer to have directly the trends would several trends from individual solutions with an associated quality indicator be preferable over a combined solution trend.

Even though meteorology has made use of ZTD for assimilation into numerical weather models, the use of ZTD by the climate community seems to be something yet to ignite. In the business of data assimilation, biases are corrected. But for climate modelling ZTD biases, even short-term, may cause erratic long-term ZTD behaviour, stressing, therefore, the importance of homogeneity.

As stated earlier, a few invited guests from the climate community participated in our second meeting. One concern that still lingers over space geodetic derived parameters for climate, such as ground GNSS, is its still short period. GNSS is barely reaching the 30-year climate normal cycle. Nonetheless, during the discussions, we were told that the climate modellers may find wealth in GNSS derived tropospheric parameters for periods shorter than 30 years. If the concern is primarily with improving the representation of processes and models, a data set that provides with something new, with something that is not provided from elsewhere, allowing to investigate and improve a particular physical process in the model, is where lies the benefit. It may be better spatial gradients in the water vapour field or better high frequency variability. If such things can be isolated, there lies a great contribution. Therefore, a few years of high-quality data can be as important as a full 30-years data.

Other activities worth mentioning were the presentation of orals during the past EGU general assemblies (2020 and 2021) and the first ICC Workshop. Sessions were also organized during these events. JWG C.2 is participating in the IAG Scientific Assembly via the ICCC.

References

Pacione, R., M. Santos, G. Dick, J. Jones, E. Pottiaux, A. Rinke, R. Van Malderen, G. Elgered (2021). "Ground-based GNSS for climate research: review and perspectives." Inter-Commission Committee on Geodesy for Climate Research (ICCC) Workshop, International Association of Geodesy, 29-31 March 2021, online event.

Pacione, R., Santos, M., Dick, G., Jones, J., Pottiaux, E., Rinke, A., Van Malderen, R., and Elgered, G. (2021). "Ground-based GNSS for climate research: review and perspectives." EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-9087, https://doi.org/10.5194/egusphere-egu21-9087.

Santos, M., M. N. Moura, T. Nikolaidou, K. Balidakis (2020). "Long-term ZTD and ZWD series and climate normals using NCEP1." Online, 4–8 May 2020, EGU2020-20989, https://doi.org/10.5194/egusphere-egu2020-20989.

Yuan, P., A. Hunegnaw, F. Alshawaf, J. Awange, A. Klos, F. N. Teferle and H. Kutterer (2021). "Feasibility of ERA5 integrated water vapor trends for climate change analysis in continental Europe: An evaluation with GPS (1994–2019) by considering statistical significance." Remote Sensing of Environment, 260, 112416, https://doi.org/10.1016/j.rse.2021.112416

JWG C.3: Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling

Chair: *Bert Wouters (Netherlands)*
Vice-Chair: *Ingo Sasgen (Germany)*

Members

- *Mike Bevis (USA)*
- *Matthias Braun (Germany)*
- *William Colgan (Denmark)*
- *Christoph Dahle (Germany)*
- *Olga Engels (Germany)*
- *Xavier Fettweis (Belgium)*
- *Dana Floricioiu (Germany)*
- *Heiko Goelzer (Denmarl)*
- *Natalya Gomez (USA)*
- *Martin Horwath (Germany)*
- *Michalea King (USA)*
- *Kristine Larson (USA)*
- *Jan Lenaerts (USA)*
- *Lin Liu (Hong Kong)*
- *Malcolm McMillan (UK)*
- *Brice Noël (Netherlands)*
- *Masashi Niwano (Japan)*
- *Louise Sandberg Sørensen (Denmark)*
- *Mirko Scheinert (Germany)*
- *Nicole Schlegel (USA)*
- *David Wiese (USA)*

Activities and publications during the period 2019-2021

The activities of this Joint Working Group in 2019-2021 were mainly focused on creating awareness of the importance of bridging the currently existing gap between the geodetic and modelling communities, and on establishing ties to relevant to relevant ongoing international activities and communities.

A large number of members were involved in the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE; Shepherd et al., 2020) which aims to come to reconciled estimates of ice sheet mass loss based on geodetic and model-based mass balance data. A similar activity was recently initiated for mountain glaciers within the Regional Assessments of Glacier Mass Change (RAGMAC; Zemp et al., 2020) initiative, which aims to bring together the research community that is assessing regional glacier mass changes, Objective is to come up with a new consensus estimate of global glacier mass changes and related uncertainties, which can be used for model calibration and initialization. Within the GrSMBMIP an intercomparison was carried out between state-of-the-art ice sheet models and geodetic data, again with the involvement of JWG members. Our members are also well represented in the recently launched Horizon 2020 PROTECT initiative, which aims to assess and project changes in the land-based cryosphere, with fully quantified uncertainties, in order to produce robust global, regional and local projections of SLR on a range of timescale. Furthermore, members have continued their contribution to ESA Climate Change Initiatives, which strives to provide easy accessible and interpretable satellite observations to a wide range of researchers. We are also involved in the INStabilities & Thresholds in ANTarctica (INSTANT) initiative of the Scientific Committee on Antarctic Research (SCAR), which aims to quantify the Antarctic ice sheet contribution to past and future global sea-level change, from improved understanding of climate, ocean and solid Earth interactions and feedbacks with the land ice, from a modelling and observational perspective.

In terms of outreach, team members were involved the successful ICCC 2021 workshop, either as co-organizer or presenters. This workshop was also promoted by a team member in the newsletter of the European Climate Research Alliance ECRA. We were also well represented at the European Polar Sciene Week 2020, where members presented their, hosted sessions and round table discussions involving researchers from both the geodetic and modelling community. At EGU 2020 and 2021, a session on Geodesy for Climate Research was organized, which included a number of presentations tied to our JWG.

With respect to future geodetic observables, group members contributed to NASA and ESA working groups in preparation of future gravimetry and altimetry missions.

References

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., Born, A., Box, J. E., Delhasse, A., Fujita, K., Gierz, P., Goelzer, H., Hanna, E., Hashimoto, A., Huybrechts, P., Kapsch, M.-L., King, M. D., Kittel, C., Lang, C., Langen, P. L., Lenaerts, J. T. M., Liston, G. E., Lohmann, G., Mernild, S. H., Mikolajewicz, U., Modali, K., Mottram, R. H., Niwano, M., Noël, B., Ryan, J. C., Smith, A., Streffing, J., Tedesco, M., van de Berg, W. J., van den Broeke, M., van de Wal, R. S. W., van Kampenhout, L., Wilton, D., Wouters, B., Ziemen, F., and Zolles, T.: GrSMBMIP: intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice Sheet, The Cryosphere, 14, 3935–3958, https://doi.org/10.5194/tc-14-3935-2020, 2020.

Shepherd, A, Ivins, E, Rignot, E et al. (86 more authors) (2020) *Mass balance of the Greenland Ice Sheet from 1992 to 2018.* Nature, 579 (7798). pp. 233-239. ISSN 0028-0836

Zemp, Michael, Matthias H Braun, Alex S Gardner, Bert Wouters, Geir Moholdt, Regine Hock (2020), EGU General Assembly Conference Abstracts

JWG C.4: Regional Sea level and vertical land motion

Chair: *Roelof Rietbroek (Netherlands)*
Vice-Chair: *Riccardo Riva (Netherlands)*

Members

- *Alvaro Santamaria (U. Toulouse III, France), GPS vertical land motion*
- *Sönke Dangendorf (U. Siegen, Germany), tide gauges*
- *Adrian Borsa (Scripps, USA), VLM.*
- *Aimée Slangen (NIOZ, NL), projections/models*
- *Ropesh Goyal (Kanpur/Curtin), Geoid modelling, India*
- *Guy Woppelmann (U. La Rochelle, France), TG & VLM*
- *Giorgio Spada (U. Urbino, Italy), TG and GIA*
- *Erik Ivins (JPL, USA), sea level & solid earth*
- *Marta Marcos (UBI, Spain), TG & oceanography*
- *Thomas Frederikse (JPL, USA), sea level & VLM*
- *Don Chambers (USF, USA), oceanography & GRACE*
- *Francisco Calafat (NOC, UK), oceanography*
- *Karen Simon (TU Delft, NL), GIA*

Activities and publications during the period 2019-2021

Despite the covid19 pandemic, there have been several online meetings with the joint working group, or a selection thereof, over the period 2019-2021. Partially these involved bringing together ideas of how to showcase and translate the scientific challenges of regional sea level and vertical land motion to a non-geodetic audience. The joint working group has discussed ideas for setting up materials, and which may potentially be hosted on the IAG website in the future.

Several of the members have represented the joint working group and participated in the organization of the ICCC workshop which was successfully held online in March 2021. They additionally contributed a keynote lecture (in collaboration with the cryosphere working group) and scientific content, and a live twitter feed targeting the general public through the @iag_climate account.

Furthermore, during the online assemblies of AGU2020 and EGU2021, joint working group members have served as conveners in sessions which were closely aligned with the ICCC goals and explicitly mentioned the ICCC and its goals in the session description.

The group members have been actively publishing scientific works which cover the goals of the joint working groups, of which a selection is listed below.

References

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., Wu, Y.-H., 2020. The causes of sea-level rise since 1900. Nature 584, 393–397. https://doi.org/10.1038/s41586-020-2591-3

Dangendorf, S., Frederikse, T., Chafik, L., Klinck, J.M., Ezer, T., Hamlington, B.D., 2021. Data-driven reconstruction reveals large-scale ocean circulation control on coastal sea level. Nature Climate Change 1–7. https://doi.org/10.1038/s41558-021-01046-1

Uebbing, B., Kusche, J., Rietbroek, R., Landerer, F.W., 2019. Processing choices affect ocean mass estimates from GRACE. Journal of Geophysical Research: Oceans 0. https://doi.org/10.1029/2018JC014341

Calafat, F.M., Marcos, M., 2020. Probabilistic reanalysis of storm surge extremes in Europe. Proceedings of the National Academy of Sciences 117, 1877–1883.

Simon, K. M., Riva, R.E.M., 2020. Uncertainty estimation in regional models of long-term GIA uplift and sea level change: An overview. Journal of Geophysical Research: Solid Earth, 125, e2019JB018983. https://doi.org/10.1029/2019JB018983

Camargo, C. M., Riva, R. E., Hermans, T. H., & Slangen, A. B. (2020). Exploring sources of uncertainty in steric sea-level change estimates. Journal of Geophysical Research: Oceans, 125(10), e2020JC016551.

Joint Working Group C.5: Understanding the monsoon phenomenon from a geodetic perspective

Chair: *Balaji Devaraju (India)*
Vice-Chair: *Matthias Weigelt (Germany)*

Members

- *Alexander Braun (Canada)*
- *Alka Singh (India)*
- *Bramha Dutt Vishwakarma (UK)*
- *Chandrakanta Ojha (India)*
- *Karim Douch (Germany)*
- *Mohammad A. Sharifi (Iran)*
- *Nabila Putri (Indonesia)*
- *Nico Sneeuw (Germany)*
- *Peng Yuan (Germany)*
- *Qiang Chen (Luxembourg)*
- *Shivam Tripathi (India)*
- *Subimal Ghosh (India)*
- *Susanna Werth (USA)*
- *Vagner Ferreira (China)*
- *Zhizhou Liu (Hong Kong, China)*

Activities and publications during the period 2019-2021

Monsoon is a large-scale atmospheric phenomenon that brings precipitation to a major section of the global population. It sustains agriculture and replenishes the water resources. In the recent decades, geodetic sensors have enabled a greater understanding of earth system processes, especially that of hydrology. In this context, the joint working group is invested in understanding the monsoon phenomenon from a geodetic perspective, and thereby improve the process understanding of monsoon, and contribute towards its monitoring and modelling. It is to be noted here that the monsoon phenomenon has not been studied widely in the geodetic literature, and to a large extent the geodetic sensors have not been used in monsoon studies. Thus, the main objective of the joint working group is to promote the use of geodetic sensors in monsoon research, and thereby demonstrate their respective abilities.

The first step in demonstrating the abilities of geodetic sensors is to choose the physical variables measured by the geodetic sensors that are more sensitive to the monsoon phenomenon, and thereby identify the signature – timing, intensity and spatial distribution. The geodetic sensors that are considered in the joint working group are satellite altimetry (radar and lidar), satellite gravimetry, GNSS and InSAR. In the first internal workshop of the joint working group, several variables like precipitable water vapour, total water storage change, vertical crustal motion due to hydrological loading, steric sea-level, wind speed and wind direction, which can all be measured by the geodetic sensors have been identified as sensitive to the monsoon phenomenon. Currently, the monsoon signatures of these variables are being investigated. To this end the joint working group is preparing a white paper on the role of geodesy in monsoon research in which all the above-mentioned issues are discussed in detail.

The joint working group is active in organizing internal workshops, contributing sessions in conferences and disseminating information through social media. As a kickstart event an internal workshop was conducted to understand the strengths of the working group members and the processes involved in the monsoon phenomenon. The joint working group contributed to the 1st ICCC workshop "Geodesy for Climate Research" both in terms of science as well as its organization. In the upcoming 18th Annual Meeting of the Asia-Oceania Geosciences Society 2021, the joint working group is conducting a session on *Data-driven approaches for studying the monsoon phenomenon*, which will have eleven contributions (eight oral and three poster presentations). In addition, our group has also applied for a dedicated session in the upcoming American Geophysical Union Fall Meeting 2021. Further activities, especially, more internal workshops and special issue publications will be planned in the second and final phase of the joint working group.

References

Here you can list references by JWG members that have advanced the topic of the JWG over the past two years.

Conference presentations:

Ray, JD, Devaraju, B, Vijayan, MSM, and Godah, W (2021). Geodetic monitoring of the hydrological changes in Nepal Himalaya. In: 1st ICCC Workshop "Geodesy for Climate Research", March 29-31, 2021, online.

Peer-reviewed publicationsFerreira, V.G., Yong, B., Tourian, M.J., Ndehedehe, C.E., Shen, Z., Seitz, K., Dannouf, R. (2020). Characterization of the hydro-geological regime of Yangtze River basin using remotely-sensed and modeled products. Sci. Total Environ. 718, 137354.

JWG C.6: Numerical Simulations for Recovering Climate-Related Mass Transport Signals

Chair: *Roland Pail (Germany)*
Vice-Chair: *Wei Feng (China)*

Members

- *Roland Pail (Germany)*
- *Wei Feng (China)*
- *Henryk Dobslaw (Germany)*
- *Laurent Longuevergne (France)*
- *Vincent Humphrey (US)*
- *Benoit Meyssignac (France)*
- *Lijing Cheng (China)*
- *Qiang Chen (Luxembourg)*
- *Sonia Seneviratne (Switzerland)*
- *Martin Horwath (Dresden)*
- *Bert Wouters (Netherlands)*
- *Erik Ivins (US)*
- *Marius Schlaak (Germany)*

Activities and publications during the period 2019-2021

The main objective of this working group is to set-up and run long-term numerical simulation studies to evaluate the feasibility to derive climate-related signals by current (GRACE, GRACE-Follow On) and future gravity field missions.

In a first step, a 100-year time series of continental hydrology was generated. For this, land water storage related variables from a variety of climate models taking part in the Coupled Model Inter-comparison Project Phases 5 and 6 (CMIP5 and CMIP6) was compared and assessed against each other (Jensen et al. 2019, 2020). Finally, a specific model run was selected that closely matches both GRACE observations, and a multi-model median.

In parallel, numerical simulation software was adapted to be capable of dealing with very long time series of up to one century, and the parameter model was extended to directly parameterize linear (and optionally quadratic) trends and annual signals. In the course of several test runs, the covariance structure and thus the arising correlation among the parameter groups was analyzed in detail. Additionally, a preparatory study was performed to evaluate the long-term behavior of various errors and their impact on single- and double-pair gravity solutions. As it is to be expected, instrument errors, e.g. related to the inter-satellite ranging system and the accelerometer, decrease with increasing time series length according to the Gaussian sqrt(n) rule in the case of a correct stochastic modelling of their colored noise behavior. This is no longer true for temporal aliasing errors related to background model errors of ocean tides and non-tidal high-frequency signals of atmosphere and ocean, because they are (partly) deterministic. This preparatory study was important to define a realistic noise environment for the long-term simulations.

Figure 1 shows the results of a long-term simulation with varying lengths of 10 to 100 years as spatial residuals in equivalent water heights (EWH) in meters, assuming a Bender double-pair constellation with a 100s sampling interval and 27 day repeat orbit. The observed signal is based on the total water storage climate signals from the chosen GFDL model, as well as realistic instrument and ocean tide background model errors. First analyses show that the linear trend improved already significantly after 50 years, whereas the annual amplitudes are already captured within the first decade of simulations. The remaining residuals for cos- and sin amplitudes are mainly caused by errors in ocean tide background models. Overall, the first results show that the global residuals are at least one magnitude smaller than the input climate signal. First results of this study will be presented at the IAG General Assembly in Beijing (Schlaak et al. 2021).

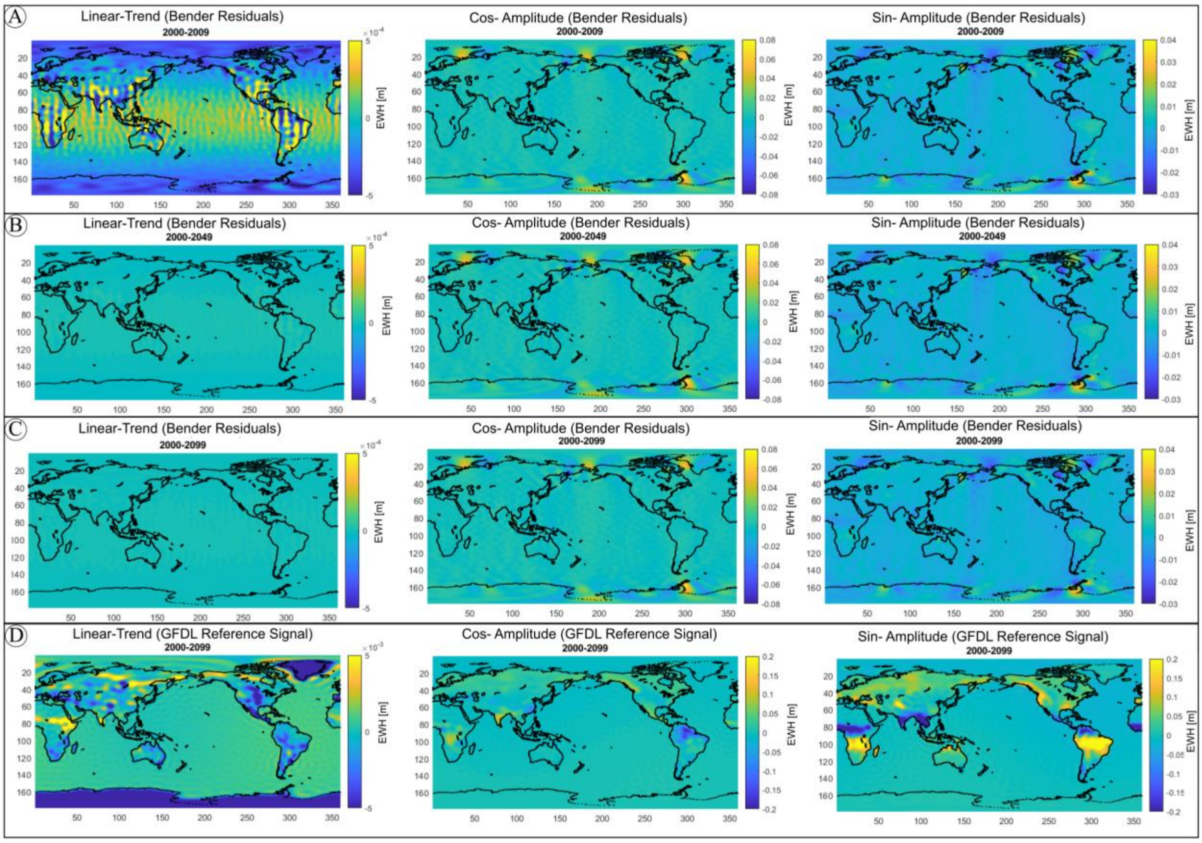


Figure 1*: Global grid of simulation output residuals with respect to the input model data in equivalent water heights (EWH). From left to right residuals of linear trend, annual cos-, and sin-amplitudes are shown for simulations of 10 years (A), 50 years (B), and 100 years (C). To show the signal magnitude the trends of the chosen GFDL climate model after 100 years is shown in (D).*

One of the main prerequisites to compare simulation results of various contributing groups is to inter-compare the performance of the different numerical mission simulators first. Therefore, an inter-comparison exercise of numerical simulators and simulation results among four Chinese groups and the simulator at Technical University of Munich was performed (Pail et al. 2019). Figure 2 shows resulting coefficient differences in terms of equivalent water height (EWH) degree RMS curves. This case study is based on a 9-day Bender double-pair constellation and temporal gravity field signals of atmosphere, ocean, hydrology, ice and solid Earth (AOHIS), and assuming realistic instrument and background model errors. The results demonstrate that very similar and thus comparable results could be achieved.

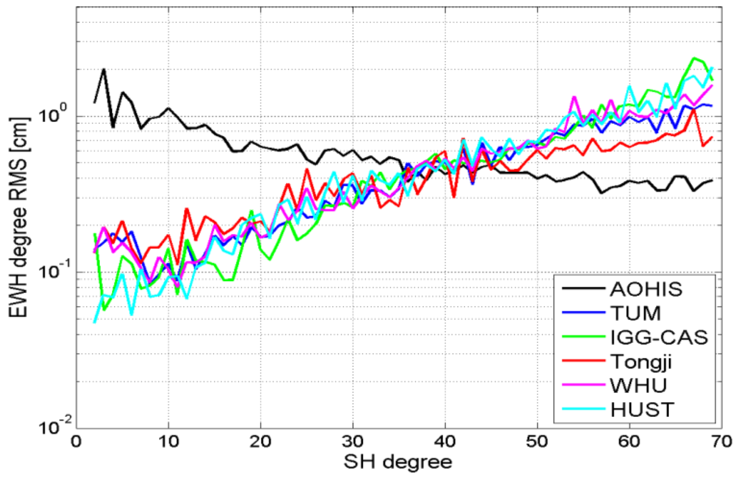


***Figure 2**: Degree (error) RMS of estimated time-variable coefficients from the true signal (black) of five groups, based on a Bender double-pair constellation with 9 days repeat period.*

The JWG C.6 also contributed to the preparation and realization of the first ICCC Workshop, that was held as an online meeting on 29-31 March 2021.

References

Jensen, L., Eicker, A., Dobslaw, H., Stacke, T., Humphrey, V. (2019). Long-Term Wetting and Drying Trends in Land Water Storage Derived From GRACE and CMIP5 Models. Journal of Geophysical Research: Atmospheres 124, 9808–9823. https://doi.org/10.1029/2018JD029989

Jensen, L., Eicker, A., Dobslaw, H., Pail, R. (2020). Emerging Changes in Terrestrial Water Storage Variability as a Target for Future Satellite Gravity Missions. Remote Sensing 12, 3898. https://doi.org/10.3390/rs12233898

Pail, R., Yeh, H.-S, Feng, W., Hauk, M., Purkhauser, A., Wang, Ch., Zhong, M., Shen, Y., Chen, Q., Luo, Z., Zhou, H., Liu, B., Zhao, Y., Zou, X., Xu, X., Zhong, B., Haagmans, R., Xu, H. (2019): Next-Generation Gravity Missions: Sino-European Numerical Simulation Comparison Exercise. Remote Sensing, 11(22), 2654, doi: https://doi.org/10.3390/rs11222654

Schlaak, M., Pail, R., Dobslaw, H., Eicker, A., Jensen, L., and IAG JWG C.6 (2021). Recovering Climate-Related Mass Transport Signals by current and next-generation gravity missions. Abstract submitted to IAG General Assembly, Beijing 2021.

JWG C.7: Satellite geodetic data assimilation for climate research

Chair: *Mehdi Khaki (Australia)*

Members

- *Hamid Moradkhani (The University of Alabama)*
- *John T. Reager (NASA Jet Propulsion Laboratory)*
- *Harrie-Jan Hendricks Franssen (Institute of Bio- and Geosciences Agrosphere, IBG-3)*
- *Gabrielle J. M. De Lannoy (Katholieke Universiteit Leuven)*
- *Benjamin Zaitchik (Johns Hopkins University)*
- *Natthachet Tangdamrongsub (university of Maryland)*
- *Luca Brocca (National Research Council)*
- *Christian Massari (National Research Council)*
- *Ibrahim Hoteit (King Abdullah University)*
- *Jan Saynisch (GFZ German Research Centre for Geosciences)*
- *Ashkan Shokri (Monash University and Hydrologist at Bureau of Meteorology)*
- *Yoshihide Wada (International Institute for Applied Systems Analysis, IIASA)*
- *Joseph Awange (Curtin University)*
- *Jayaluxmi Indu (Indian Institute of Technology Bombay)*

Activities and publications during the period 2019-2021

The working group has been established in late 2019. Soon after contacting the potential members, multiple activities have been arranged. These are summarized below.

Website and sharing materials

As proposed in the working group's initial objectives, a website was created to introduce members and their activities, as well as providing a platform for sharing relevant materials. The website (www.satellite-da.com) has been constantly updated to cover the latest news and upcoming events. It is decided in the latest meeting by the group members that more parts should be invested in educational objectives. We are currently working on this and all group members are contributing to offer documents/videos in this line.

Meetings

Proposed and agreed by the members, frequent meetings will be held. Previously this has been done online for 2 hours starting with activity updates followed by free discussions and scientific presentations by members. So far, Dr. J. Indu – (Indian Institute of Technology Bombay), Christian Massari (the National Research Council (CNR) of Perugia), Dr. Jan Saynisch-Wagner (GFZ-Potsdam), and Dr. Natthachet Tangdamrongsub (University of Maryland).

Session contributions

The working group has been involved with two session organizations. The first one was the 2021 Australian Earth Sciences Convention (AESC), February 2021 Tasmania (Australia). The conference aim was to showcase current trends and advances in earth science, including the latest findings on the deep structure and composition of our planet, our diverse crust and surface environments, developments in the energy and resources sectors and critically, the essential role that geoscience plays in our sustainable future. The second event was ICCC Workshop "Geodesy for Climate Research" March 29-30, 2021. The working group represents two sessions in the event; Session 1 (Hydrology I) and Session 8 (Hydro II).

References

Relevant publications of the group members for the period of 2019-2021 are listed below.

Felsberg, A., De Lannoy, G.J M., Girotto, M., Poesen, J., Reichle, R.H., Stanley, T. with Felsberg, A. (corresp. author) (2021). Global soil water estimates as landslide predictor: the effectiveness of SMOS, SMAP and GRACE observations, land surface simulations and data assimilation. Journal Of Hydrometeorology. doi: 10.1175/JHM-D-20-0228.1 Open Access

Gavahi, K., P. Abbaszadeh, H. Moradkhani, X. Zhan, and C. Hain (2020) Multivariate Assimilation of Remotely Sensed Soil Moisture and Evapotranspiration for Drought Monitoring, Journal of Hydrometeorology, doi: 10.1175/JHM-D-20-0057.1

N Tangdamrongsub, MF Jasinski, P Shellito (2021). Development and evaluation of 0.05° terrestrial water storage estimates using CABLE land surface model and GRACE data assimilation, Hydrology and Earth System Sciences Discussions, 1-45

H Toye, P Zhan, F Sana, S Sanikommu, N Raboudi, I Hoteit (2021). Adaptive ensemble optimal interpolation for efficient data assimilation in the red sea, Journal of Computational Science 51, 101317

N Tangdamrongsub, M Šprlák (2021). The Assessment of Hydrologic-and Flood-Induced Land Deformation in Data-Sparse Regions Using GRACE/GRACE-FO Data Assimilation. Remote Sensing 13 (2), 235

Sadeghi, M., Lun Gao, Ardeshir Ebtehaj, Jean-Pierre Wigneron, Wade T Crow, John T Reager, Arthur W Warrick (2020). Retrieving Global Surface Soil Moisture from GRACE Satellite Gravity Data. Journal of Hydrology.

Xu, Lei., P.Abbaszadeh, H. Moradkhani, N. Chen, X. Zhang (2020) Continental drought monitoring using satellite soil moisture, data assimilation and an integrated drought index, Remote Sensing of Environment, doi: 10.1016/j.rse.2020.112028

Abbaszadeh, P., K. Gavahi, and H. Moradkhani (2020) Multivariate Remotely Sensed and In-situ Data Assimilation for Enhancing Community WRF-Hydro Model Forecasting, Advances in Water Resources, doi:10.1016/j.advwatres.2020.103721

Bechtold, M., De Lannoy, G., Reichle, R., Roose, D., Balliston, N., Burdun, I., Devito, K., Kurbatova, J., Strack, M., Zarov, E. with Bechtold, M. (corresp. author) (2020). Improved Groundwater Table and L-band Brightness Temperature Estimates for Northern Hemisphere Peatlands Using New Model Physics and SMOS Observations in a Global Data Assimilation Framework. Remote Sensing Of Environment, 246, Art.No. 111805. doi: 10.1016/j.rse.2020.111805 Open Access

W Yin, T Li, W Zheng, L Hu, SC Han, N Tangdamrongsub, M Šprlák (2020) Improving regional groundwater storage estimates from GRACE and global hydrological models over Tasmania, Australia, Hydrogeol. J 28, 1809-1825

W Yin, SC Han, W Zheng, IY Yeo, L Hu, N Tangdamrongsub (2020). Improved water storage estimates within the North China Plain by assimilating GRACE data into the CABLE model, Journal of Hydrology 590, 125348

N Tangdamrongsub, SC Han, IY Yeo, J Dong, SC Steele-Dunne (2020) Multivariate data assimilation of GRACE, SMOS, SMAP measurements for improved regional soil moisture and groundwater storage estimates, Advances in Water Resources 135, 103477

Irrgang, C., Dill, R., Boergens, E., Saynisch-Wagner, J., Thomas, M. (2020): Self-validating deep learning for recovering terrestrial water storage from gravity and altimetry measurements. - Geophysical Research Letters, 47, 17, e2020GL089258. https://doi.org/10.1029/2020GL089258

Azimi, S., Dariane, A. B., Modanesi, S., Bauer-Marschallinger, B., Bindlish, R., Wagner, W., Massari, C. (2020). Assimilation of Sentinel 1 and SMAP–based satellite soil moisture retrievals into SWAT hydrological model: the impact of satellite revisit time and product spatial resolution on flood simulations in small basins. Journal of Hydrology, 581, 124367, doi: 10.1016/j.jhydrol.2019.124367. https://doi.org/10.1016/j.jhydrol.2019.124367.

Khaki, M. (2020), Satellite Remote Sensing in Hydrological Data Assimilation. Springer International Publishing, ISBN 978-3-030-37375-7, doi:10.1007/978-3-030-37375-7.

Khaki, M., Hendricks Franssen, H.J., Han, S.C. (2020), Multi-mission satellite remote sensing data for improving land hydrological models via data assimilation. Sci Rep 10, 18791, doi:10.1038/s41598-020-75710-5.

Khaki, M., Ait-El-Fquih, B., Hoteit, I. (2020), Calibrating land hydrological models and enhancing their forecasting skills using an ensemble Kalman filter with one-step-ahead smoothing. Journal of Hydrology, Volume 584, doi:10.1016/j.jhydrol.2020.124708.

Khaki, M., Awange, J. (2020), Altimetry-derived surface water data assimilation over the Nile Basin, Science of The Total Environment, Volume 735, doi:10.1016/j.scitotenv.2020.139008.

Khaki, M., Zerihun, A., Awange, J., Gibberd, M. (2020), Integrating satellite soil-moisture estimates and hydrological model products over Australia, Australian Journal of Earth Sciences, 1-13, doi:10.1080/08120099.2019.1620855.

J. Indu, Akhilesh S Nair, (2020). Assessment of Groundwater Sustainability and Identifying Factors Inducing Groundwater Depletion in India, Geophysical Research Letters, doi/10.1029/2020GL087255

AS Nair, R Mangla, J Indu (2020). Remote sensing data assimilation, Hydrological Sciences Journal, 1-33

Abbaszadeh, P., H. Moradkhani, and D.N. Daescu (2019), The Quest for Model Uncertainty Quantification: A Hybrid Ensemble and Variational Data Assimilation Framework, Water Resources Research, 55, doi: 10.1029/2018WR023629.

Li, B., Rodell, M., Kumar, S., Beaudoing, H.K., Getirana, A., Zaitchik, B.F., et al. (2019). Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges. Water resources research, 55 (9), 7564-7586. doi: 10.1029/2018WR024618 Open Access

S Desamsetti, HP Dasari, S Langodan, ES Titi, O Knio, I Hoteit (2019). Efficient dynamical downscaling of general circulation models using continuous data assimilation, Quarterly Journal of the Royal Meteorological Society 145 (724), 3175-3194

Girotto, M., Reichle, R.H., Rodell, M., Liu, Q., Mahanama, S., De Lannoy, G.J M. (2019). Multi-sensor assimilation of SMOS brightness temperature and GRACE terrestrial water storage observations for soil moisture and shallow groundwater estimation. Remote sensing of environment, 227, 12-27. doi: 10.1016/j.rse.2019.04.001 Open Access

A Shokri, JP Walker, AIJM van Dijk, VRN Pauwels (2019) On the use of Adaptive Ensemble Kalman Filtering to Mitigate Error Misspecifications in GRACE Data Assimilation, Water Resources Research

Khaki, M., Awange, J. (2019), The Application of Remotely Sensed Products to Enhance Model-derived Water Storage Changes over South America. Science of The Total Environment, 647:1557-1572, doi:10.1016/j.scitotenv.2018.08.079.

Khaki, M., Hoteit, I., Kuhn, M., Forootan, E., Awange, J. (2019), Assessing data assimilation frameworks for using multi-mission satellite products in a hydrological context. Science of The Total Environment, 647:1031-1043, doi:10.1016/j.scitotenv.2018.08.032.

Khaki, M., Filmer, M.S., Featherstone, W.E., Kuhn, M., Bui, L. K., Parker, A.L. (2019), A Sequential Monte Carlo Framework for Noise Filtering in InSAR Time Series. IEEE Transactions on Geoscience and Remote Sensing, 1-9, doi: 10.1109/TGRS.2019.2950353

Yang, Y., Lin, P., Fisher, C.K., Turmon, M., Hobbs, J., Emery, C.M., Reager, J.T., David, C.H., Lu, H., Yang, K. and Hong, Y. (2019). Enhancing SWOT discharge assimilation through spatiotemporal correlations. Remote Sensing of Environment, 234, 111450

Morris, M., Chew, C., Reager, J. T., Shah, R., & Zuffada, C. (2019). A novel approach to monitoring wetland dynamics using CYGNSS: Everglades case study. Remote Sensing of Environment, 233, 111417.

Ehalt Macedo, H., Beighley, R. E., David, C. H., & Reager, J. T. (2019). Using GRACE in a streamflow recession to determine drainable water storage in the Mississippi River basin. Hydrology and Earth System Sciences, 23(8), 3269-3277

Stampoulis, D., Reager, J. T., David, C. H., Andreadis, K. M., Famiglietti, J. S., Farr, T. G., ... & Lundgren, P. R. (2019). Model-data fusion of hydrologic simulations and GRACE terrestrial water storage observations to estimate changes in water table depth. Advances in Water Resources, 128, 13-27.

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., & Reager, J. T. (2019). Contributions of GRACE to understanding climate change. Nature Climate Change, 1.

Wang, J., Song, C., Reager, J. T., Yao, F., Famiglietti, J. S., Sheng, Y., & Wada, Y. (2019). Recent global decline in endorheic basin water storages (vol 11, pg 926, 2018). Nature geoscience, 12(3), 220-220.

Purdy, A. J., David, C. H., Sikder, M., Reager, J. T., Chandanpurkar, H., Jones, N. L., & Matin, M. A.(2019). An open-source tool to facilitate the processing of GRACE Observations and GLDAS outputs: An evaluation in Bangladesh. Frontiers in Environmental Science, 7, 155.

Oaida, C.M., J.T. Reager, K.M. Andreadis, C.H. David, S.R. Levoe, T.H. Painter, K.J. Bormann, A.R. Trangsrud, M. Girotto, and J.S. Famiglietti (2019): A high-resolution data assimilation framework for snow water equivalent estimation across the Western United States and validation with the Airborne Snow Observatory. J. Hydrometeor., 0.

W Nie, BF Zaitchik, M Rodell, SV Kumar, KR Arsenault, B Li, A Getirana (2019). Assimilating GRACE into a land surface model in the presence of an irrigation-induced groundwater trend, Water Resources Research 55 (12), 11274-11294

Gebler, S. ; Kurtz, W. ; Pauwels, V. R. N. ; Kollet, S. J. ; Vereecken, H. ; Hendricks Franssen, H. -J. Assimilation of High-Resolution Soil Moisture Data Into an Integrated Terrestrial Model for a Small-Scale Head-Water Catchment Water resources research 55(12), 10358-10385 (2019) [10.1029/2018WR024658]

JWG C.8: Methodology of comparing/validating climate simulations with geodetic data

Chair: Jürgen Kusche (Germany)

Members

- *Felix Landerer (USA)*
- *Vincent Humphrey (USA, Switzerland)*
- *Ben Marzeion (Germany)*
- *Petra Friederichs (Germany)*
- *Henryk Dobslaw (Germany)*
- *Anna Klos (Poland)*
- *Laura Jensen (Germany)*
- *Anne Springer (Germany)*

Activities and publications during the period 2019-2021

The group membership has been consolidated; members are Felix Landerer (USA, Ocean Science), Vincent Humphrey (USA, Climate Science), Ben Marzeion (Germany, Glacier modeling), Petra Friederichs (Germany, Atmospheric Science), Henryk Dobslaw (Germany, Geodesy), Anna Klos (Poland, Geodesy/Troposphere), Laura Jensen (Germany, Geodesy), Anne Springer (Germany, Geodesy), and myself (Jürgen Kusche). Group members have participated in several activities related to the group's ToR including the ICCC workshop; unfortunately the group as a whole has not been too active - this is to blame on the chairman's involvement in several other "challenges" (some related to climate science). Nethertheless, the group has agreed to produce a white paper on the methodology of validating climate simulations with geodetic data (working title) which is meant to address the following questions: "What is meant by 'validating climate simulations'? What different purposes exist? How is it conventionally done in climate science (e.g. which variables, how do we deal with ensembles)? What metrics are/should be used for validation? What is required from geodetic data sets (we consider TWS, water vapor, sea level and ocean mass) from climate model validation perspective? How are long geodetic data sets conventionally constructed, for what purpose, and what are the problems in using them for climate model validation? What new methods of constructing/reconstructing long and dense data sets are being considered? What recommendations should be formulated for the climate community and the geodesy community"

Inter-Commission Committee on Marine Geodesy (ICCM)

President: Yuanxi Yang (China)
Vice President: Heidrun Kopp (Germany)

Structure

Joint Study Group 5.1: Seafloor Geodesy
Joint Study Group 5.2: Ocean tide and vertical datum
Joint Study Group 5.3: Ocean remote sensing and topography survey
Joint Study Group 5.4: Marine positioning and undersea navigation
Joint Study Group 5.5: Ocean disaster monitoring

Overview

This report presents the activities of the entities of ICCM for the reporting period 2019-2021. As shown above, till now ICCM has proposed 5 Joint Study Groups (JSG).

Terms of reference

The Inter-Commission Committee on Marine Geodesy (ICCM) was first proposed by the Chinese National Committee to the IAG Executive Committee (EC) in Kobe, Japan in 2017 and then passed at the Sixth/Seven Meetings of the IAG EC, 2018. The Inter-Commission Committee on Marine Geodesy (ICCM) was formally approved and established following the IUGG General Assembly in Montreal, Canada, 2019.
The main objectives of the ICCM are:

- to shorten the gaps between theory and applications in marine geodesy, and to encourage transdisciplinary integration of the contemporary geodetic sensors, including marine geophysical sensors, oceanic sonar and physical oceanography instrumentation;
- to improve the global realization of the International Terrestrial Reference Frame (ITRF) by connecting the seafloor geodetic network component with the ITRF, and to improve current marine geodetic models by including the space, surface and subsurface geodetic observations;
- to encourage development of marine geodetic methodology, especially for the fusion methods of multi-marine geodetic observations;
- to promote international collaborations in regional marine geodetic surveys, and to develop and establish international conventions for marine geodetic data processing, the seafloor reference frame, and other standards.

ICCM's Steering Committee 2019-2023

President	Yuanxi Yang (China)
Vice President	Heidrun Kopp (Germany)
Commission 1	Chris Danezis (Cyprus)
Commission 2	Xiaoli Deng (Australia)
Commission 3	Cezary Specht (Poland)
Commission 4	Ana Paula Camargo Larocca (Brazil)
IERS	Henryk Dobslaw (Germany)
	Ruediger Haas (Sweden)
GGOS	Marie-Françoise Lalancette-Lequentrec (France)
	Yusuke Yokota (Japan)

According to the last IAG EC meeting minutes, ICCM have finalized the above steering committee.

Summary on activities

Preparing the ToR of each subgroup

The member list has gradually been extended, e.g., the new added Prof. Laurent Testut's from LIENSs Laboratory at La Rochelle University, France, and Prof. Bofeng Li from the Tongji university. With regard to the currently received participants, we have reduced six groups previously planned to be five groups. Three subgroup ToRs have been completed and the left two groups needs to be further discussed and enclosed. A Tencent virtual meeting was held in June 7, 2021 for discussing the preparation plan and for preparing the midterm report of ICCM.

Launched a special issue on Seafloor Geodesy and Acoustic Positioning, the international journal the Marine Geodesy

During March to April, we made arrangements with the Marine Geodesy to publish a series of special issue according to the ICCM missions. In April 9 2021, we have launched one special issue on Seafloor Geodesy and Acoustic Positioning. Till now, we have received five papers, and now the special issue is still open for submitting papers. The submitted manuscripts should describe methods, techniques, models and algorithms in seafloor geodesy and acoustic positioning. Results related to seafloor geodetic data processing and sonar propagation error reduction are encouraged. Topics may include, but not limited to: 1) Acoustic positioning and navigation model of high precision; 2) Surface and subsurface geodetic network processing method; 3) Acoustic ray error processing and efficient ray tracing algorithm; 4) Strategies for the seafloor geodetic station maintenance; Models and algorithm for seafloor geodesy; Subsea multi-sensor navigation.

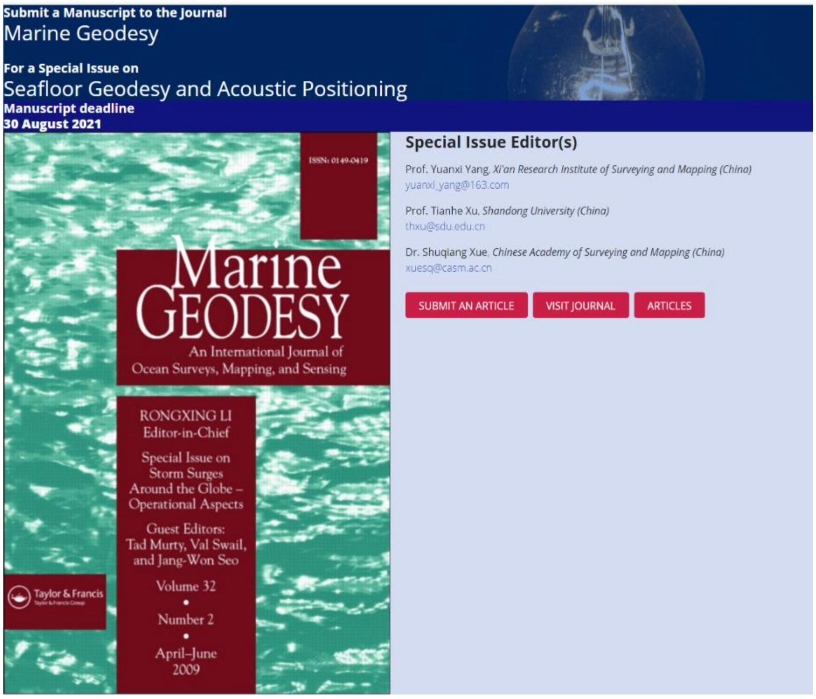


Figure 1. Call for paper web access

(**https://think.taylorandfrancis.com/special_issues/seafloor-geodesy-acoustic-positioning**)

Technology Seminars and symposiums

Marine geodetic datum and under water navigation technology symposium was held in Beijing, June 2,2019 for reporting the new progresses in the marine geodesy and undersea navigation. Seafloor geodesy seminar was held in Beijing during Nov. 11-12 for discussing the key techniques of the seafloor geodesy and the new progresses on the geodetic positioning. During March 23-24 2021, a seminar on the marine positioning, navigation and timing (PNT) was held in Jinan, China, and there are more than 30 scholars participating this seminar.

A marine geodesy and undersea navigation symposium will be held from July 17 to 18, 2021 during the 4th CONGRESS OF CHINA GEODESY AND GEOPHYSICS（CCGG). CCGG is an academic conference to report the latest progress and achievements in theory, technology and application of geodesy and geophysics in China, and to promote interdisciplinary, integrated and interdisciplinary researches.

Summary on activities of study groups

The activities of the ICCM are related namely to research activities carried out by members of its joint sub groups. Their midterm reports specify main research areas under investigation, achieved results and outputs (mainly from their publications). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the preparation progress is is not necessarily the same for all the joint study groups. The activities are gradually covering some of ICCM objectives, such as the development of marine geodetic methodology, especially for the fusion methods of multi-marine geodetic observations, a deep-sea network trial for test the realization of a local seafloor geodetic frame to remedy the International Terrestrial Reference Frame (ITRF) coverage.

Great achievements have been made in developing new models for the marine positioning and undersea navigation, including solving the problems of ocean gross error control, systematic error correction or parameterization, temporal and spatial correlation error processing, precision evaluation and precision calibration. The second activity is development of GNSS-Acoustic (GNSS/A) observation systems which are capable of real-time and long-term monitoring of seafloor crustal deformation. As currently implemented, the GNSS/A measurements are performed using vessels, which restricts temporal resolution and real-time detection of crustal deformation. The next objective is, therefore, to achieve continuous and real-time measurements of GNSS/A using other sea-surface platform rather than vessels. Only one study group have not technical report as this group is ongoing to prepare the ToR. We cannot get contact with the chair of JSG 5.5 to collect the mid-term report, but we only received a report from one member of this group.

Joint Study Group 5.1: Seafloor geodesy

Chair: Pierre Sakic (Germany) [TBD]

Members

Ian Church (Canada)
Valérie Ballu (France)
Shuqiang Xue (China)

Activities and publications during the period 2019-2021

The ToR of JSG5.1 was draft and the objectives are as follows: 1) To shorten the theoretical gaps between the seafloor geodetic frame and Terrestrial Reference Frame (ITRF), and to develop the standards and conventions for GNSS-A data processing; 2) To encourage development of seafloor geodetic methodology and models for high precision positioning, especially for the fusion methods of multi seafloor geodetic observations; 3) To investigate the ocean environment influence on the positioning and to develop ocean environment influence estimation and inversion tools; 4) To monitor deformation on the seafloor and to better understanding tectonic processes and assess related ocean hazards; 5) To promote international collaborations in regional seafloor geodesy.

The activities of JSG5.4 in the period 2020-2021 included in particular:

1. Performed GNSS-acoustic sailing line optimization and the China south sea trial;
2. Proposed resilient functional model and stochastic model for seafloor geodetic positioning;
3. Launched a special issue on Seafloor Geodesy and Acoustic Positioning, the international journal of Marine Geodesy
4. Investigated the ocean environment influence on the positioning;
5. Developed multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning, and acoustic ray tracing tools of high-efficient.

GNSS-acoustic sailing line optimization and the China south sea trial

Bi-symmetrical positioning configuration for seafloor geodesy was proposed where both sailing line and seafloor geodetic network have symmetrical structures. Under the observability condition, generally three seafloor acoustic beacons can be used to determine the three-dimensional position of the submarine vehicle, and the regular triangle configuration should be the optimal configuration. If further considering the time synchronization requirement, we need at least four necessary geodetic stations and one backup station to form the simplest network, then the regular pentagon is the optimal configuration, as shown in Figure 2. As to submarine PNT applications in special regions, the seafloor geodetic network can be realized by extending or densifying the above-mentioned basic configurations. When the regular polygon network cannot be laid due to the limitation of the seafloor topography and sediment conditions, we can minimize the geometric dilution of precision (GDOP) at the network center, and the optimization criterion can be expressed as $\min \mathrm{GDOP} = \min \sqrt{\mathrm{tr}(A^T \mathrm{A})^{-1}}$ where A is the design matrix of the underwater positioning and navigation model. It is definite that the mean GDOP of the regional coverage can be used as the network optimization criterion, which might be more suitable for underwater PNT applications.

Figure 2. Seafloor geodetic Network

Figure 3. Seafloor geodetic station

Applying the above-mentioned seafloor geodetic shelter development strategy, seafloor geodetic location selection criterion and geodetic network layout strategy, we conducted a deep-sea experiment in a sea areas of 3000 m depth in July, 2019. Fig.1 illustrates the seafloor geodetic network and the surface ship tracking lines, where the five seafloor stations adopt the configuration as shown in Figure 4, and the radius of each circle tracking line is about 0.5 times the seawater depth. In addition, a circle tracking line with the radius of 1.5 times the seawater depth and a series of cross lines are laid for locating the station. Based on the developed seafloor geodetic shelter and sufficient verification in the shallow sea experiment, a long-term seafloor geodetic station in the deep-sea area of 3000 m depth was established for the first time, and the preliminary positioning result shows that the internal precision of this station is better than 5 cm.

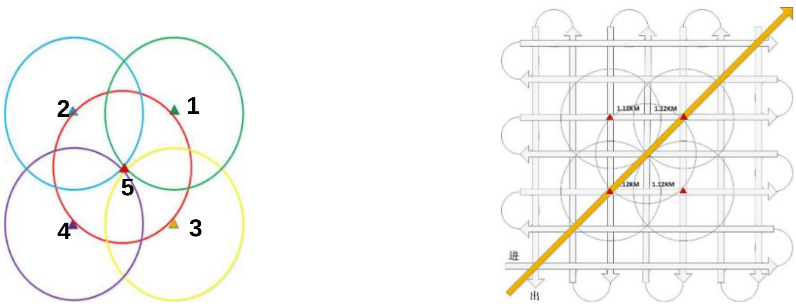


Figure 4. Surface GNSS/acoustic tracking line

Proposed resilient functional model and stochastic model for seafloor geodetic positioning

The Sound velocity error is an important error source of underwater positioning, which mainly includes the uncertainty of sound velocity measurement and the sound velocity error caused by the temporal-spatial variation of the sound speed field. We establish a resilient model to compensate various systematic errors. A simple resilient observational model with range bias and time bias parameters is established, and the resilient observational model with periodic error terms for compensating the sound speed systematic errors of the acoustic ranges are also proposed, and the square root of variance of the coordinate component is better than 0.4 cm and the root mean square errors (RMSE) of the one-way slant range residuals are better than 11 cm.

Based on the constant gradient sound ray tracking model, we derive a mathematical model for the sound ray disturbance analysis about the incident angle, sound velocity gradient and water depth. The results show that, for the same water depth and sound velocity error, the greater the incident angle is, the greater the impact of incident angle perturbation on the sound ray, and the greater the impact of sound ray bending will be. Figure 5 shows that RMS of ranging error is inversely proportional to the elevation angle.

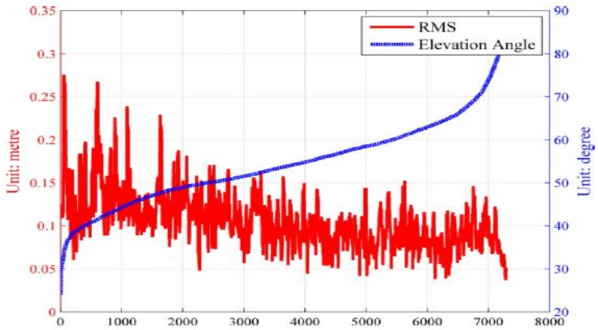


Figure 5. Relationship between ranging error RMS and elevation angle

Establish four stochastic models based on the sound ray incidence angle. The results show that the established incidence angle stochastic models have advantages over the equal weight model, especially that the positioning result of using the segmental cosine model is the best. Moreover, according to the derived function response relation between incident angle disturbance and acoustic ray disturbance, a piecewise exponential function stochastic model of underwater positioning based on incident angle correlation is established. The positioning results of the piecewise-exponential weight function random model are compared with the equal weight model.

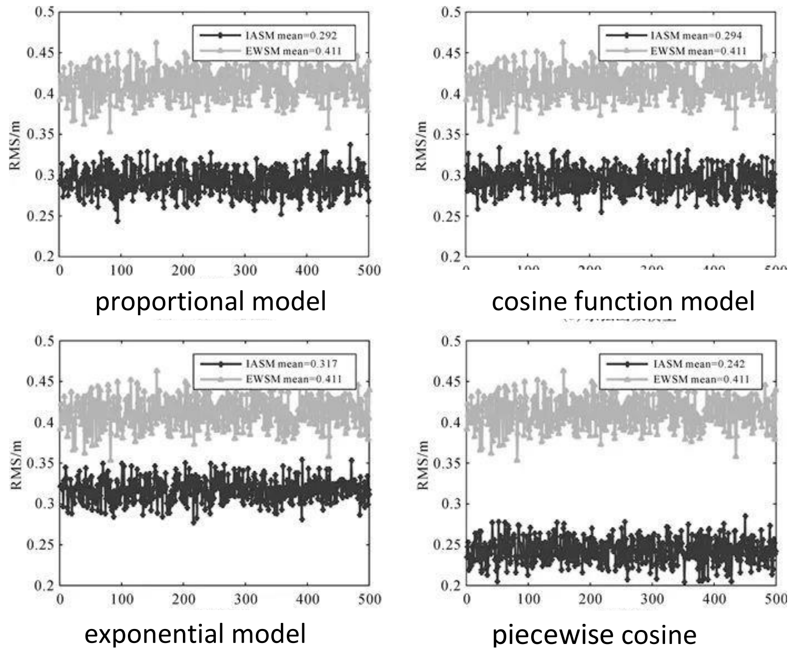


Figure 6. Potential stochastic models

Proposed relationship between the epoch-differential solution and non-differential solution and realize a fast algorithm for seafloor geodetic epoch-differential positioning

Differential approaches have been widely used in geodetic positioning. Seafloor geodetic positioning using the shipborne GNSS/acoustic (GNSS-A) technique is unlike GNSS positioning having synchronous satellite observations, and therefore the epoch-differential approach was proposed to reduce the influence of spatial-temporal systematic errors on the seafloor geodetic positioning. We discuss systematic error sources in the undersea acoustic positioning, and establish conversion formulae between the epoch-differential and non-differential solution. It shows that: (1) the non-differential solution can be converted into the epoch-differential solution requiring only a few of calculations, and this attributes to perform the eigenvalue decomposition upon the differential equivalent weight matrix proposed; (2) the equivalence between the epoch-differential and the non-differential solution is that, the sum of direction-cosines of the observations is zero, i.e., GNSS-A tracking line should be exactly symmetrical in the whole three-dimensional space around the seafloor geodetic station, but this is obviously unrealistic to form a symmetrical geometry in the height direction; (3) For observations with the same elevation angle, the epoch-differential model becomes rank-deficient along the height direction.

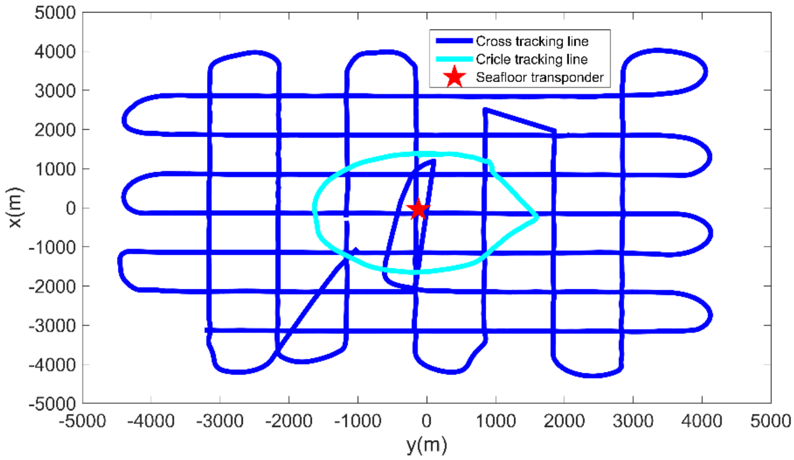


Figure 7. Surface GNSS-A tracking lines

The proposed results have been verified in the China Sea 3000 depth trial as shown in Figure 4. It shows that, the strict differential model regarding the correlations among differential observations can produce a more precise positioning result which more precisely reflects the actual precision level along the height direction. This indicates that, the epoch-differential model ensures the horizontal positioning, but removes some positioning information in the height direction which might be unreliable.

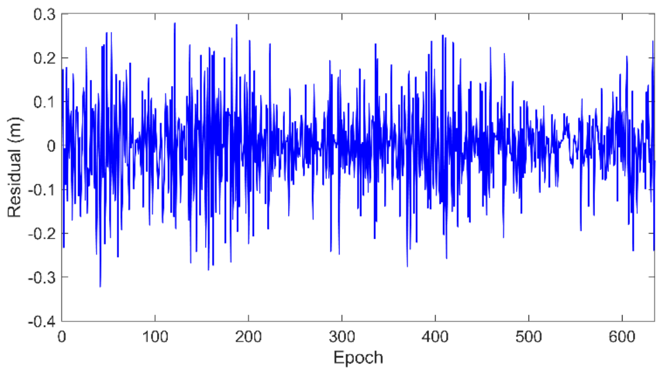
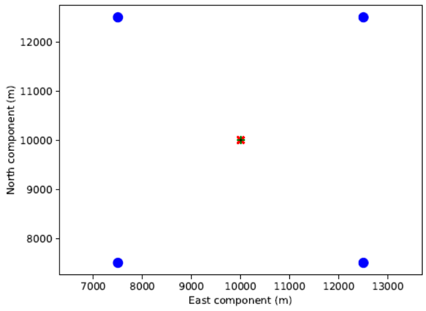


Figure 8. Residuals of differential observations

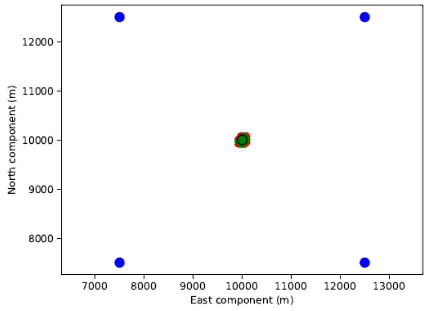
As shown by Figure 8, the differential model can produce a stationary residual sequential that can be utilized to facilitate the outlier detection. The deep-sea acoustic positioning trial uses a medium-frequency about 8Hz sonar system and the nominal precision of the acoustic ranging is better than 0.15m, which is indirectly confirmed by the residual sequential deviation.

Developed multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning and high-efficient acoustic ray tracing positioning algorithm.

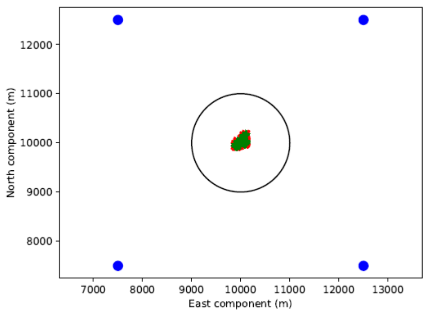
<u>Multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning</u>. Monitoring deformation on the seafloor is a major challenge for modern geodesy; it is a key to better understanding tectonic processes and assess related hazards. The extension of the geodetic networks offshore can be achieved by combining satellite positioning (GNSS) of a surface platform with acoustic ranging to seafloor transponders. This approach is called GNSS-Acoustic (GNSS-A). A least-squares inversion method to get the absolute position of a seafloor transponder array was proposed. This method also considered the baseline lengths and the relative depth-differences between different pairs of them.



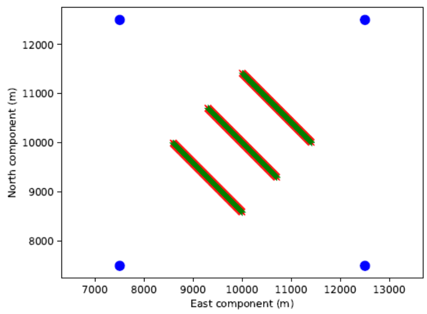
(a) Stationary drift within a 10 m diameter circle



(b) Stationary drift within a 100 m diameter circle



(c) Stationary drift within a 1000 m diameter circle (free trajectory)



(d) Straight trajectories (three passes in a 2000 m × 2000 m square)

Figure 9. Trajectories design for test the proposed results

High-efficient acoustic ray tracing positioning algorithm. The computational efficiency of seafloor geodetic positioning based on the ray tracing is mainly limited to a great amount of calculation of ray inverse problem. We propose two kinds of p-order secant methods to improve the efficiency of traditional method, and the proposed methods can be regarded as a generalization of the traditional secant method from two points to p points for rapidly solving the inverse problem. In the proposed methods, the calculation information in previous iterations is utilized to fit a polynomial model to speed up the algorithm convergence. In the first-kind method, the inverse problem is calculated by solving a polynomial equation approximating the function mapping from the emission angle to the radial distance of the ray. In the second-kind method, the inverse problem is however directly solved by approximating the function mapping from the radial distance to the emission angle. As the first-kind method needs to solve a p-order polynomial equation, the practicability of this method is limited to the complexity of solving the high-order equation, while the second-kind method can directly approximate the solution of the inverse problem, which is more practical and flexible.

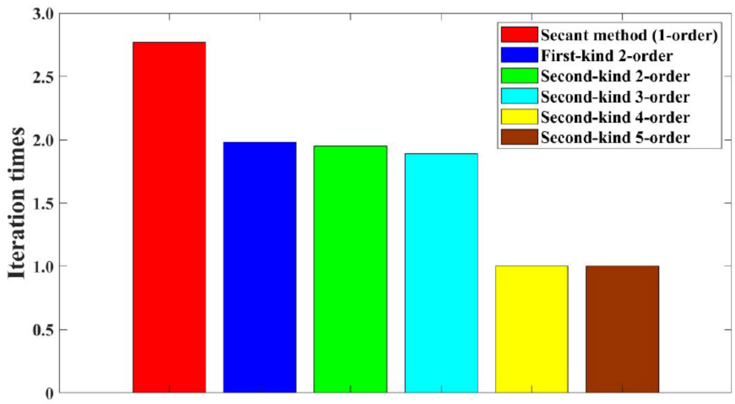


Figure 10. The computational efficiency comparison

The proposed methods have been verified in deep-sea trial. It shows that, the proposed methods can precisely produce the solution of the acoustic ray inverse problem within one iteration, and the computational efficiency of proposed method is about 6 times faster than that of the traditional method as shown in Figure 10.

Publications

Yang, YY and Qin XP (2021), Resilient Observation Models for Seafloor Geodetic Positioning, Journal of Geodesy(accepted)

Yang, YY., Liu, YY., Sun, DJ. et al. Seafloor geodetic network establishment and key technologies. Sci. China Earth Sci. 63, 1188–1198 (2020). https://doi.org/10.1007/s11430-019-9602-3

Sakic P , Chupin C , Ballu V , et al. Geodetic Seafloor Positioning Using an Unmanned Surface Vehicle—Contribution of Direction-of-Arrival Observations[J]. Frontiers in Earth Science, 2021, 9:636156.

Chupin, C.; Ballu, V.; Testut, L.; Tranchant, Y.-T.; Calzas, M.; Poirier, E.; Coulombier, T.; Laurain, O.; Bonnefond, P.; FOAM Project, T. Mapping Sea Surface Height Using New Concepts of Kinematic GNSS Instruments. Remote Sens. 2020, 12, 2656. https://doi.org/10.3390/rs12162656

Sakic, P. , Royer, J. Y. , V Ballu, H Piété, & Beauverger, M. (2019). GEODESEA : une expérience de positionnement géodésique en fond de mer.

Sakic P, V Ballu, Royer J Y . A Multi-Observation Least-Squares Inversion for GNSS-Acoustic Seafloor Positioning[J]. Remote Sensing, 2020, 12(3):448.

Church, I. (2020), Multibeam sonar ray-tracing uncertainty evaluation from a hydrodynamic model in a highly stratified estuary, Marine Geodesy, DOI: 10.1080/01490419.2020.1717695

Liu Y, Shuqiang Xue, Qu G , et al. Influence of the ray elevation angle on seafloor positioning precision in the context of acoustic ray tracing algorithm[J]. Applied Ocean Research, 2020, 105:102403.

Ke,Qi, Guoqing Qu, Shuqiang, Xue et al (2019)). "Analytical optimization on GNSS buoy array for underwater positioning." Acta Oceanologica Sinic.

Zhao S et al (2021). Investigation on total adjustment of the transducer and seafloor transponder for GNSS/Acoustic precise underwater point positioning[J]. Ocean Engineering, 221:108533.

Joint Study Group 5.2: Ocean tide and vertical datum

Chair: Ole Baltazar Andersen (Denmark)

Members

- *Xiaoli Deng (Australia)*
- *Felipe Nievinski (Brazil)*
- *Sajad Tabibi (Luxembourg)*
- *Testut Laurent (France)*

Activities and publications during the period 2019-2021

The activities of JSG5.4 is ongoing to prepare the ToR and the objectives.

Joint Study Group 5.3: Ocean remote sensing and topography survey

Chair: Bofeng Li (China)
Co-Chair: Rongxing (Ron) Li, Fanlin Yang (China)

Members

- *Samuel F. Greenaway, NOAA*
- *Brian R. Calder, U. of New Hampshire*
- *Ian William Church, U. of New Brunswick*
- *Chung-Yen Kuo, Taiwan*

Activities of the group

Due to the pandemic, the planned group's activities have been delayed. However, during the period of 2021-2023, the group aims to establish continuous online meetings to discuss and address research challenges on the topic of ocean remote sensing and topography survey and to hopefully achieve the main objectives of this study group.

Achievements and results

Some of the ocean remote sensing and topography survey research outcomes of the group members are listed below:

- A Simplified calibration method for multibeam footprint displacements due to non-concentric arrays: when the offset between the transmitter and the receiver in the multibeam is large, neglecting the offset will introduce depth errors into the multibeam footprints. To solve the issues, Yang et al. (2020) drew on the advantages of both the virtual concentric cone algorithm (VCCA) and the NCCA, and proposed a simplified method. By using two separately intersecting triangles, the analytical expression of the footprint coordinates can be directly developed, which avoids calculating the complex hyperbolic equations. Consequently, the proposed calibration method is relatively simple with less computational complexity, which has significance in improving the efficiency of data processing.
- An automatic sidelobe effect suppression method for multibeam water column images: Yang et al (2019) proposed an adaptive soft threshold denoising algorithm for the water column images (WCI). The WCI data are divided into background areas and target-noise mixing areas by analyzing the mathematical features of all angle sequences; thus, the target, noise, and sidelobe artefacts are separated using adjustable threshold parameters and by suppressing noise and sidelobe artefacts to obtain a clearer image. Lastly, the measured data

are used for verification. The results indicate that the algorithm has a certain reference value for sidelobe suppression of multibeam WCI.

- Construction of multibeam automatic seabed sediment classification system: Cui and Yang et al. (2019; 2021a; 2021b) summarized the latest progress and technical architecture of the current acoustic seabed sediment classification technology, and compared and discussed the application effects of classic classification methods in large-scale multibeam data. On this basis, a feature optimization method based on fuzzy ranking and a deep learning classification method based on DBN are proposed, which overcomes the problem of high-dimensional acoustic feature optimization, and further improves the efficiency and stability of the seabed sediment classification modeling.
- Propagated Uncertainty Models for the airborne LiDAR bathymetry (ALB) and noises removal for ALB: Yang et al studied the various uncertainty sources for an ALB measurement and proposed a uncertainty model that considering ten different effects from four aspects: the device aspect (laser pointing deflection, trajectory uncertainty, and boresight/lever arm offset), environmental aspect (atmospheric limitation, refraction on the sea surface, refraction in water, scattering in water, and water level fluctuation), target aspect (irregular bottom), and other aspect (accuracy of coordinate transformation model). In addition, Yang et al (2020) also proposed a bidirectional cloth simulation filtering (BCSF) method to avoid current filtering algorithms' limitations, such as cannot identify negative anomalies or avoid over-filtering of the data.
- Registration and merging for seabed points cloud from ALB and multibeam echo sounder (MBES): To reduce the effects of point density and data gaps on the performance of registration method, Yang et al. (2021) proposed a registration algorithm based on Point-to-TIN model for airborne LiDAR bathymetry (ALB) and multibeam echo sounder (MBES) point clouds. The method was tested using the dataset around Yuanzhi Island in the South China Sea. The results indicate that the proposed method performs well for the registration of ALB and MBES datasets, with advantages in accuracy and robustness.

Interactions with the IAG Commissions

The Scientific Assembly of the International Association of Geodesy (IAG) is going to be held in Beijing, China on June 28–July 2, 2021, and a number of the group members had submitted papers concerning the research topics, such as multibeam data processing, et al.

Publications

Bu, X., Yang, F., Ma, Y., Wu, D., Zhang K., Xu. F., (2020). “Simplified calibration method for multibeam footprint displacements due to non-concentric arrays”. Ocean Engineering, 197.

Liu, H., Yang, F., Zheng, S., Li, Q., Li, D., and Zhu, H., (2019), "A method of sidelobe effect suppression for multibeam water column images based on an adaptive soft threshold", Applied Acoustics, (148):467-475.

Cui, X., Xing, Z., Yang, F., Fan, M., Ma, Y., and Sun, Y., (2019). “A method for multibeam seafloor terrain classification based on self-adaptive geographic classification unit”. Applied Acoustics, (157):107029

Cui, X., Liu, H., Fan, M., Ai, B., Ma, D., and Yang F., (2021). “Seafloor habitat mapping using multibeam bathymetric and backscatter intensity multi-features SVM classification framework”. Applied Acoustics, (174):107728

Cui, X., Yang, F., Wang, X., Ai, B., Luo Y., and Ma, D., (2021). “Deep learning model for seabed sediment classification based on fuzzy ranking feature optimization”. Marine Geology, (432):106390

Yang, A., Wu, Z., Yang, F., Su, D., Qi, C., (2020). “Filtering of airborne LiDAR bathymetry based on bidirectional cloth simulation”. ISPRS Journal of Photogrammetry and Remote Sensing, 163:49-61.

Wang, X., Yang, F., Zhang, H., (2021). "Registration of Airborne LiDAR Bathymetry and Multibeam Echo Sounder Point Clouds." IEEE Geoscience and Remote Sensing Letters, doi: 10.1109/LGRS.2021.3076462.

Joint Study Group 5.4: Marine positioning and undersea navigation

Chair: Keiichi Tadokoro (Japan)

Members

- *Pierre Sakic (Germany)*
- *Stéphane Calmant (France)*
- *Tianhe Xu (China)*

Activities and publications during the period 2019-2021

The activities of JSG5.4 were firstly concentrated on precise data processing method of marine geodetic observation. Considering the complex ocean observation environment and the application of navigation and positioning, it is necessary to systematically solve the problems of ocean gross error control, systematic error correction or parameterization, temporal and spatial correlation error processing, precision evaluation and precision calibration. The research of the above methods can provide technical support for marine geodetic datum positioning and marine acoustic navigation. The second activity is development of GNSS-Acoustic (GNSS/A) observation systems which are capable of real-time and long-term monitoring of seafloor crustal deformation. As currently implemented, the GNSS/A measurements are performed using vessels, which restricts temporal resolution and real-time detection of crustal deformation. The next objective is, therefore, to achieve continuous and real-time measurements of GNSS/A using other sea-surface platform rather than vessels.
The activities of JSG5.4 in the period 2020-2021 included in particular:

1. A systematic error compensation model of observation model combined with KF based on the random walk model is proposed to eliminate the influence of systematic error for marine acoustic navigation and positioning.
2. An inversion method of ocean sound speed space-time field based on neural network algorithm is developed and applied to ocean topographic survey to improve its sounding accuracy.
3. Development and operation test of the measurement systems of GNSS/A installed on an Unmanned Surface Vehicle (USV) and a moored buoy.

Marine acoustic navigation and positioning method based on systematic error compensation and adaptive robust Kalman filtering

In order to better explore the marine geography and physical environment, the construction and maintenance technology of marine geodetic datum need to be solved and improved. The data processing method of marine precise observation plays an important role in the construction of marine geodetic datum.

The accuracy of underwater acoustic positioning is greatly influenced by both systematic error and gross error. Aiming to the above problem, a robust zero-difference Kalman filter based on the random walk model and the equivalent gain matrix is proposed (Wang et al., 2020). The proposed algorithm is verified by the simulation experiment and a real one for underwater acoustic positioning. Figure 11 shows the calculation results of robust zero-difference Kalman filter (R-KF). The result proves that the R-KF can estimate the systematic errors by the random walk process, and provide robust solutions by using the equivalent gain matrix, which has higher precision and stability for underwater acoustic positioning.

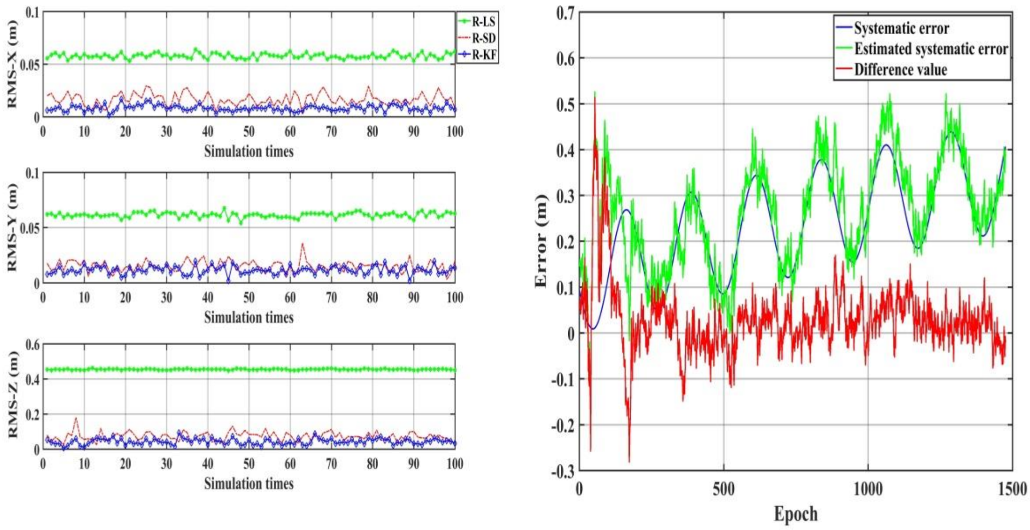


Figure 11. The calculation results of different algorithms (left) and the estimated results of systematic error (right)

In order to further verify the effectiveness of the R-KF algorithm, the acoustic positioning data of single transponder is used. From Table 1, compared with the robust least square (R-LS) and the robust single-difference (R-SD), the RMS of the validated residuals of the R-KF is greatly reduced from 1.63 m and 1.81 m to 0.85 m respectively, which proves the higher precision of R-KF.

Table 1. The residuals statistics of different algorithms

Method	**RMS (m)**	**Max (m)**	**Min (m)**
LS	1.73	2.16	0.99
SD	1.91	2.59	1.39
KF	1.24	2.12	0.51
R-LS	1.63	2.17	0.92
R-SD	1.81	2.55	1.26
R-KF	0.85	1.69	0.04

Autonomous underwater vehicle (AUV) acoustic navigation is challenged by unknown system noise and gross errors in the acoustic observations caused by the complex marine environment. Since the classical unscented Kalman filter (UKF) algorithm cannot control the dynamic model biases and resist the influence of gross errors, an adaptive robust UKF based on the Sage-Husa filter and the robust estimation technique is proposed for AUV acoustic navigation (Wang et al., 2020). The effectiveness of the algorithm is verified by the simulated long baseline positioning experiment of the AUV. Figure 12 shows that the adaptive robust UKF can estimate system noise using the Sage-Husa filter and achieve robust estimation with the equivalent gain matrix. Therefore, the robust UKF performs as the best algorithm in terms of positioning accuracy and reliability.

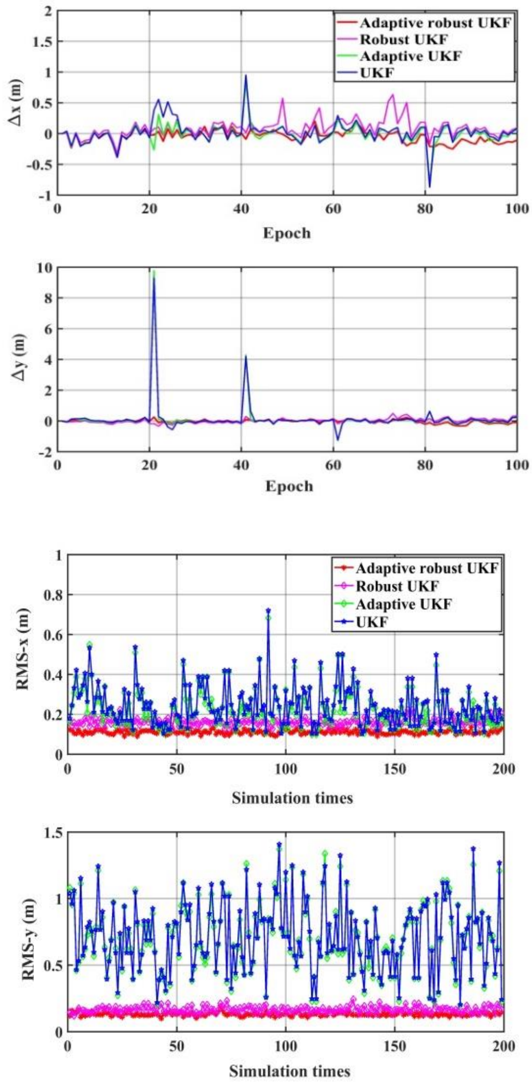


Figure 12. The difference between the true value (left) and the calculation value and the statistical RMS-x and RMS-y of 200 simulations (right).

Inversion method of ocean sound speed space-time field

Sound speed error is the main error source of marine acoustic navigation and positioning. In order to correct the influence of sound speed error, the key point is to obtain the real-time ocean sound velocity profile.

Aiming at the high-precision construction of sound speed field (SSF) in the complex marine environment, a sound speed field model based on back propagation neural network (BPNN) by considering the correlation of learning samples is proposed (Wang et al., 2020). The proposed algorithm is validated by the global Argo data as well as compared with the spatial interpolation and the empirical orthogonal function (EOF) algorithm. Figure 13 shows that present the construction results of sound velocity profile in the two selected positions. From the results, we can see that the sound speed by four algorithms differs little from the true values due to the small variation of sound speed in the deep-sea isotherm. In the main thermocline and the seasonal thermocline, the performance of spatial interpolation method is poor because of the obvious change of sound speed with depth. The EOF algorithm can improve the accuracy of sound speed construction through the orthogonal function compared to the spatial interpolation method. The BPNN algorithm can fully use the measured environmental parameters to construct the real sound speed field, and the construction accuracy is significantly improved especially in the region where the sound speed changes greatly.

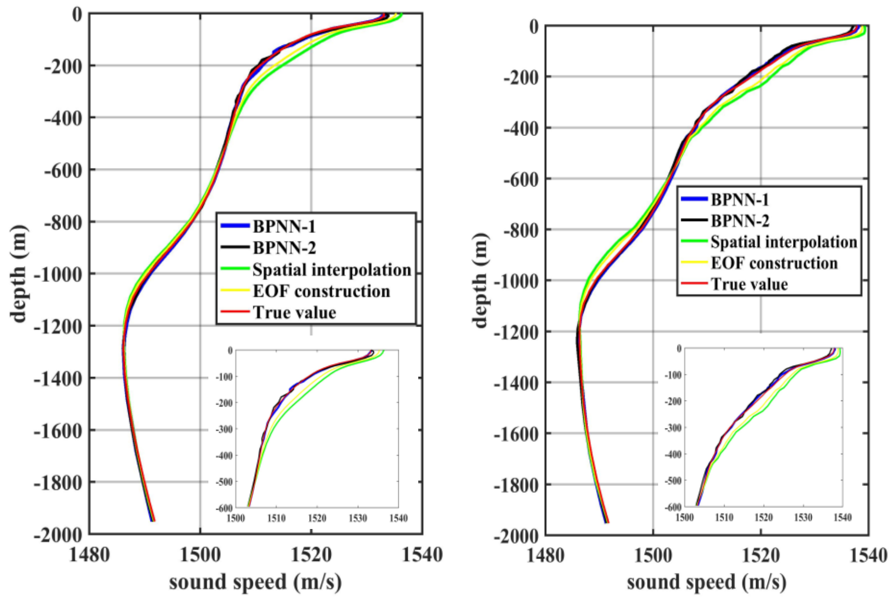


Figure 13 The comparison of SSPs for different algorithm

As a marine environmental parameter, sound velocity has an important impact on sound propagation in the ocean. In the same sea area, the sound velocity profile (SVP) changes dynamically due to the influence of marine environment, season change and other factors. To accurately obtain the SVP of seawater in time and to improve the underwater positioning accuracy for marine research and development, a method of SVP inversion and prediction based on radial basis function (RBF) neural network is proposed (Yu et al., 2020). The proposed SVP prediction method is verified with the Argo data of At-lantic Ocean from 2004 to 2018. In the Figure 14, V_0 is the actual SVP of the sea area, V_1 is the monthly average SVP, V_2 is the SVP predicted by the BP neural network, V_3 is the SVP predicted by the RBF neural network, V_4, V_5, and V_6 represent the difference between V_1 and V_0, the difference between V_2 and V_0, and the difference between V_3 and V_0 respectively. As shown in Figure 14, the prediction accuracy based on the BPNN and RBFNN respectively are significantly better than that of the average sound velocity method. Especially in shallow water, the accuracy of the SVPs predicted is greatly improved by involving the sea surface temperature and salinity in the construction of the prediction models.

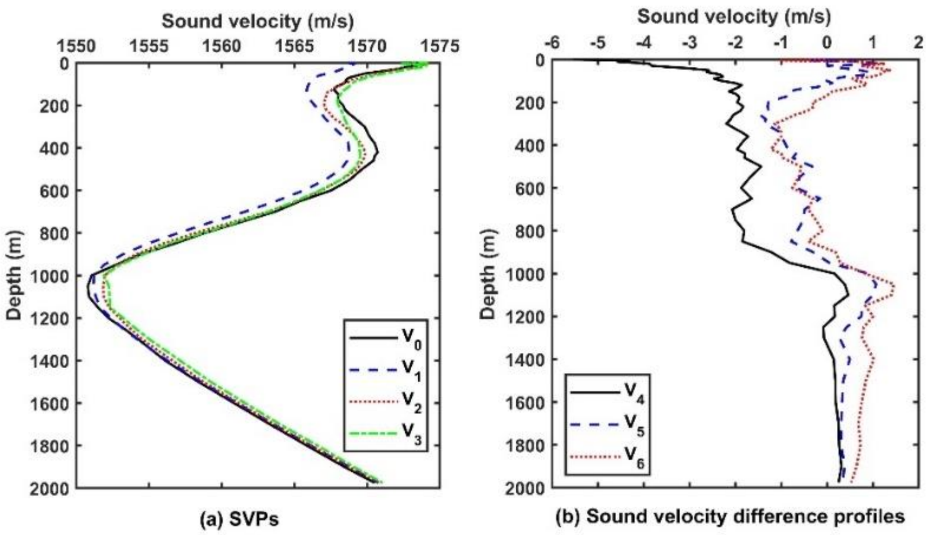
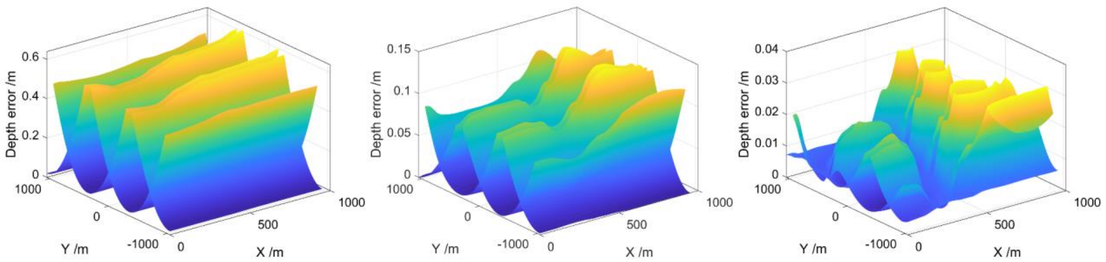


Figure 14 Sound velocity profile prediction results in May 2018

Based on the sound velocity profile inversion method, a method for correcting underwater topography distortion is proposed (Liu et al., 2021). The method can reduce the representative error of sound velocity profile to improve the precision of sounding. The proposed algorithm is verified by three types of experiments based on measured SVPs. As shown in Table 2, compared with these sounding errors calculated by Method-1 (Max 0.6397; Mean 0.2000; RMS 0.2577; MRE 0.4300) and Method-2 (Max 0.1448; Mean 0.0211; RMS 0.0223; MRE 0.0890), these of Method-3 are smaller (Max 0.0325; Mean 0.0325; RMS 0.0325; MRE 0.0180). The RMS values of sounding errors of Method-3 are 54.79% and 91.39% lower than Method-2 and Method-1, respectively. According to Figure 15, among these methods, the sounding error calculated by Method-3 is the smallest in UUT. The above results can improve that the proposed method has a high precision for the multi-beam sounding. Meanwhile, the distortion of underwater topography can be efficiently corrected by the proposed method.

Table 2 Various sounding errors calculated by the three methods in UUT(Max, Min and Mean represent the maximum sounding error, the minimum sounding error and the mean sounding error, respectively, and the unit is m)

Method	Max	Min	Mean	MRE	RMS
Method-1	0.6397	0.0183	0.2000	0.4300	0.2577
Method-2	0.1448	1.5E-07	0.0363	0.0890	0.0491
Method-3	0.0324	2.2E-07	0.0211	0.0180	0.0222



(a) (b) (c)

Figure 15 Sounding errors calculated by three methods in UUT. (a) Method-1; (b) Method-2; (c) Method-3.

New system for continuous and real-time GNSS/A measurements using USV and moored buoy

A compact GNSS/Acoustic experimental instrument was developed and installed in an Unmanned Surface Vehicle (USV) with the length of 3 m (Sakic et al., 2021). The system was tested from July 23 to 25, 2019 in the shallow, 40 m, waters of the Bay of Brest, France. The test was performed with three different acquisition protocols: 1) the USV navigated for about 20–30 min along repeated circles with diameters of 10 m, 2) the USV remained stationary for 10–15 min just above each transponder, and 3) the USV remained stationary during 1 hour just above the barycenter of the three seafloor transponders. The test results show a repeatability of ~5 cm in the locations of the transponders. Post-processing of the GNSS data, instead of Real-Time Kinematic (RTK) positioning during the test, significantly improved the travel time residuals of acoustic signal. In addition, it was also considered supplementary Direction-of-Arrival observations (acoustic ray's reception angles) in the data processing (Sakic et al., 2021). These works were the preliminary tests related to the geodetic network of the FOCUS project, combining BOTDR optical fiber deformation monitoring and precise acoustic positioning off the coasts of Sicily (Gutcher et al., 2019). This is the first operational geophysics-oriented GNSS/A experience in Europe. In parallel, the European group engaged discussions regarding common exchange standards with the American community federated under the leadership of the UNAVCO (Sakic et al., 2020).

The Japanese group of JAMSTEC (Japan Agency for Marine-Earth Science and Technology) and Tohoku University developed a GNSS/Acoustic observation system mounted on another USV, Wave Glider (Iinuma et al., 2021). The acquired data are transmitted to land via satellite communication. The equipment has already been used for the GNSS/A observations at Japan Trench, and it efficiently retrieve data at several seafloor transponders.

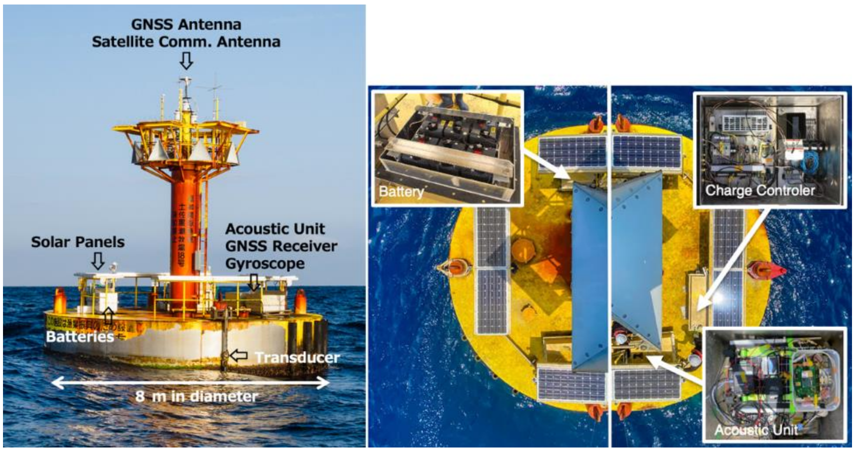


Figure 6. GNSS/A measurement system mounted on the moored buoy. (Left) Side view and (Right) top view.

Tadokoro et al. (2020) reported observation system for GNSS/A technique mounted on a moored buoy of 8-m diameter located at more than 30 km from the Japanese coast (Figure 6). The long-term operation test was performed for almost three years, from March 28, 2018 to January 15, 2021. The continuous acoustic ranging between the buoy and the three seafloor transponders was succeeded for 6 and 10 months in 2019 and 2020-2021, respectively (Figure 7) which was interrupted due to poor power supply during the winter season before it was improved in 2020. The total number of acoustic ranging was 257,413 times. The data of the acoustic ranging, the GNSS positioning employed the PPP-AR technique, and the gyroscope were transmitted to the land base station via a commercial satellite communication network. Because some troubles have happened on the modem and the cable of the satellite communication, only 69 % of acoustic ranging data were received at the land base station. The seafloor position, the barycenter position of seafloor transponder array, was estimated with the method of Kinugasa et al. (2020) for the period between August 18, 2020 and January 15, 2021. The present test site is under the strong ocean current, and it was expected that the sound speed structure under the sea had noticeable amount and temporal variation of horizontal gradient. The method used here estimates the horizontal gradient of sound speed structure and its temporal change as well as the seafloor position using the acoustic travel-time data for 28 days employed the B-spline function. The positioning result are shown in Figure 8. The RMS error of the seafloor position was about 3 cm.

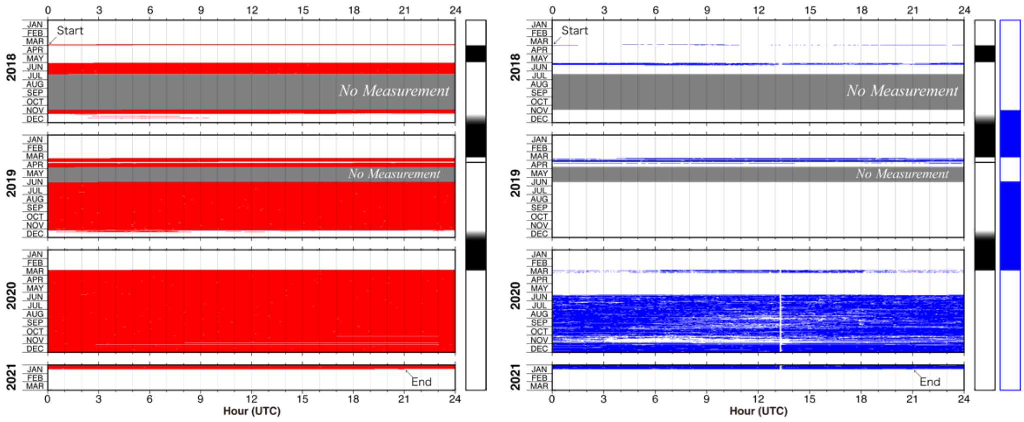


Figure 7. Result of three-years operation test. Red and blue bars show periods of (left) acoustic ranging and (right) data transmission to the ground base station. Periods of no power supply and of no connected satellite modem are indicated by vertical black and blue bars, respectively.

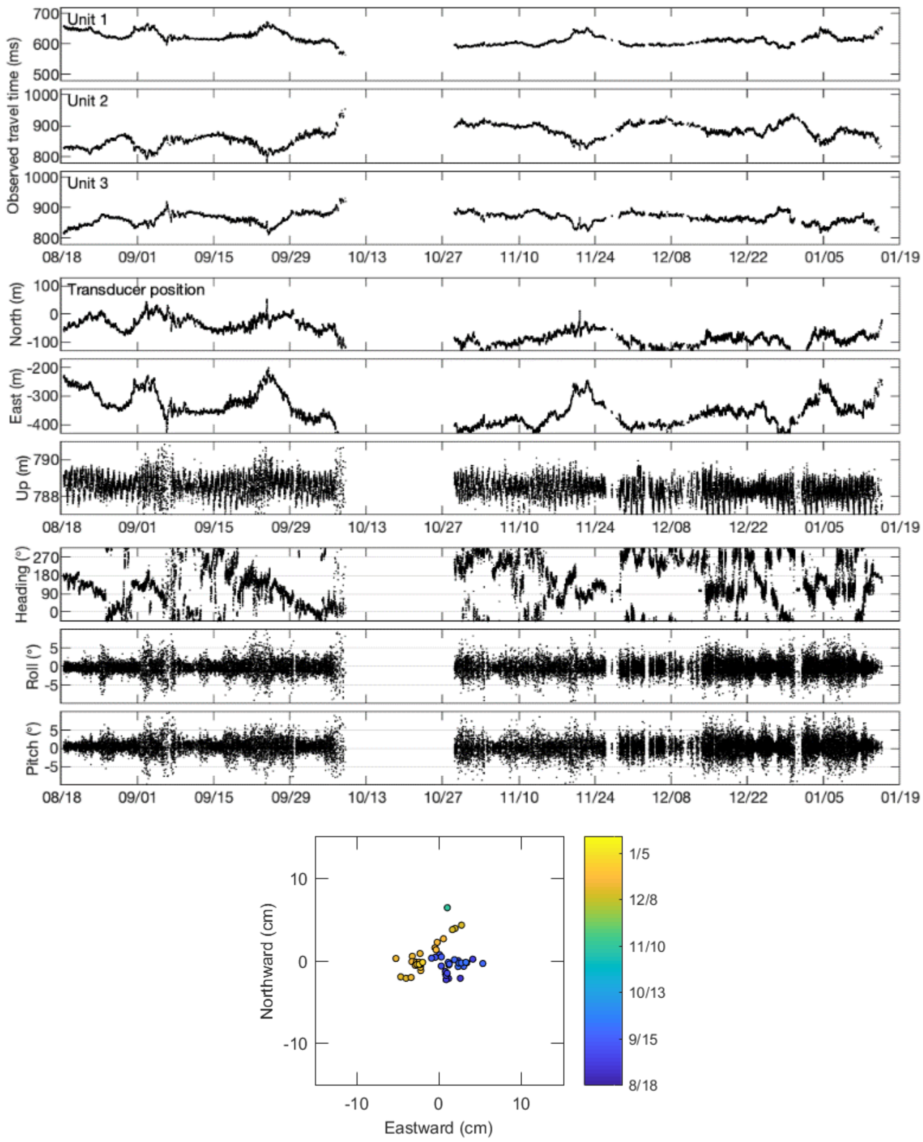


Figure 8. (a) Acoustic travel time for the three seafloor transponders, (b) Transducer position w.r.t. the local coordinate whose origin is 32.48662°N and 133.20850°E, (c) attitude of the buoy, and (d) 28-days averaged barycenter position of seafloor transponder array.

References (Including Publications)

Gutscher, M.-A., Royer, J.-Y., Graindorge, D., Murphy, S., Klingelhoefer, F., Aiken, C., Cattaneo, A., Barreca, G., Quetel, L., Riccobene, G., Petersen, F., Urlaub, M., Krastel, S., Gross, F., Kopp, H., Margheriti, L., and Beranzoli, L. (2019). Fiber optic monitoring of active faults at the seafloor: I the FOCUS project. Photoniques, 3, 32 – 37. doi: 10.1051/photon/2019S432

Iinuma, T., M. Kido, Y. Ohta, T. Fukuda, F. Tomita, and I. Ueki (2021) GNSS-Acoustic Observations of Seafloor Crustal Deformation Using a Wave Glider, *Front. Earth Sci.*, 9, 87, doi: 10.3389/feart.2021.600946

Kinugasa, N., K. Tadokoro, T. Kato, and Y. Terada (2020) Estimation of temporal and spatial variation of sound speed in ocean from GNSS-A measurements for observation using moored buoy, *Prog. Earth Planet Sci.*, 7, 21, doi:10.1186/s40645-020-00331-5.

Liu, Y., Xu, T., Wang, J., and Mu, D. (2021) Multibeam underwater topography distortion correction based on SVP inversion. Journal of Marine Science and Technology. (Under review)

Sakic, P., Ballu, V., Kopp, H., Lange, D., and Royer, J.-Y. (2020). Towards common file formats and data standards for seafloor geodesy. Community Whitepaper for UNAVCO’s “Future Directions for Seafloor Geodesy” Committee.

Sakic, P., C. Chupin, V. Ballu, T. Coulombier, P. Y. Morvan, P. Urvoas, M. Beauverger, and J. Y. Royer (2021) Geodetic Seafloor Positioning Using an Unmanned Surface Vehicle—Contribution of Direction-of-Arrival Observations, *Front. Earth Sci.*, 9, 184, doi: 10.3389/feart.2021.636156

Tadokoro, K., N. Kinugasa, T. Kato, Y. Terada, and K. Matsuhiro (2020) A Marine-Buoy-Mounted System for Continuous and Real-Time Measurment of Seafloor Crustal Deformation, *Front. Earth Sci.*, 8, 123, doi: 10.3389/feart.2020.00123

Wang J. T., Xu T. H., and Wang Z J. (2020) Adaptive Robust Unscented Kalman Filter for AUV Acoustic Navigation, Sensors, 2020, 20(1), 60. https://doi.org/10.3390/s20010060

Wang, J., Xu, T., Zhang, B., and Nie, W. (2020). Underwater acoustic positioning based on the robust zero-difference Kalman filter. Journal of Marine Science and Technology. 1-16. https://doi.org/ 10.1007/s00773-020-00766-x.

Wang, J., Xu, T., Nie, W., and Yu, X. (2020). The construction of sound speed field based on back propagation neural network in the global ocean. Marine Geodesy, 43(6), 1-14. https://doi.org/ 10.1080/01490419.2020.1815912.

Yu, X., Xu, T., and Wang, J. (2020) Sound Velocity Profile Prediction Method Based on RBF Neural Network. China Satellite Navigation Conference (CSNC) 2020 Proceedings: Volume III. CSNC 2020. Lecture Notes in Electrical Engineering, vol 652. Springer, Singapore. https://doi.org/10.1007/978-981-15-3715-8_43

Joint Study Group 5.5: Ocean disaster monitoring

Chair: Morelia Urlaub (Germany)

Members

Lifeng Bao (China)

Activities and publications during the period 2019-2021

The activities of JSG5.4 were to investigate the relevant literatures to propose the ToR and the Objectives. The investigations of JSG5.4 in the period 2019-2021 included in particular: 1) Development of Earth Observations services for Monitoring Marine Hazards; 2) 2 influence studying of main ocean disaster (storm surge) for coastal areas; 3) Impact of ocean tidal changes for coastal flooding.

Development of Earth Observations services for Monitoring Marine Hazards

In the recent years, Earth observations (EO), and in particular satellite remote sensing, provide invaluable information: satellite-borne sensors allow an effective monitoring of the quasi-global ocean, with synoptic views of large areas, good spatial and temporal resolution, and sustained time-series covering several years to decades (Melet et al. 2020). Satellite observations offer great potential for a long-term, synoptic, and rather high-frequency monitoring of the Earth's surface, thanks to a variety of sensors. The use of EO to monitor coastal metocean conditions, coastland hydro-geo-morphological setting, and hazards has significantly developed with the increasing number of satellites with radar sensors.

Benveniste et al. (2020) provide a tour of satellite missions for ocean Hazards Monitoring, of relevant applications, as well as the downstream International Services such as the Copernicus Ocean and Land Monitoring Services. Earth observation (EO) satellite remote sensing provides global, repetitive and long-term observations with increasing resolution with every new generation of sensors. They permit the monitoring of small-scale signals like the ones impacting the coastal zone. The Earth observations (EO) product have many applications, including sea surface temperature, sea-level variations and trends, wave height, hurricane monitoring, storm surge monitoring, sediment transport and coastal Erosion. Significant wave height (SWH) was derived from the radar altimeter measurement. Figure 4 shows an example of satellite-derived climatology for the month of January estimated in the ESA GlobWave Project. The SWH implication for safeguarding ships in extreme weather. As an example, while Hurricane Florence was impacting.

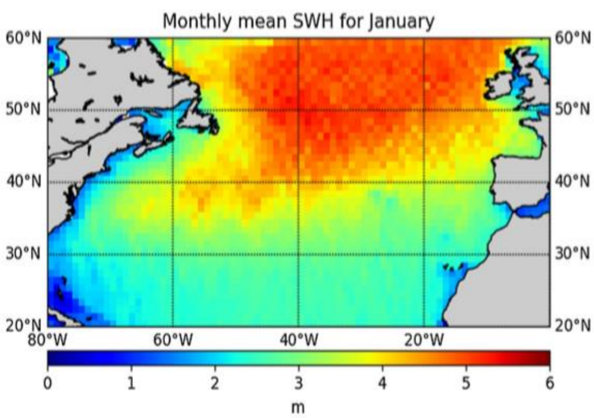


Figure 4 Significant wave height (SWH) as derived from the radar altimeter measurement for the month of January. Source: GlobWave, SatOC.

Influence studying of main ocean disaster (storm surge) for coastal areas

Storm surge is one of the most serious ocean disasters in the world. Risk assessment of storm surge disaster for coastal areas has important implications for planning economic development and reducing disaster losses (Marcos et al. 2019; Couasnon et al. 2020; Ganguli et al. 2020). Coastal flooding is caused by a combination of factors, among which storm surges and wind waves are of major relevance due to their potentially large contributions to coastal extreme sea levels and their widespread effects, severe storm episodes may lead to extreme storm surges, and at the same time, to heavy precipitation and high river runoff. Quantifying compound flood hazard under climate change poses a particular challenge in geodesy.

Based on global scale numerical simulations of these storm surges and wind waves, Marcos et al. (2019) investigated the relationship between extreme storm surges and waves along the world coastlines. they found that in more than half of the coastal regions, storm surges tend to be accompanied by large wind waves, thus increasing the potential coastal flooding. Hence, for a given level of probability, neglecting these dependencies leads to underestimating extreme coastal water levels. Translated in terms of return periods, this means that along 30% of global coastlines, extreme water levels expected at most once in a century without considering dependence between storm surges and waves become a 1 in 50 - year event. The joint 50 - year return levels for storm surges and wave height Hs are mapped in Figures 8a and 8b for coastal grid points where there is dependence between both extreme values. The median value in the ratio of increase along the coastal regions where there is dependence between surge and waves is 2.5 and maxima values reach a twentyfold increase (Figure 8).

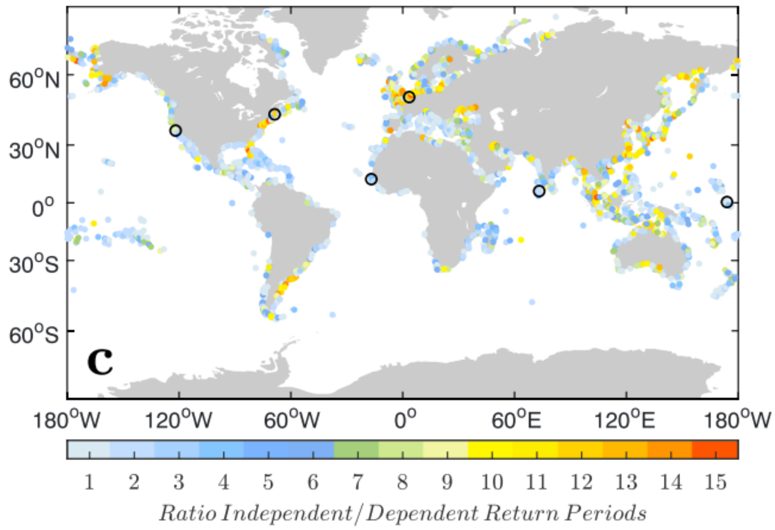


Figure 8. Ratio between the joint return period (50-year) and the independent return periods assuming independence, with selected grid points highlighted (Marcos et al. 2019).

Ganguli et al. (2020) combined projected storm surges and river floods with probabilistic, localized relative sea - level rise scenarios to assess the future compound flood hazard over northwestern coastal Europe in the high (RCP8.5) emission scenario. They used high - resolution, dynamically downscaled regional climate models to drive a storm surge model and a hydrological model, and analyze the joint occurrence of high coastal water levels and associated river peaks in a multivariate copula - based approach. Their results suggest decreasing compound flood hazard over the majority of sites by 2050s (2040–2069) compared to the reference period (1985–2005), an increase in projected compound flood hazard is limited to around 34% of the sites. Further, they show the substantial role of sea - level rise, a driver of compound floods, which has frequently been neglected.

Impact of ocean tidal changes for coastal flooding

Nuisance flooding (NF) is defined as minor, nondestructive flooding that causes substantial, accumulating socioeconomic impacts to coastal communities. While sea-level rise is the main driver for the observed increase in NF events (Li et al. 2021). Li et al. (2021) first show that secular changes in tides also contribute. An analysis of 40 tidal gauge records from U.S. coasts finds that, at 18 locations, NF increased due to tidal amplification, while decreases in tidal range suppressed NF at 11 locations. Estuaries show the largest changes in NF attributable to tide changes, and these can often be traced to anthropogenic alterations. Limited long-term measurements from estuaries suggest that the effects of evolving tides are more widespread than the locations considered here. The total number of NF days caused by tidal changes has increased at an exponential rate since 1950, adding ~27% to the total number of NF events observed in 2019 across locations with tidal amplification.

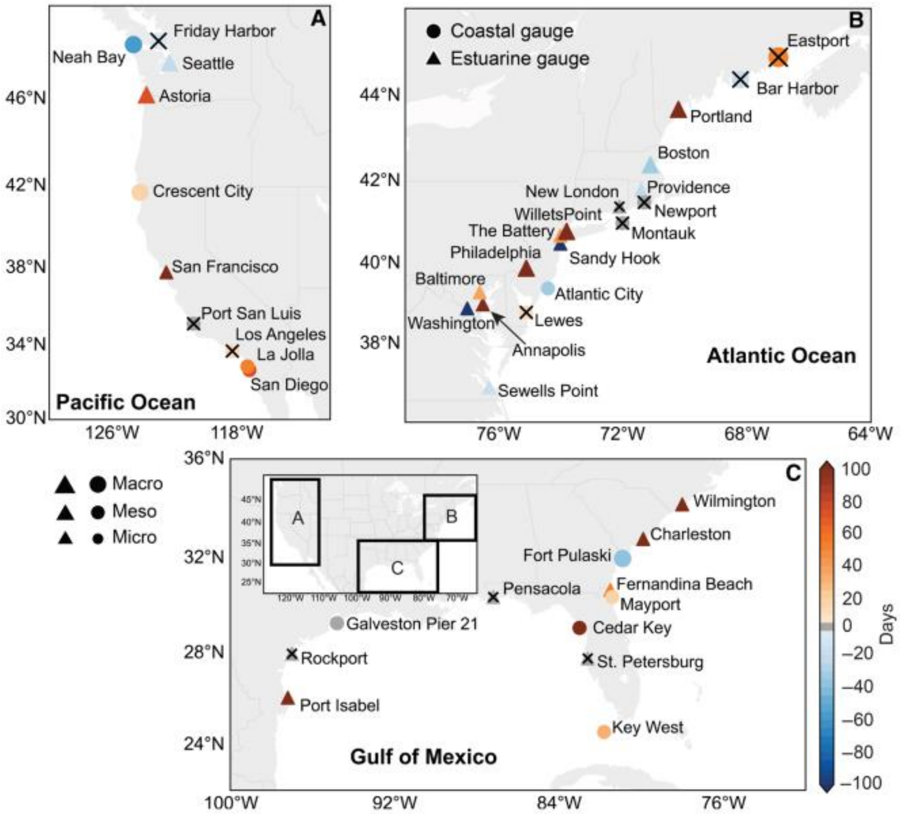


Figure 9 Effect of tidal changes on cumulative NF days at 40 tide gauge locations (Li et al. 2021).

References

Melet, A, Teatini, P, Cozannet, G.L, et al. 2020. Earth observations for monitoring marine coastal hazards and their drivers. Surveys in Geophysics (8).

Benveniste, J, Mandea, M, Melet, A, et al. 2020. Earth observations for coastal hazards monitoring and international services: a European perspective. Surveys in Geophysics, 41(6), 1185-1208.

Shepherd A, Ivins E, Rignot E, et al. 2020 Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature 579:233–239.

Kulp, SA, Strauss, BH. 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat Commun 10:4844.

Marcos, M, Rohmer, J, Vousdoukas, M. I, et al. 2019. Increased extreme coastal water levels due to the combined action of storm surges and wind waves. Geophysical Research Letters, 46, 4356–4364.

Ganguli, P, Paprotny, D, Hasan, M, Güntner, A, & Merz, B. 2020. Projected changes in compound flood hazard from riverine and coastal floods in northwestern Europe. Earth Future 8, e2020EF001752.

Couasnon, A, Eilander, D, Muis, S, et al. 2020. Measuring compound flood potential from river discharge and storm surge extremes at the global scale and its implications for flood hazard, Nat. Hazards Earth Syst. Sci 20, 489–504.

Ray, R.D, Foster, G, 2016 Future nuisance flooding at Boston caused by astronomical tides alone. Earth Future 4, 578–587.

Moftakhari, H.R, AghaKouchak, A, Sanders, B.F, et al. 2018. What is nuisance flooding? Defining and monitoring an emerging challenge. Water Resour. Res.54, 4218–4227.

Li, S, Wahl, S.A, Talke, D.A, et al. (2021) Evolving tides aggravate nuisance flooding along the U.S. coastline. Science Advance 7, eabe2412.

Project Novel Sensors and Quantum Technology for Geodesy (QuGe)

http://quge.iag-aig.org

President: **Jürgen Müller** (Germany)
Vice President: **Marcelo Santos** (Canada)

Structure

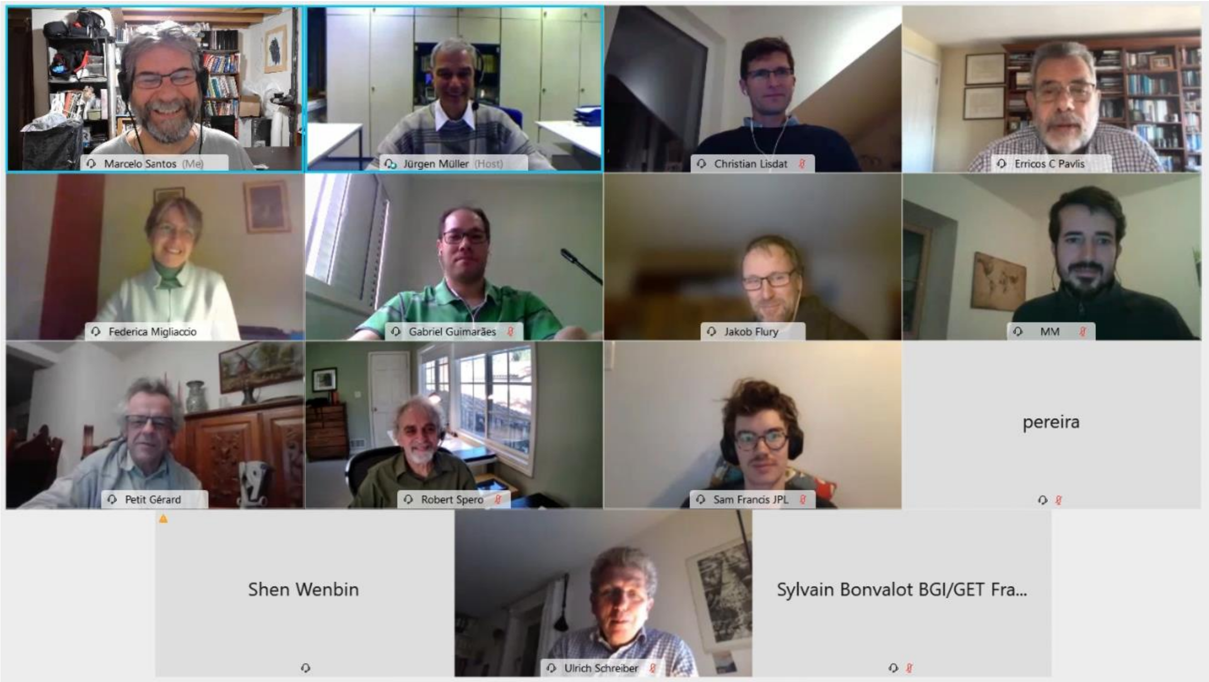
Working Group Q.1:	Quantum gravimetry in space and on ground
Working Group Q.2:	Laser interferometry for gravity field missions
Working Group Q.3:	Relativistic geodesy with clocks

Overview

Like any other component of the IAG, the new Project Novel Sensors and Quantum Technology for Geodesy (QuGe) was strongly affected by the COVID-19 pandemic. The kick-off meeting was planned to take place during the 2020 EGU General Assembly, the sudden cancellation of personal attendance prevented the kick-off to happen there. The paralysis that followed was later broken with a virtual kick-off meeting involving all members of QuGe. It took place on December 3rd, via WEBEX, with the presence of seventeen participants. During this first QuGe meeting several plans of action could be presented and discussed, among them activities of each one of the working groups and participation in meetings such as the COSPAR and EGU, and the IAG Scientific Assembly 2021. QuGe has organized its own symposium at the IAG SA, Symposium 6.4, with 21 contributions and jointly organized four others, sessions 1.6, 2a.2, 2a.1, 2b.6 and 5.2. At COSPAR 2021, IAG QuGe co-sponsored a dedicated session and will do so at COSPAR 2022 in Athens. Similarly, at EGU 2020 and 2021, always a session addressing QuGe-related topics has been scheduled. Those activities will be continued in the next years where then also sessions at AGU and similar conferences will be prepared.

Plans were made towards organization of special workshops (one being organized by WG Q.1 in May 2021, see below), intra-relations among QuGe WGs and inter-relations with other IAG entities and external organizations, such as national metrology institutes and related industry.

More information can be obtained from our QuGe website (https://quge.iag-aig.org) which was set-up in 2020 and reflects any recent activities. There, you can also find the list of the QuGe executive board as well as a list of recent publications of the WGs.



A screen capture showing some of the participants of the first QuGe meeting

Working Groups of QuGe

WG Q.1: Quantum gravimetry in space and on ground

Chair: *Franck Pereira dos Santos* (France)
Vice-Chair: *Michel van Camp* (Belgium)

Members

- *Olivier Carraz* (ESA)
- *Yuichi Imanishi* (Japan)
- *Jeffrey Kennedy* (USA)
- *Markus Krutzik* (Germany)
- *Marie-Françoise Lalancette* (France)
- *Thomas Lévèque* (France)
- *Federica Migliaccio* (Italy)
- *Roland Pail* (Germany)
- *Ernst Rasel* (Germany)
- *Alex Rülke* (Germany)
- *Steffen Schön* (Germany)
- *Shuqing Wu* (China)
- *Nan Yu* (USA)

Description

On ground, quantum sensors based on matter wave interferometry with cold atoms are very well suited for rapid and very precise gravity sensing. They can perform continuous absolute gravity measurements with sub-µGal stability. Mobile devices are developed for field campaigns and large-scale stationary devices for achieving extreme accuracy. While the former enables new strategies for local and regional gravity surveys, the latter will provide a new gravity standard in the future.

In space, the long-term stability and low noise level of quantum sensors will allow improving the spatial gravity field models in GOCE-type gradiometer missions. The determination of mass transport processes on Earth at low and medium degrees in GRACE-type missions will benefit from quantum accelerometers providing the measurement of the specific non-conservative forces. In addition, hybrid systems (i.e., a combination of electrostatic and atom-interferometric accelerometers) can cover a wider spectral range, which will greatly support navigation and inertial sensing on ground and in space.

The goal of this WG is to elaborate the major benefit and most promising applications of atom interferometry for gravimetry and inertial sensing in space and on ground.

Objectives

- Terrestrial quantum gravimeters and applications scenarios (including airborne and marine instruments).
- (Hybrid) accelerometers for space missions and spacecraft navigation.
- Atom interferometric gradiometry.
- Elaboration of further applications / space demonstrator (e.g., pathfinder) like atmosphere research, relativity tests, etc.
- Elaboration of synergies between different science topics in a single mission (Earth observation and fundamental physics, navigation and space exploration, several scenarios for Earth observation, e.g., gravimetry, atmospheric research and magnetometry).

Meetings

Two meetings were organized. The kick-off meeting occurred on January the 26th of 2021, where members of the group introduced themselves and their activities. A follow-up meeting was organized in March to discuss the organization of the workshop on May 26-27.

Website

We have updated the content of the webpage dedicated to WG Q1 on the QuGe website, with a list of selected publications, the list of the WG members, as well as illustrative pictures of quantum gravity sensors developed by the community.

Workshop

An online workshop has been successfully scheduled on the 26th and 27th of May 2021. This (virtual) meeting aimed at covering a broad scope of quantum gravity sensing, from the development of the sensors and their characterization to a large panel of present and future applications. One major objective was to bring together instrument scientists from the quantum physics community and users from the geoscience community. Almost 300 attendees registered for the meeting, which confirms the great interest of the community.

The program was as follows:

Wednesday, the 26th of May

2:00 – 2:35	Bastian Leykauf	HU Berlin	Precision gravimetry with an atom interferometer
2:35 – 3:10	Jean Paul Montagner	IPGP	Prompt Earthquake Gravity Anomalies - Speed-of-light Seismology
3:10 – 3:45	Thomas Lévèque	CNES	Development of quantum sensors for space geodesy
3:45 – 4:20	Roland Pail	TUM	Impact of new measurement technologies for the monitoring of mass transport processes in the Earth system
4:20 – 4:55	Glyn Williams-Jones	SFU	Volcano gravimetry – insights from past successes and future opportunities

Thursday, the 27th of May

2:00 – 2:35	Yannick Bidel	ONERA	Airborne and marine quantum gravimetry
2:35 – 3:10	Andreas Güntner	GFZ	Applications of terrestrial gravimetry in hydrology
3:10 – 3:45	Qiang Lin	Zhejiang U. of Technology	Absolute gravity measurement for field applications based on quantum gravimeter
3:45 – 4:20	Alain Dassargues	ULiege	Land subsidence due to induced water pressure changes in aquifers and confining layers
4:20 – 4:55	Frédéric Domps	European Commission	Quantum Space Gravimetry at European Commission

Selected Publications

Abend S., M. Gersemann, H. Ahlers, M. Sahelgozin, J. Matthias, N. Grove, H. Heine, N. Gaaloul, W. Herr, C. Schubert, W. Ertmer, E.M. Rasel, M. Gebbe, H. Müntinga, C. Lämmerzahl, L. Timmen, J. Müller (2019): Atom-chip–based quantum gravimetry with BECs. Proceedings of the International School of Physics "Enrico Fermi", IOS press e-book: Foundations of Quantum Theory, vol. 197, p. 393-397, Doi:10.3254/978-1-61499-937-9-393

Abrykosov, P., Pail, R., Gruber, T., Zahzam, N., Bresson, A., Hardy, E., Christophe, B., Bidel, Y., Carraz, O., Siemes, C., 2019. Impact of a novel hybrid accelerometer on satellite gravimetry performance. Advances in Space Research 63, 3235–3248. https://doi.org/10.1016/j.asr.2019.01.034

R. Caldani, S. Merlet, F. Pereira dos Santos, G. Stern, A.-S. Martin, B. Desruelle, V. Ménoret, "A prototype industrial laser system for cold atom inertial sensing in space", Eur. Phys. J. D 73, 248 (2019), Selected as EPJ D Highlight "Laser-based prototype probes cold atom dynamics"

R. Caldani, K. Weng, S. Merlet, F. Pereira dos Santos, "Simultaneous accurate determination of both gravity and its vertical gradient", Phys. Rev. A 99, 033601 (2019)

B. Canuel, S. Abend, P. Amaro-Seoane, F Badaracco, Q. Beaufils, A. Bertoldi, K. Bongs, P. Bouyer, C. Braxmaier, W. Chaibi, N. Christensen, F. Fitzek, G. Flouris, N. Gaaloul, S. Gaffet, C. L. Garrido Alzar, R. Geiger, S. Guellati-Khelifa, K. Hammerer, J. Harms, J. Hinderer, J. Junca, S. Katsanevas, C. Klempt, C. Kozanitis, M. Krutzik, A. Landragin, I.

Làzaro Roche, B. Leykauf, Y-H. Lien, S. Loriani, S. Merlet, M. Merzougui, M. Nofrarias, P. Papadakos, F. Pereira dos Santos, A. Peters, D. Plexousakis, M. Prevedelli, E. Rasel, Y. Rogister, S. Rosat, A. Roura, D. O. Sabulsky, V. Schkolnik, D. Schlippert, C. Schubert, L. Sidorenkov, J.-N. Siemes, C. F. Sopuerta, F. Sorrentino, C. Struckmann, G.M. Tino, G. Tsagkatakis, A. Viceré, W. von Klitzing, L. Woerner, X. Zou, "ELGAR - a European Laboratory for Gravitation and Atom-interferometric Research", Quantum and Classical Gravity 37, 225017 (2020)

Pierre Gillot, Bing Cheng, Romain Karcher, Almazbek Imanaliev, Ludger Timmen, Sébastien Merlet, Franck Pereira dos Santos, "Calibration of a superconducting gravimeter with an absolute atom gravimeter", Journal of Geodesy 95, 62 (2021)

R. Geiger, A. Landragin, S. Merlet, F. Pereira dos Santos, "High-accuracy inertial measurements with cold-atom sensors", AVS Quantum Sci. 2, 024702 (2020)

Haagmans, R., Siemes, C., Massotti, L., Carraz, O., Silvestrin, P., 2020. ESA's next-generation gravity mission concepts. Rend. Fis. Acc. Lincei. https://doi.org/10.1007/s12210-020-00875-0

Nina Heine, Jonas Matthias, Maral Sahelgozin, Waldemar Herr, Sven Abend, Ludger Timmen, Jürgen Müller, Ernst Maria Rasel, A transportable quantum gravimeter employing delta-kick collimated Bose–Einstein condensates. Eur. Phys. J. D 74, 174 (2020). https://doi.org/10.1140/epjd/e2020-10120-x

R. Karcher, F. Pereira dos Santos, S. Merlet, "Impact of direct-digital-synthesizer finite resolution on atom gravimeters", Phys. Rev. A 101, 043622 (2020)

Maike D. Lachmann, Holger Ahlers, Dennis Becker, Aline N. Dinkelaker, Jens Grosse, Ortwin Hellmig, Hauke Müntinga, Vladimir Schkolnik, Stephan T. Seidel, Thijs Wendrich, André Wenzlawski, Benjamin Carrick, Naceur Gaaloul, Daniel Lüdtke, Claus Braxmaier, Wolfgang Ertmer, Markus Krutzik, Claus Lämmerzahl, Achim Peters, Wolfgang P. Schleich, Klaus Sengstock, Andreas Wicht, Patrick Windpassinger, Ernst M. Rasel, Ultracold atom interferometry in space. Nat Commun 12, 1317 (2021). https://doi.org/10.1038/s41467-021-21628-z

Migliaccio, F., Reguzzoni, M., Batsukh, K., Tino, G.M., Rosi, G., Sorrentino, F., Braitenberg, C., Pivetta, T., Barbolla, D.F., Zoffoli, S., 2019. MOCASS: A Satellite Mission Concept Using Cold Atom Interferometry for Measuring the Earth Gravity Field. Surv Geophys 40, 1029–1053. https://doi.org/10.1007/s10712-019-09566-4

F Müller, O Carraz, P Visser, and O Witasse, 2020. Cold atom gravimetry for planetary missions, Planetary and Space Science 194, 105110

Müller, J., Wu, H. (2020): Using quantum optical sensors for determining the Earth's gravity field from space. Journal of Geodesy, Vol. 94, Nr. 71 doi: 10.1007/s00190-020-01401-8

M. Reguzzoni, F. Migliaccio, K. Batsukh (2021). "Gravity Field Recovery and Error Analysis for the MOCASS Mission Proposal Based on Cold Atom Interferometry". Accepted for publication, in print in Pure and Applied Geophysics, https://doi.org/10.1007/s00024-021-02756-5

L. L. Richardson, D. Nath, A. Rajagopalan, H. Albers, C. Meiners, C. Schubert, D. Tell, E. Wodey, S. Abend, M. Gersemann, W. Ertmer, E. M. Rasel, D. Schlippert, M. Mehmet, L. Kumanchik, L. Colmenero, R. Spannagel, C. Braxmaier, and F. Guzman (2020): Optomechanical resonator-enhanced atom interferometry, Commun. Phys. 3, 208

F. Sansò, F. Migliaccio (2020). "Quantum Measurement of Gravity for Geodesists and Geophysicist", pp. 1-139, Springer. DOI:10.1007/978-3-030-42838-9_6, ISSN 2364-9119, ISSN 2364-9127 (electronic), Springer Geophysics ISBN 978-3-030-42837-2, ISBN 978-3-030-42838-9 (eBook), https://doi.org/10.1007/978-3-030-42838-9

M. Schilling, É. Wodey, L. Timmen, D. Tell, K. H. Zipfel, D. Schlippert, C. Schubert, E. M. Rasel, and J. Müller (2020): Vertical Gravity Profile in a 10 m Atom Interferometer, J. Geod. 94, 122 (2020)

B. Tennstedt, C. Schubert, D. Schlippert, S. Schön, and E. M. Rasel (2019): Impact of Uncertainties in Atom Interferometry on Strapdown Navigation Solutions, 2019 DGON Inertial Sensors and Systems (ISS), 2019, DOI: 10.1109/ISS46986.2019.8943632

Tennstedt B, Schön S. (2020): Dedicated calculation strategy for atom interferometry sensors in inertial navigation, IEEE/ION Position, Location and Navigation Symposium (PLANS), April 20-23, Portland, OR, USA DOI: 10.1109/PLANS46316.2020.9110142

Tennstedt B., Weddig N., and Schön S. (2021): A hybrid CAI/IMU solution for higher navigation performance, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-9776, https://doi.org/10.5194/egusphere-egu21-9776 DOI: 10.5194/egusphere-egu21-9776

Trimeche, A., Battelier, B., Becker, D., Bertoldi, A., Bouyer, P., Braxmaier, C., Charron, E., Corgier, R., Cornelius, M., Douch, K., Gaaloul, N., Herrmann, S., Müller, J., Rasel, E.M., Schubert, C., Wu, H., Pereira dos Santos, F., 2019. Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry. Class. Quantum Grav. https://doi.org/10.1088/1361-6382/ab4548

C. Vogt, M. Woltmann, H. Albers, D. Schlippert, S. Herrmann, E. M. Rasel, and C. Lämmerzahl (2020): Evaporative cooling from an optical dipole trap in microgravity, Phys. Rev. A 101, 013634

E. Wodey, D. Tell, E. M. Rasel, D. Schlippert, R. Baur, U. Kissling, B. Kölliker, M. Lorenz, M. Marrer, U. Schläpfer, M. Widmer, C. Ufrecht, S. Stuiber, and P. Fierlinger (2020): A scalable high-performance magnetic shield for Very Long Baseline Atom Interferometry, Rev. Sci. Instrum. 91, 035117

WG Q.2: Laser interferometry for gravity field missions

Chair: *Michael Murböck* (Germany)
Vice-Chair: *Robert Spero* (USA)

Members

- *Vitali Müller* (Germany)
- *Gerhard Heinzel* (Germany)
- *Jürgen Kusche* (Germany)
- *Felix Landerer* (USA)
- *David Wiese* (USA)
- *Peter Bender* (USA)
- *Gilles Metris* (France)
- *Christophe Le Poncin-Lafitte* (France)
- *Shuanggen Jin* (China)
- *Christopher Woodruff* (USA)
- *Frank Flechtner* (Germany)
- *Markus Hauk* (Germany)
- *Thomas Papanikolaou* (Denmark)

Description

GRACE has excellently demonstrated the great potential of inter-satellite tracking to determine time-variable gravitational signals which are related to mass transport processes in the Earth system. Examples are ice mass loss in Greenland and Antarctica, ground water loss in Asia, droughts in USA, quantification of the global water cycle, mass contribution to sea level rise, mass variation due to land uplift in North America and Scandinavia, or mass changes related to earthquakes. To increase the resolution and to extend the time series, GRACE-FO was launched in May 2018 also carrying a Laser Ranging Interferometer (LRI) as demonstrator which is able to approach an accuracy of tens of nm for inter-satellite ranging. Optical sensing of the motion of test masses in the gravitational field with nanometer accuracy and beyond can be realized in various measurement concepts such as for ranging between satellites like in GRACE-FO or future swarms of satellites. Further concepts apply LRI for sensing single test-mass motion (accelerometry) or multiple test-mass constellations within one satellite (GOCE-type gradiometry). The overall goal of this WG is to study optical sensing for inter-satellite tracking, accelerometry and gradiometry, and its applications for next generation gravity field missions.

Activities

The first year was covered by organizing that WG, to collect the members, to fill the website and to develop (in sub-groups) the further strategy of the collaborations, etc. In order to define the topics and tasks for the near future in more detail, we will organize a workshop with interdisciplinary discussions and small group work.

Selected Publications

Abich, K., Abramovici, A., Amparan, B., Baatzsch, A., Okihiro, B. B., Barr, D. C., Bize, M. P., Bogan, C., Braxmaier, C., Burke, M. J., Clark, K. C., Dahl, C., Dahl, K., Danzmann, K., Davis, M. A., de Vine, G., Dickson, J. A., Dubovitsky, S., Eckardt, A., Ester, T., Barranco, G. F., Flatscher, R., Flechtner, F., Folkner, W. M., Francis, S., Gilbert, M. S., Gilles, F., Gohlke, M., Grossard, N., Guenther, B., Hager, P., Hauden, J., Heine, F., Heinzel, G., Herding, M., Hinz, M., Howell, J., Katsumura, M., Kaufer, M., Klipstein, W., Koch, A., Kruger, M., Larsen, K., Lebeda, A., Lebeda, A., Leikert, T., Liebe, C. C., Liu, J., Lobmeyer, L., Mahrdt, C., Mangoldt, T., McKenzie, K., Misfeldt, M., Morton, P. R., Mueller, V., Murray, A. T., Nguyen, D. J., Nicklaus, K., Pierce, R., Ravich, J. A., Reavis, G., Reiche, J., Sanjuan, J., Schuetze, D., Seiter, C., Shaddock, D., Sheard, B., Sileo, M., Spero, R., Spiers, G., Stede, G., Stephens, M., Sutton, A., Trinh, J., Voss, K., Wang, D. Wang, R. T., Ware, B., Wegener, H., Windisch, S., Woodruff, C., Zender, B., Zimmermann, M. (2019) In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer, *Phys. Rev. Lett. 123*, 031101, https://doi.org/10.1103/PhysRevLett.123.031101

Abrykosov, P., Pail, R., Gruber, T., Zahzam, N., Bresson, A., Hardy, E, Christophe, B., Bidel, Y., Carraz, O., Siemes, C. (2019). Impact of a novel hybrid accelerometer on satellite gravimetry performance. *Advances in Space Research*, *63*(10), 3235-3248. https://doi.org/10.1016/j.asr.2019.01.034

Bender, P. L., & Betts, C. R. (2016). Ocean calibration approach for data from the GRACE Follow-On mission. *Journal of Geophysical Research: Solid Earth*, *121*(2), 1218-1235. https://doi.org/10.1002/2015JB012433

Dahle, C., Murböck, M., Flechtner, F., Dobslaw, H., Michalak, G., Neumayer, K. H., Abrykosov, O., Reinhold, A., König, R., Sulzbach, R., & Förste, C. (2019). The GFZ GRACE RL06 monthly gravity field time series: Processing details and quality assessment. *Remote Sensing*, *11*(18), 2116. https://doi.org/10.3390/rs11182116

Darbeheshti, N., Wegener, H., Müller, V., Naeimi, M., Heinzel, G., & Hewitson, M. (2017). Instrument data simulations for GRACE Follow-on: observation and noise models. *Earth System Science Data*, *9*(2), 833-848. https://doi.org/10.22027/AMDC2

Flechtner, F., Neumayer, K.H., Dahle, C., Dobslaw, H., Fagiolini, E., Raimondo, J.C., Güntner, A. (2016) What Can be Expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications?. *Surv Geophys 37*, 453–470 (2016). https://doi.org/10.1007/s10712-015-9338-y

Ghobadi-Far, K., Han, S. C., McCullough, C. M., Wiese, D. N., Yuan, D. N., Landerer, F. W., Sauber, J., & Watkins, M. M. (2020). GRACE Follow-On laser ranging interferometer measurements uniquely distinguish short-wavelength gravitational perturbations. *Geophysical Research Letters*, *47*(16), e2020GL089445. https://doi.org/10.1029/2020GL089445

Giorgi, G., Schmidt, T. D., Trainotti, C., Mata-Calvo, R., Fuchs, C., Hoque, M. M., Berdermann, J., Furthner, J., Günther, C., Schuldt, T., Sanjuan, J., Gohlke, M., Oswald, M., Braxmaier, C., Balidakis, K., Dick, G., Flechtner, F., Ge, M., Glaser, S., König, R., Michalak, G., Murböck, M., Semmling, M., & Schuh, H. (2019). Advanced technologies for satellite navigation and geodesy. *Advances in Space Research*, *64*(6), 1256-1273. https://doi.org/10.1016/j.asr.2019.06.010

Hauk, M., & Pail, R. (2019). Gravity field recovery using high-precision, high–low inter-satellite links. *Remote Sensing*, *11*(5), 537. https://doi.org/10.3390/rs11050537

Nicklaus, K., Cesare, S., Massotti, L., Bonino, L., Mottini, S., Pisani, M., & Silvestrin, P. (2020). Laser metrology concept consolidation for NGGM. *CEAS Space Journal*, *12*(3), 313-330. https://doi.org/10.1007/s12567-020-00324-6

Wiese, D. N., Nerem, R. S., & Lemoine, F. G. (2012). Design considerations for a dedicated gravity recovery satellite mission consisting of two pairs of satellites. *Journal of Geodesy*, *86*(2), 81-98. https://doi.org/10.1007/s00190-011-0493-8

WG Q.3: Laser interferometry for gravity field missions

Chair: *Gerard Petit* (France)
Vice-Chair: *Jakob Flury* (Germany)
Consultant from Physics: *Christian Lisdat* (Germany)

Members

- *Claude Boucher* (France)
- *Davide Calonico* (Italy)
- *Pascale Defraigne* (Belgium)
- *Pacôme Delva* (France)
- *Ropesh Goyal* (India)
- *Gesine Grosche* (Germany)
- *Hua Guan* (China)
- *Chris Hughes* (UK)
- *Sergei Kopeikin* (USA)
- *Jürgen Kusche* (Germany)
- *Claus Lämmerzahl* (Germany)
- *Marie-Françoise Lequentrec* (France)
- *Guillaume Lion* (France)
- *Andrew Ludlow* (USA)
- *Helen Margolis* (UK)
- *Elena Mazurova (Russia)*
- *Nathan Newbury* (USA)
- *Bijunath Patla* (USA)
- *Nikos Pavlis* (USA)
- *Paul-Eric Pottie* (France)
- *Ulrich Schreiber* (Germany)
- *WenBin Shen* (China)
- *Simon Stellmer* (Germany)
- *Yoshiyuki Tanaka* (Japan)
- *Pieter Visser* (Netherlands)

Description

Optical clocks are sensitive to the gravity potential in which they are operated. The comparison of two clocks will reveal a frequency offset from the value expected from side-by-side comparisons that can directly be related to the potential difference between both clocks. The best optical clocks now reach resolutions of 0.1 m^2/s^2, transportable ones about 2 m^2/s^2. They can be achieved already after few hours of averaging.

We will evaluate how this technique can be used to generate unified and long-term stable height networks and reference systems. This will include discussion about the feasibility to realize a datum by reference to a, e.g., space-borne clock with ideally negligible gravitational interference. Future clock networks might also be used as ground-truth for space missions or even to bridge gaps in satellite observations.

Other aspects to be addressed are the application of observed time-variable signals in de-aliasing of satellite observations. In cooperation with the two previous WGs, sensor fusion concepts will be discussed to utilize the different spatial integration characteristics of clocks and the other gravity sensors to disentangle local and extended signal sources.

In summary, the goals of this WG are using clocks measurements for determining differences of physical heights and gravity potential for various geodetic applications.

Activities

During the year 2020, the membership was consolidated.

After some delay to adapt to the COVID crisis, the kick-off meeting was held virtually on December 21, 2020. It included several presentations by Jürgen Müller (The IAG project QuGe), Gérard Petit (Activities at the BIPM and CCTF related to this WG), Jakob Flury (Related IAG activities, IHRS), Yoshiyuki Tanaka (Progress about chronometric levelling in Japan), Claus Lämmerzahl (Last activities in relativistic modelling) and Chris Hughes (Global hydrodynamic levelling). The presentations and the minutes of the meeting are available at https://quge.iag-aig.org/quge-meetings/ko-meeting-wgq3.

Several members of the working group are directly involved in the work of the Consultative Committee for Time and Frequency (CCTF) which, at its 22nd meeting in October 2020 and March 2021 (see https://www.bipm.org/en/committees/cc/cctf/meetings), initiated a Task Force in view of a future redefinition of the second in terms of optical transitions. The work of this Task Force will have considerable intersection with the activities of the WG, in the aim of fulfilling the criteria needed for the redefinition. This notably concerns the techniques for optical clock comparisons and the computation of the relativistic frequency shift, to a level equivalent to 10^{-18} in relative frequency.

Selected Publications

Delva P., Denker H., Lion G. (2019): Chronometric Geodesy: Methods and Applications, in Relativistic Geodesy Foundations and Applications, Springer, Puetzfeld D., Lämmerzahl C Ed.

Kopeikin S. (2019): Reference-Ellipsoid and Normal Gravity Field in Post-Newtonian Geodesy, in Relativistic Geodesy Foundations and Applications, Springer, Puetzfeld D., Lämmerzahl C Ed. (see also further contributions in that book)

Müller, J., Wu, H. (2020): Using quantum optical sensors for determining the Earth's gravity field from space. Journal of Geodesy, Vol. 94, Nr. 71 doi: 10.1007/s00190-020-01401-8

Philipp, D., Hackmann, E., Lämmerzahl, C, Müller, J. (2020): The Relativistic Geoid: Gravity Potential and Relativistic Effects. Physical Review D, Vol. 101, No. 6, DOI: 10.1103/PhysRevD.101.064032

Schröder S., Stellmer S., Kusche J. (2021): Potential and scientific requirements of optical clock networks for validating satellite-derived time-variable gravity data, Geophysical Journal International, Volume 226, Issue 2, Pages 764–779, https://doi.org/10.1093/gji/ggab132

Wu, H., Müller, J. (2020): Towards an International Height Reference Frame Using Clock Networks. IAG symposia volume of the IUGG2019 General Assembly, Springer, https://doi.org/10.1007/1345_2020_97

Wu, H., Müller, J., Lämmerzahl C. (2019): Clock networks for height system unification: a simulation study, Geophysical Journal International, 216(3):1594-1607, DOI: 10.1093/gji/ggy508

Global Geodetic Observing System

https://www.ggos.org

President: Basara Miyahara (Japan)
Vice President: Laura Sánchez (Germany)

As the observing system of the IAG, the Global Geodetic Observing System (GGOS) facilitates a unique and essential combination of roles centering upon advocacy, integration, and international relations. GGOS aims to provide the observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution, to provide the global geodetic frame of reference for measuring and consistently interpreting key global change processes and for many other scientific and societal applications, and to benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built. To complete its mission, GGOS develops and maintains working relationships among a variety of internal and external groups and organizations.

GGOS Structure

The GGOS structure is illustrated in Figure 1. The decision-making entities are the Consortium, the Coordinating Board and its Executive Committee. Permanent Standing Committees and limited-term Working Groups are the thematic working bodies of GGOS and are distributed over two Bureaus, the Science Panel and the Focus Areas, as well as affiliated organizations. In addition to being the Secretariat of GGOS, the Coordinating Office coordinates the activities of GGOS including communications, outreach, and external relations; as well as maintaining and developing the GGOS website and social media presence.

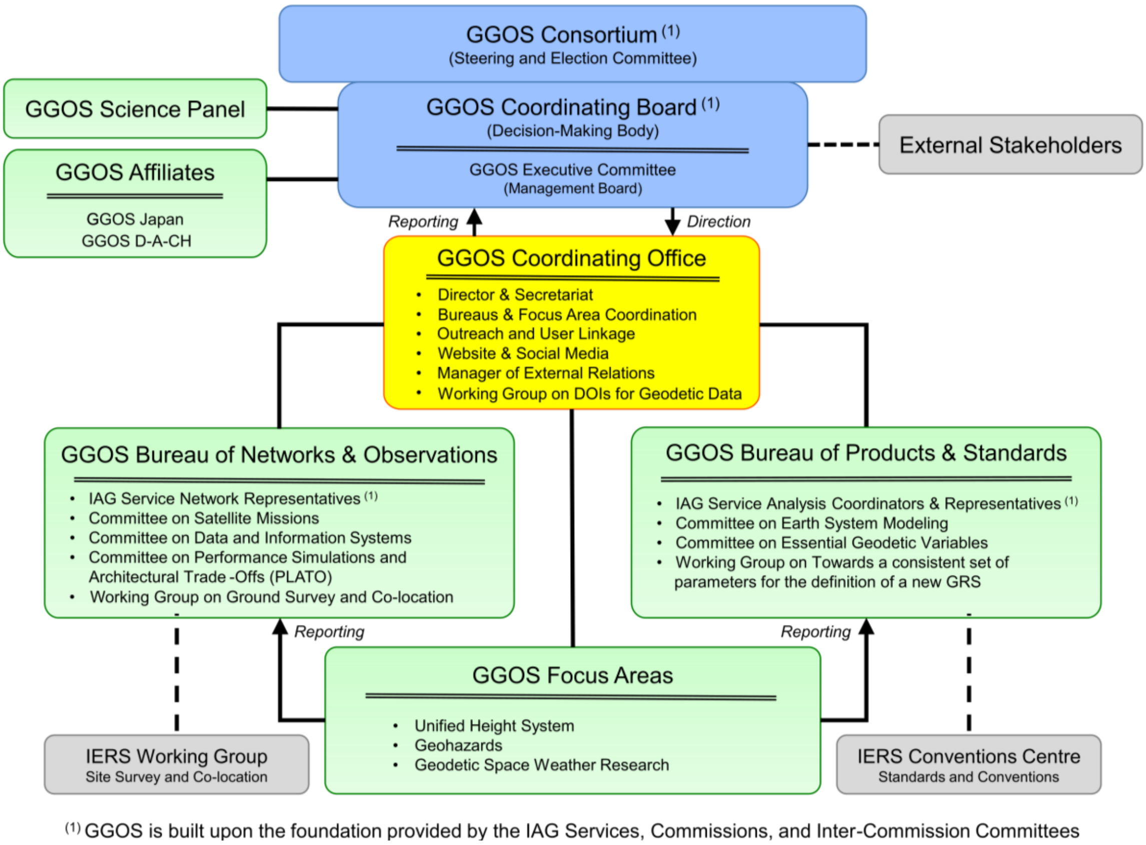


Figure 1. Organization chart of GGOS.

Overview

The GGOS renewed its structure in 2019 including the election of new President and Vice President and the restructuring of the GGOS Consortium and GGOS Coordinating Board. A Working Group on "DOIs for Geodetic Data Sets" was newly established within the GGOS Coordinating Office. The Working Group on "ITRS Standards for ISO TC 211" completed its work and was dissolved with successful contribution to ISO 19161-1. The Working Group on "Establishment of the Global Geodetic Reference Frame (GGRF)" was renewed and renamed to Working Group on "Towards a consistent set of parameters for the definition of a new GRS" and continues to work on the challenge to define a new GRS four more years. The GGOS Focus Area "Sea Level Change" was terminated in 2019.

The GGOS Bureau of Products and Standards (BPS) published a 2nd updated version of the BPS inventory in the Geodesist's Handbook 2020 to compile and refine an inventory on standards and conventions used for the generation of IAG products.

The GGOS Focus Area "Unified Height System" defined a strategy for the implementation of the International Height Reference System (IHRF) and is currently working in the first computation of the IHRF. The Focus Area "Geohazards" played a central role in the development of the initiative "GNSS enhancement to tsunami early warning systems (GTEWS)" and presently is supporting the creation of the GTEWS Consortium within the Community Activity "Geodesy for the Sendai Framework" of the Group on Earth Observations (GEO). The Focus Area "Geodetic Space Weather Research" identified four central challenges and established four dedicated working groups.

As a mechanism to increase participation in GGOS, the second of two GGOS Affiliates was established in 2021. GGOS D-A-CH is a regional affiliate group of German-speaking countries and its name is comprised of the country codes D (Germany), A (Austria) and CH (Switzerland). GGOS D-A-CH has been created by strong collaboration between the national geodetic commissions of these countries and developed based upon a strategic White Paper on "Geodesy 2030". Its founding chair is Hansjörg Kutterer of Karlsruhe Institute of Technology. Moving forward, GGOS D-A-CH will formulate Terms of Reference with a clear focus on strategic topics in GGOS-related science. As a GGOS Affiliate, the group will have a representative to GGOS Consortium and GGOS Coordinating Board.

One of the main forces of GGOS during the period 2019-2021 is outreach and communication. GGOS renewed its website (https://www.ggos.org) to enhance outreach and communication to non-geodesists at the end of 2020. The new website focuses two faces of GGOS: one as an organization to foster collaboration between stakeholders mainly in IAG, and another as the geodetic observing system, which underpins science and society as fundamental infrastructure for monitoring the Earth. The new website put IAG Services in the front page to make them more visible and to provide easier access to their Internet portals. The new site also provides "products" and "observation" pages, which describe the role and importance of Geodesy, its observation techniques and products to non-geodesists with easy and brief explanations as well as eye-catching visual aids. The new site provides articles on Geodesy, which are also helpful for non-geodesists to understand what Geodesy is and why Geodesy is so important for science and society. Another new fundamental tool is the repository of main documents in the GGOS Cloud (https://cloud.ggos.org), which enables us to share the GGOS related materials such as Terms of Reference, reports, papers and presentations and ensures their long-term availability.

GGOS also further strengthened and expanded its external relations and stakeholder engagement. Continued participation in GEO included establishment of a geodesy advocacy Community Activity within GEO, titled “Geodesy for the Sendai Framework” as well as ongoing and diverse participation in the GEO Programme Board. GGOS also continues to strongly support the actions and initiatives of the UN GGIM Subcommittee on Geodesy, and intends to expand this support to the new UN Global Geodetic Centre of Excellence scheduled to commence operations in early 2022.

In addition to external advocacy, GGOS routinely looks inward to identify the best ways to cite and track the impact of the geodetic data, products, and other resources that the IAG and its services make freely and openly available to the general public. At the Unified Analysis Workshop in 2019, Digital Object Identifiers (DOIs) were discussed as unique identifiers of data as well as publications. DOIs are already widely used by publishers, and their implementation for data sets is expected to be beneficial for both users as well as data providers. Users can get easy access to data cited in journals, and use of DOIs improves traceability of published results and discoverability of data sets. This eliminates confusion about data used and enable wider distribution of data sets. Data providers can include information about data set on landing page (metadata), and DOIs easily allow number of data publications to be tracked and number of times data is used to be counted. Data providers can receive proper credit for their published data. Considering these benefits, the GGOS established a new Working Group on DOIs for Geodetic Data Sets in 2019. Its chair is Kirsten Elger of GFZ Potsdam and more than 20 members are participating in the WG, mainly from IAG Services. The WG has analyzed use cases and best practices both in geodesy as well as in other scientific fields, and is currently working on how to establish parameters and procedures for properly assigning DOIs to geodetic data set.

Consortium

The GGOS Consortium functions as the large steering committee and collective voice of GGOS, and is comprised of one representative from each GGOS Affiliate and up to two representatives from each IAG Service, Commission, and Inter-Commission Committee. According to the GGOS Terms of Reference, the Consortium membership is reviewed and refreshed every four years, which last one took place coincident to the 2019 IUGG General Assembly. The members of the GGOS Consortium during 2019–2023 are listed in Table 1.

The President of GGOS is also the chair of the GGOS Consortium. The GGOS Consortium meets annually, which during 2019–2021 took place during the GGOS Days:

1. GGOS Days 2019, Rio de Janeiro, Brazil, 12-14 November 2019
2. GGOS Days 2020, held virtually via Video Conference, 5-7 October 2020

Table 1. Members of the GGOS Consortium During 2019–2023

Organization	Name	Title
GGOS	Basara Miyahara	Chair
GGOS Affiliate: GGOS Japan	Yusuke Yokota	Designated GGOS Representative
GGOS Affiliate: GGOS D-A-CH	Markus Rothacher	Designated GGOS Representative (2021-2023)
IAG Service Representatives		
International Gravimetric Bureau (BGI)	Sylvain Bonvalot	Director
	Sean Bruinsma	Designated GGOS Representative
International Centre for Global Earth Models (ICGEM)	E. Sinem Ince	Designated GGOS Representative

International DORIS Service (IDS)	Laurent Soudarin	Director, Central Bureau
	Frank Lemoine	Chair, Governing Board
International Earth Rotation and Reference Systems Service (IERS)	Daniela Thaller	Director, Central Bureau
	Robert Heinkelmann	Analysis Coordinator
International Service for Geoid (ISG)	Urs Marti	Designated GGOS Representative
	Jianliang Huang	Designated GGOS Representative
International Gravity Field Service (IGFS)	Riccardo Barzaghi	Chair
	Georgios Vergos	Director, Central Bureau
International GNSS Service (IGS)	Nicholas Brown	Designated GGOS Representative
	Arturo Villiger	Designated GGOS Representative
The International Laser Ranging Service (ILRS)	Toshimichi Otsubo	Chair, Governing Board
	Erricos Pavlis	Chair, Analysis Working Group
International VLBI Service for Geodesy and Astrometry (IVS)	Axel Nothnagel	Chair, Directing Board
	Dirk Behrend	Director, Coordinating Center
Permanent Service for Mean Seal Level (PSMSL)	Elizabeth Bradshaw	Director
	Andy Matthews	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Christoph Foerste	Designated GGOS Representative
	Hartmut Wziontek	Designated GGOS Representative
International Digital Elevation Model Service (IDEMS)	Kevin M. Kelly	Director
	Christian Hirt	Designated GGOS Representative
IAG Commissions Representatives		
Commission 1: Reference Frames	Christopher Kotsakis	President
	Tonie van Dam	Designated GGOS Representative
Commission 2: Gravity Field	Adrian Jäggi	President
	Mirko Reguzzoni	Vice President
Commission 3: Earth Rotation and Geodynamics	Janusz Bogusz	President
	Chengli Huang	Vice President
Commission 4: Positioning and Applications	Paweł Wielgosz	President
	Michael Schmidt	Vice President
IAG Inter Commission Committee (ICC) Representatives		
ICC on Theory (ICCT)	Pavel Novák	President
	Dimitrious Tsoulis	Designated GGOS Representative
ICC on Climate Research (ICCC)	Anette Eicker	President
	Carmen Boening	Vice President
ICC on Marine Research (ICCM)	Yuanxi YANG	President
	Heidrun Kopp	Designated GGOS Representative

Coordinating Board

The Coordinating Board is the decision-making body of GGOS. The members of the GGOS Coordinating Board during 2019–2023 are listed in Table 2.

The President of GGOS is the Chair of the Coordinating Board. The Coordinating Board meets twice-per-year, which during 2019–2021 took place during GGOS Days and around the EGU:

1. GGOS Days 2019, Rio de Janeiro, Brazil, 12-14 November 2019
2. GGOS CB Meeting, held virtually via Video Conference, 8 May 2020
3. GGOS Days 2020, held virtually via Video Conference, 5-7 October 2020
4. GGOS CB Meeting, held virtually via Video Conference, 7 May 2021

Table 2. Members of the GGOS Coordinating Board During 2019–2023

Position	Voting	Name
Chair	Yes	Basara Miyahara
Vice Chair	Yes	Laura Sánchez
Chair, Science Panel	Yes	Kosuke Heki
Director, Coordinating Office	Yes	Martin Sehnal
Manager, External Relations	Yes	Allison Craddock
Director, Bureau of Networks & Observations	Yes	Mike Pearlman
Director, Bureau of Products & Standards	Yes	Detlef Angermann
Representative, GGOS Affiliates	Yes	Toshimichi Otsubo
	Yes	Hansjörg Kutterer (2021-2023)
Representative, IAG President	Yes	Zuheir Altamimi
Representative, IAG Services	Yes	Riccardo Barzaghi
	Yes	Daniela Thaller
	Yes	Sean Bruinsma
	Yes	Robert Heinkelmann
Representative, IAG Commissions and ICC	Yes	Tonie Van Dam
	Yes	Adrian Jäggi
Member-at-Large	Yes	Maria Cristina Pacino (2019-2021) Claudia Tocho (2021-2023)
	Yes	Nicholas Brown
	Yes	Ludwig Combrinck
GGOS Focus Area (FA) Leads		
FA Unified Height System	No	Laura Sánchez
FA Geohazards	No	John LaBrecque
FA Geodetic Space Weather Research	No	Michael Schmidt
GGOS Committee Chairs		
Committee on Satellite and Space Missions	No	Roland Pail
Committee on Data and Information Systems	No	Martin Sehnal (2019) Nicholas Brown (2020-2023)
Committee on Contribution to Earth System Modelling	No	Maik Thomas
Committee on PLATO (IAG WG)	No	Daniela Thaller
Committee on Essential Geodetic Variables	No	Richard Gross
GGOS Working Group Chairs		
JWG: Ground Survey and Co-Location	No	Ryan Hippenstiel
JWG: Definition of a new GRS	No	Urs Marti
WG: DOIs for Geodetic Data Sets	No	Kirsten Elger
Others		
Manager, GGOS Web and Social Media	No	Martin Sehnal
Immediate Past Chair of GGOS	No	Richard Gross

Executive Committee

The Executive Committee of the GGOS Coordinating Board serves at the direction of the Coordinating Board to accomplish the day-to-day activities of the tasks of GGOS. The members and guest observers of the Executive Committee during 2019–2023 are listed in Table 3. The President of GGOS is the Chair of the Executive Committee. The Executive Committee holds monthly conference calls and meets face-to-face or virtual during the meetings of the Coordinating Board (see above).

Table 3. Members of the GGOS Executive Committee During 2019–2023

Position	**Status**	**Name**
Chair	Member	Basara Miyahara
Vice Chair	Member	Laura Sánchez
Director, Coordinating Office	Member	Martin Sehnal
Manager, External Relations	Member	Allison Craddock
Director, Bureau of Networks & Observations	Member	Mike Pearlman
Director, Bureau of Products & Standards	Member	Detlef Angermann
Representative, IAG Services	Member	Riccardo Barzaghi
Representative, IAG Commissions	Member	Adrian Jäggi
Immediate Past Chair of GGOS	Guest	Richard Gross
Chair, Science Panel	Guest	Kosuke Heki
Representative, IAG President	Guest	Zuheir Altamimi

GGOS Coordinating Office

Director:	*Martin Sehnal (Austria)*
Manager of External Relations:	*Allison Craddock (USA)*
Chair of WG on DOIs:	*Kirsten Elger (Germany)*

Working Group (WG) affiliated with GGOS Coordinating Office:

- GGOS Working Group on "DOIs for Geodetic Data Sets"

Purpose and Scope

The GGOS Coordinating Office (CO) serves as a centralized administrative and organisational entity and interacts with the GGOS Bureaus and Focus Areas for organisational matters. The CO performs the day-to-day activities and generates reports in support of the various components of GGOS especially the GGOS Executive Committee and the GGOS Coordinating Board. The CO ensures information flow, maintains and archives documentation and in its long-term coordination role ensures consistency and continuity in the contributions of the GGOS components. The CO implements and operates the GGOS website and outreach.

The Manager of External Relations connects GGOS with external organisations.

The Director of the CO and the Manager of External Relations are both ex-officio members of the GGOS Coordinating Board and GGOS Executive Committee.

Activities and Actions

New Director of GGOS Coordinating Office

The director of the GGOS Coordinating Office changed in September 2019. Helmut Titz (BEV, Austria) stepped down due to health issues and Martin Sehnal (BEV, Austria) followed him interimistically and was finally approved by the BEV (Federal Office of Metrology and Surveying, Austria) as the new director of GGOS CO in July 2020.

Day-to-day activities and organisational matters

- Communicate with all entities of GGOS by sending and answering on emails
- Organizing GGOS Executive Committee Teleconferences
- Creating posters, brochures, logos, images and templates
- Collecting/Distributing reports
- Meeting preparation

New GGOS website – https://ggos.org

One major goal of GGOS is to communicate and advocate the benefits of Geodesy to scientists, user communities, policy makers, funding organizations and society. To reach this goal, it is essential to establish a strong online presence. The GGOS website serves as a source of information about GGOS, geodetic data, products, and services, as well as other non-technical resources for the IAG community.

After the transition of the GGOS CO from ASI (Agenzia Spaziale Italiana, Italy) to BKG (Bundesamt für Kartographie und Geodäsie, Germany) in 2015, it was transitioned again to

BEV (Federal Office of Metrology and Surveying, Austria) in 2016. BEV installed a completely new server system and launched a new designed GGOS website in 2017. In 2019 the GGOS Executive Committee decided to refresh and further develop it again to optimize the usability.

The new GGOS website (see image), which was published in December 2020, now emphasizes more on the "Observing System" than on the "GGOS organization" itself. Therefore, the website was enhanced to provide an extensive information platform to bring the IAG observations, products and services in the focus and to attract users from other disciplines. Visually attractive graphics navigate users to easy understandable introductions about geodetic products or observation techniques. Observation and product descriptions are complemented with a huge selection of web links containing scientific descriptions and data repositories provided by the IAG Services and additional data sources.

From 2019 to 2021, the GGOS Coordinating Office worked intensively together with all GGOS components and other important persons of the geodetic scientific community, to establish and launch this new information platform. Furthermore, the contributions of the IAG Services and other providers of geodetic products are gratefully acknowledged. The new GGOS website contributes to make geodesy more visible and to promote IAG and GGOS at global and multidisciplinary levels.

*New GGOS Cloud – https://*cloud.ggos.org

A first version of the GGOS Cloud service was installed in September 2017 and was based on the OwnCloud software. But due to several organizational and technical issues it was switched off. Together with the new GGOS Website, the GGOS Cloud was new developed and was published again in 2020. It is now based on the worldwide often used, regularly updated and free software Nextcloud. GGOS Cloud is fully integrated in the GGOS Website and is used as a file hosting platform for public files. Additionally, it is used to share files within the GGOS community.

*GGOS Blog & GGOS Newsletter – https://*blog.ggos.org

A blog was set up on the GGOS website, where users can find latest news and events of GGOS as well as short introductions into Geodesy and GGOS. Interested persons can subscribe to the GGOS mailing list to receive this news via the GGOS Newsletter https://ggos.org/newsletter/.

GGOS General Outreach Articles

In 2020 the idea was born to publish popular articles regularly (about 2-4 times a year) via email mailing list and also within the GGOS website. The aim of these articles is to strengthen the GGOS Outreach Activities by addressing readers with little or no knowledge of geodesy and its techniques or products. Therefore, the target audience consists of non-geodesists, geoscientists, geodesy students, politicians, etc. It is not the goal to offer updates to the geodetic scientific community. The first articles are planned to publish in 2021 or 2022.

GGOS social media presence via Twitter

A GGOS Twitter account named @IAG_GGOS is operated by the GGOS CO to be present in the social media and to speed up dissemination of GGOS-related information to the customers.

Organized Conferences & Meetings

- Unified Analysis Workshop (UAW) (2019) - together with IERS
- Virtual GGOS Coordinating Board (CB) meetings (2020, 2021)
- GGOS Days 2019, Rio de Janeiro, Brasilia
- GGOS Days 2020, virtual conference

Conference attendance

- European Geosciences Union (EGU) (2020, 2021)
- American Geophysical Union (AGU) (2019, 2020)
- IAG Scientific Assembly (2021)

GGOS External Relations

Manager of External Relations: Allison Craddock (USA)

The position of GGOS Manager of External Relations was officially approved at the Vienna GGOS Days in October 2017. External Relations is based in the Coordinating Office, and works to ensure that GGOS, the IAG, and geodesy in general is represented and visibly contributing to stakeholder initiatives in service to science, Earth observation applications, and society.

Stakeholder Organization Participation

Figure: GGOS external relations with stakeholder organizations, as of December 2020.

Group on Earth Observations (GEO)

Participation at the Programme Board level ensures that IAG/GGOS efforts in alignment with GEO's global priorities (supporting the UN SDGs, Sendai Framework, as well as the Paris Agreement on Climate Change) are well supported and complimentary to other related work – as well as preventing unnecessary redundancy of work. Geodetic observations have a clear role in helping to reduce the risk of disasters, as well as contribute to disaster preparedness with better mitigation and response. Earth observations also play a major role in monitoring progress toward, and achieving, the SDGs.
GGOS has represented the IAG in the Group on Earth Observations (GEO) Programme Board since 2018, and was selected to serve on the GEO Executive Committee in 2021. GGOS Executive Committee members Richard Gross and Allison Craddock have served as IAG representatives to the GEO Programme Board since 2018. Within the Programme Board, IAG has been represented and contributed to the following Subgroups:

- **Subgroup on Sustainable Earth Observations:** which works in tandem with the GEOSS In-Situ Earth Observation Resources foundational task to assess the current Foundational Tasks focusing on both GEOSS Satellite and In-Situ Earth Observation Resources, and to evaluate strengths and weaknesses of observing systems for GEO's activities over the past decade, and to clarify the challenges in coordination of in-situ observations as well as in integrating in-situ and satellite observations toward coordinated observation systems in the future to implement GEOSS.
- **Subgroup on the Sendai Framework:** This subgroup supports GEO's strategic engagement priority area on the Sendai Framework for Disaster Risk Reduction, in the realm of championing and supporting the development of policy objectives that add value, drive efficiencies, and promote the uptake of Earth observations in alignment with Sendai and other disaster risk reduction initiatives. This is particularly relevant to supporting the GGOS Geohazards Focus Area and its Global Navigation Satellite System to Enhance Tsunami Early Warning Systems (GTEWS).
- **Subgroup on Equality, Diversity, and Inclusion:** This subgroup supports the strategic aim of developing GEO as an institution that provides a fair, supportive and encouraging networking environment with which a diverse set of participants engage responsibly. This subgroup aims to ensure that equality, diversity and inclusivity are fully considered, addressed, and embedded within GEO activities and decisions.

Additional IAG representation and participation at the Programme Board level included supporting **Work Programme Engagement Teams** on Climate Change, Cross-Cutting Applications, Sustainable Development Goals, and Disaster Risk Reduction/Hazards.

GGOS also represents IAG in leadership and participation in GEO Working Groups, which were established in 2020 and are open to participation from all GEO stakeholders. GGOS currently participates on behalf of IAG in the Working Groups on Disaster Risk Reduction, Capacity Development (co-chair), Climate Change, and Open Data Policies.

Group on Earth Observations Community Activity: Geodesy for the Sendai Framework

In late 2019 at the GEO Canberra Ministerial Summit, the IAG/GGOS proposal to form a GEO Community Activity dedicated to supporting applications of geodesy to disaster risk reduction was officially approved as a component of the GEO Work Programme 2020-2022. The activity, titled "Geodesy for the Sendai Framework" and often shortened to "Geodesy4Sendai", supports technical and scientific work of the GGOS Geohazards Focus Area with political advocacy for geodesy, and support for geodetic capacity building as a part of broader Earth observations for disaster risk reduction.

UN World Conference on Disaster Risk Reduction 2015 Sendai Japan

Geodesy4Sendai is jointly led by IUGG and IAG/GGOS, represented by John LaBrecque and John Rundle. The GGOS Manager of External Relations, Allison Craddock, serves as its executive secretary. To date, the work of Geodesy4Sendai has focused on the following objectives:

- Supporting geodetic development and capacity building for disaster risk reduction and resilience
- Identifies existing resources and stakeholder communities, and makes connections
- Identifies geodetic elements of targets and indicators of the Sendai Framework for Disaster Risk Reduction
- Provides opportunity for other GEO efforts to interact with geodesy community

- Integration with UN Sustainable Development Goals and UN-GGIM World Bank Integrated Geospatial Information Framework

Geodesy4Sendai strongly aligns with and contributes to implementation of the Sendai Framework for Disaster Risk Reduction, Targets F (Substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of this framework by 2030) and G (Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030), growing international cooperation and resilience – especially in small island developing states – by supporting access to early warning systems and other DRR information.

Committee on Earth Observation Satellites (CEOS)

GGOS has participated in CEOS Plenaries, discussing what GGOS might need from participation in CEOS as an Agency/Partner Update. This is an opportunity for GGOS to speak about its plans and strategies in relation to CEOS, as well as the benefits and expectations of CEOS from the GGOS perspective.

GGOS has recently supported the contributions of geodesy to disaster risk reduction by taking an active role in the CEOS Working Group on Disasters, and Working Group on Capacity Development, especially where the work of these two groups overlaps with GEO and/or UN GGIM.

UN GGIM Subcommittee on Geodesy

GGOS supports and, as needed, represents the IAG at the United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM). IAG works closely with the International Federation of Surveyors (FIG) as Observer participants of the Sub-Committee on Geodesy (SCoG), to provide stability and long-term planning for the GGRF. As the work of the Subcommittee transitions from ideological to implementation-based, especially in the realm of member states making commitments for infrastructure or other contributions, IAG/GGOS participation within both the member state Delegations as well as IAG observers will be important to ensure best possible support of this initiative.

Numerous GGOS members were active in the UN GGIM SCoG on behalf of the IAG this past year:

- Harald Schuh, IAG; SCoG Working Group on Governance
- Detlef Angermann, IAG; SCoG Working Group on Policy, Standards, and Conventions
- Mike Pearlman, IAG

GGOS members also participate on behalf of their member state (country) and in consultation with GGOS External Relations, including:

- Richard Gross, USA; SCoG Working Group on Governance
- Allison Craddock, USA; SCoG Working Group on Communications and Outreach, Working Group on Education, Training and Capacity Building
- Basara Miyahara, Japan; SCoG Working Group on Education, Training and Capacity Building
- Gary Johnston, Australia; SCoG Co-chair (until end of 2019)

- Nicholas Brown, Australia; SCoG Co-chair (2020-present)

In the near future, GGOS will expand its involvement in GGIM as a component of strong IAG support for the proposed UN Global Geodetic Center of Excellence, scheduled to start operations in Bonn, Germany in early 2022.

For more information, please visit the UN-GGIM website: http://ggim.un.org/UN_GGIM_wg1.html.

International Telecommunications Union (ITU)
Focus Group on Artificial Intelligence for Natural Disaster Management (AI4NDM)

In early 2021, GGOS collaborated with GEO Geodesy4Sendai and IUGG GeoRisk Commission to propose a geodesy use case for the newly established ITU Focus Group "AI for Natural Disaster Management." The focus group, which is co-chaired by ITU, the World Meteorological Organization (WMO) and the UN Environment Program (UNEP), examines how Artificial intelligence (AI) and associated machine learning technologies and techniques can enhance our understanding of natural disasters and support disaster relief/early warning.

GGOS is a co-chair of a topic group examining the possible use of artificial intelligence and machine learning for "enabling Natural Hazards Risk Information Sharing Using Derived Products of Export-Restricted Real-Time GNSS Data for Detection of Ionospheric Total Electron Disturbances." This project seeks to explore the feasibility of using AI for novel decentralized domestic processing of GNSS data in countries where:

- Exporting of real-time GNSS data either prohibited by law, or;
- Participation/data sharing is restricted by limited internet bandwidth capacity (such as in small island developing states).

The project will establish guidelines for possible development and sharing of export-permitted data-derived products through artificial intelligence, federated machine learning, or a combination thereof. There is the potential for this to ultimately enable sharing of life-saving geodetic real-time tsunami risk information within the parameters of data export restrictions and/or constrained data transmission infrastructure.

External Relations Geodesy Advocacy Initiatives:
Connecting GGOS with the United Nations Sustainable Development Goals and Sendai Framework for Disaster Risk Reduction

There is tremendous potential to increase the exposure and impact of GGOS by identifying potential contributions and connecting existing relevant work to efforts in support of both UN SDGs and the Sendai Framework. GGOS has the potential to facilitate linkages to agencies and other providers of geodetic data, make existing geodetic data discoverable and easily accessible, and to work toward standardization.

The first External Relations Project, proposed in October 2017, sought to support the wide reach of the GATEW initiative by identifying numerous clear alignments with United Nations Sustainable Development Goals (SDGs) and Sendai Framework for Disaster Risk Reduction. The Manager of External Relations has worked with John LaBrecque, Lead of the Geohazards Monitoring Focus Area, to brainstorm strategies for aligning our work in natural hazards with the United Nations SDGs and Sendai Framework. These two prominent initiatives can clearly benefit from the focus group's involvement, will make GGOS more visible to organizations such as GEO, CEOS, and the UN, and could potentially lead to greater participation in GATEW/GTEWS and other GGOS efforts.

GATEW/GTEWS successfully submitted a chapter/paper for the 2019 UN Global Assessment Report on Disaster Risk Reduction (GAR19), which is a major UN report addressing disaster risk reduction that contributes to regional and global platforms for disaster risk reduction, as well as the high-level political forum on sustainable development.

The complete GAR19, published in May of 2019, is available to download here: https://gar.unisdr.org/sites/default/files/reports/2019-05/full_gar_report.pdf

Following the success of advocating for geodetic contributions to tsunami early warning systems in the 2019 GAR, GGOS worked closely with the International GNSS Service to develop a second successful contribution to a GAR report, scheduled for publication in 2022. This contribution highlights the current and emerging geodetic contributions to complex disaster (wildfire) risk systems modelling, and is in strong support of recent work done by the IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC) by highlighting and advocating the use of geodetic observations for climate studies. It further builds upon work to reinforce the utility of geodetic observations for disaster risk reduction and resilience, as well as introducing public health and wellbeing benefits.

The GAR22 paper, titled "Transdisciplinary application of Global Navigation Satellite System Radio Occultation (GNSS-RO) to characterize atmospheric hazards and model systemic risk," will also identify discrete geodetic contributions to UN Sustainable Development Goals for air quality, specifically Sustainable Development Goal 11: (Make cities and human settlements inclusive, safe, resilient, and sustainable); Indicator 11.6.2 specifically seeks to measure the annual mean levels of fine particulate matter (such as PM 2.5 and PM 10) in cities.

Future Connections

As GGOS connections with the SDGs and Sendai Framework mature, more opportunities to support these initiatives will become available. GGOS External Relations will pursue the most relevant and impactful avenues to ensure that IAG/GGOS enables the greatest use of geodetic data in support of these United Nations initiatives and beyond.

GGOS Working Group on DOIs for Geodetic Data Sets

Chair: Kirsten Elger (Germany)

Members

Chair: Kirsten Elger (GFZ, Germany), Detlef Angermann (TU Munich, Germany), Yehuda Bock (UCDC, US), Sylvain Bonvalot (GET, France), Markus Bradke (GFZ, Germany), Elizabeth Bradshaw (NOC, UK), Carine Bruyninx (ROB, Belgium), Daniela Carrion (Politecnico Milan, Italy), Glenda Coetzer (SARAO, South Africa), Pierre Fridez (CODE/AIUB, Switzerland), Elmas Sinem Ince (GFZ, Germany), Philippe Lamothe (Geodetic Survey Canada), Vicente Navarro (ESA), Carey Noll (CDDIS/NASA, US), Mirko Reguzzoni (Politecnico Milan, Italy), Jim Riley (UNAVCO, US), Dan Roman (NGS, US), Laurent Soudarin (CLS, France), Daniela Thaller (BKG, Germany), Yusuke Yokota (GGOS Japan)

Associated Members

Godfred Amponsah (NGS, US), Sandra Blevins (CDDIS/NASA, US), Roelf Botha (SARAO, South Africa), Francine Coloma (NOAA CORS, US), Allison Craddock (JPL/NASA, US), Michael Craymer (Canadian Geodetic Networks, Canada), Theresa Damiani (NOAA CORS, US), Patrick Michael (CDDIS/NASA, US), Basara Miyahara (GGOS, Japan), Mike Pearlman (Harvard Smithsonian – Center for Astrophysics, US), Nacho Romero (ESA), Christian Schwatke (TU Munich, Germany), Martin Sehnal (GGOS, BEV, Austria), Lori Tyahla (CDDIS/NASA, US)

Motivation and purpose

Data publications with digital object identifiers (DOI) are best practice for FAIR sharing data. Originally developed with the purpose of providing permanent access to (static) datasets described in scholarly literature, DOI today are more and more assigned to dynamic data. These DOIs are providing a citable and traceable reference of various types of sources (data, software, samples, equipment) and means of rewarding the originators and institutions. As a result of international groups, like the Coalition on Publishing Data in the Earth, Space and Environmental Sciences (COPDESS) and the Enabling FAIR Data project, data with assigned DOIs are fully citable in scholarly literature and many journals require the data underlying a publication to be available – even before accepting an article. Initial metrics for data citation allows data providers to demonstrate the value of the data collected by institutes and individual scientists.

This is especially relevant for geodesy, because geodesy researchers are often much more involved in operational aspects and data provision than researchers in other fields might be. Therefore, compared to other scientific disciplines, geodesy researchers appear to be producing less "countable scientific" output. Consequently, geodesy data and equipment require a structured and well-documented mechanism which will enable citability, scientific recognition and reward that can be provided by assigning DOI to data and data products.

To address these challenges and to identify opportunities for improved coordination and advocacy within the geodetic community, the International Association of Geodesy's (IAG) Global Geodetic Observing System (GGOS) has established a Working Group on "Digital Object Identifiers (DOIs) for Geodetic Data Sets". This Working Group is designated to establish best practices and advocate for the consistent implementation of DOIs across all IAG Services and in the greater geodetic community.

Objectives

The main objectives and activities of this working group are

(1) to identify what the community needs from consistent usage of DOIs for data in terms of being able to discover data, permanently cite data, and acknowledge the data providers;
(2) to develop recommendations for DOI minting strategies for different geodetic data types and granularity across IAG Services (static, dynamic, observational data, data products, combination products, networks);
(3) to develop recommendations for a consistent method for data citation across all IAG Services, to support data providers, and to provide quantitative support detailing the use of geodetic datasets and other resources;
(4) to develop recommendations for connecting metadata standards for data discovery (e.g. DataCite, ISO19115) with community metadata standards (GeodesyML, Station Logs)

Activities and Actions

- physical kickoff meeting during AGU2019, monthly to bi-monthly video conferences.
- collection of data products and already existing and planned DOI activities for IAG services and geodetic data centres (living document).
- Outside the box: exploration of DOI minting and citation practices from other communities in the Earth sciences for potential adoption for geodetic data sets: e.g. network DOIs, persistent identifier for instruments, DOI citation recommendations for data compilations and hierarchical data products.

Outcomes

- support for the development of a DOI Service for the International Service for the International Service for the Geoid (IGS) in collaboration with GFZ Data Services (start July 2020).
- development of a concept for assigning DOI to hierarchical products (use case: ICGEM/ COST-G[1]), adoption for ITRF2020 products agreed by IERS CB (May 2021).
- DOIs for "fast living" products (rapid and ultra-rapid products) are supported only if the data are archived for the long term by the datacentre (e.g. AIUB and GFZ have assigned DOIs to their rapid and ultra-rapid IGS products, these DOIs are assigned on the product level and for individual datasets)

Ongoing discussions and future plans

Latest and future discussions explore geodetic metadata standards, like GeodesyML, and the possibility to include existing persistent identifier (PID), like ORCID for researchers, ROR for institutions, PID for instruments and other DOI-related discovery metadata in the geodetic metadata (for stations and data). These activities are aligned with current activities by the IGS infrastructure group to implement GeodesyML in GNSS station metadata. Early adopters are UNAVCO and ROB within M^3G[2], a common initiative between EPOS[3] and EUREF[4]. Our activities will include discussions with the developers of GeodesyML, the recommendation of

---

[1] Monthly GRACE series: https://doi.org/10.5880/ICGEM.COST-G.001, Monthly GRACE-FO series: https://doi.org/10.5880/ICGEM.COST-G.002)
[2] https://gnss-metadata.eu
[3] https://www.epos-eu.org/
[4] http://www.euref.eu/

controlled vocabularies describing geodetic datasets (to be used in metadata for stations and data, ideally the same vocabularies to facilitate cross-references between stations, sensory, data and networks). Moreover, we will explore the potential implementation of the new RDA[5]-derived concept for using PIDs for instruments[6] and include the harmonization of DOI-related metadata from different data centres in our recommendations.

Publications and conference presentations

Blevins, S. M., Tyahla, L., Michael, B. P., Noll, C. E. (2020) IN046-06 - DOIs for geodetic data and derived product collections at the NASA GSFC CDDIS. AGU 2020 Fall Meeting (Online 2020).

Bruyninx, C., Fabian, A., Legrand, J., & Miglio, A. (2020). GNSS Station Metadata Revisited in Re-sponse to Evolving Needs. Copernicus GmbH. https://doi.org/10.5194/egusphere-egu2020-18634

Craddoc, A., Elger, K., Sehnal, M., Fridez, P. (2019) DOIs for Geodetic Datasets. Unified Analysis Workshop, October 2-4, 2019, Paris, France.

Elger, K. (2020): G022-02 - What are the benefits for assigning DOI to Geodetic data? First ideas of the GGOS DOI Working Group - Abstracts, AGU 2020 Fall Meeting (Online 2020).

Elger, K. and the GGOS DOI WG (2020) Report from the GGOS Working Group on DOI for geo-detic data. Oral presentation during the GGOS Days 2020 (October 5-7, 2020, online)

Elger, K., Angermann, D., Bock, Y., Bonvalot, S., Botha, R., Bradke, M., Bradshaw, E., Bruyninx, C., Carrion, D., Coetzer, G., Elger, K., Fridez, P., Ince, E. S., Lamothe, P., Navarro, V., Noll, C., Reguzzoni, M., Riley, J., Roman, D., Soudarin, L., Thaller, D., Yokota, Y., Members, A., Amponsah, G., Blevins, S., Craddock, A., Craymer, M., Michael, P., Miyahara, B., Pearlman, M., Romero, N., Schwatke, C., Sehnal, M., Tyahla, L. (2021): News from the GGOS DOI Working Group - Abstracts, EGU General Assembly 2021 (Online 2021). https://doi.org/10.5194/egusphere-egu21-15081

Elger, K., Coetzer, G., Botha, R., GGOS DOI Working (2020): Why do Geodetic Data need DOIs? First ideas of the GGOS DOI Working Group - Abstracts, EGU General Assembly 2020 (Online 2020). https://doi.org/10.5194/egusphere-egu2020-17861

Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., Schuh, H. (2019): ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services and future plans. - Earth System Science Data, 11, 647-674. https://doi.org/10.5194/essd-11-647-2019

Miglio, A., Bruyninx, C., Fabian, A., Legrand, J., Pottiaux, E., Van Nieuwerburgh, I., & Moreels, D. (2020). Towards FAIR GNSS data: challenges and open problems. Copernicus GmbH. https://doi.org/10.5194/egusphere-egu2020-18398

Reguzzoni, M., Carrion, D., De Gaetani, C. I., Albertella, A., Rossi, L., Sona, G., Batsukh, K., Toro Herrera, J. F., Elger, K., Barzaghi, R., Sansó, F. (2021): Open access to regional geoid models: the International Service for the Geoid. - Earth System Science Data, 13, 4, 1653-1666. https://doi.org/10.5194/essd-13-1653-2021

Sehnal, M., Craddock, A. B., Elger, K. (2020): GGOS Coordinating Office – Recent Achievements and Activities. - Abstracts, AGU 2020 Fall Meeting (Online 2020).

Sehnal, M., Craddock, A., Elger, K. (2020): GGOS Coordinating Office – Recent Achievements and Activities - Abstracts, EGU General Assembly 2020 (Online 2020) https://doi.org/10.5194/egusphere-egu2020-6540

Yokota Y, Ishikawa T, Miyahara B, Otsubo M (2020): Issues and progress of Open Science in geodesy, JpGU-AGU meeting 2020, MGI36-11

Yokota Y, Miyahara B, Otsubo M, Murayama Y, Munekane H, Ishikawa T (2020): Activities of WG on DOIs in GGOS and Data DOI WG in GGOS Japan, JpGU-AGU meeting 2020, SGD01-05

[5] RDA = Research Data Alliance (https://www.rd-alliance.org/)

[6] Persistent Identification of Instruments Working Group: https://www.rd-alliance.org/groups/persistent-identification-instruments-wg

GGOS Affiliate: GGOS Japan

Chair: Toshimichi Otsubo (Japan)
Secretary: Basara Miyahara (Japan)

This multi-institution entity was initially established as GGOS Working Group of Japan in 2013, later approved as GGOS Affiliate in 2017 and renamed as GGOS Japan in 2019. The purpose was to strengthen collaboration among Japan's geodetic stations and colleagues and to foster Japanese space geodetic activities internationally.

In recent years, GGOS Japan has constantly hosted its own annual meetings for broad range of space geodetic research and activities, and also organise smaller-size meetings on specific topics such as data DOI minting (2019) and co-location local tie (2020). It was remarkable that Japanese institutes were nicely collaborated to conduct local tie campaigns for the ITRF2020 project. A new aspect of GGOS Japan is to co-organise existing domestic meetings in the field of VLBI and SLR in 2020 where GGOS Japan core members are often given an opportunity of invited talks, and GGOS Japan is updating the terms of reference in 2021 so that co-hosting or supporting related meetings can be accommodated as one of its roles. It should be noted that in accordance with the renewal of GGOS website the webpages of GGOS Japan were largely updated, utilizing the GGOS Cloud function.

GGOS Japan is a loose organization of public sectors and university members. It does not have membership qualification, but its core members are selected. As of May 2021 they are:

- Chair: Toshimichi Otsubo (Hitotsubashi University)
- Secretary: Basara Miyahara (Geospatial Information Authority of Japan)
- Outreach: Shinobu Kurihara (Geospatial Information Authority of Japan)
- Data DOI WG Lead: Yusuke Yokota (University of Tokyo)
- Technique Representatives:
  - VLBI: Yu Takagi (Geospatial Information Authority of Japan)
  - SLR: Shun-ichi Watanabe (Japan Coast Guard)
  - GNSS: Hiroshi Takiguchi (Japan Aerospace Exploration Agency)
  - DORIS: Yuichi Aoyama (National Institute of Polar Research)
  - Gravity: Koji Matsuo (Geospatial Information Authority of Japan)

These members have actively involved in session planning of annual JpGU meetings and annual Geodetic Society of Japan meetings, where "GGOS" is always seen as (a part of) a session name. Likewise we should make every effort to utilize the "GGOS" keyword for budget hunting, aiming at future GGOS Core sites in Japan or Antarctica. Encouraging geodetic technology development is also in our scope - in addition to high precision and high operability, we are aware that we should significantly reduce costs per geodetic facility envisaging a denser global geodetic network in the future.

GGOS Science Panel

Chair: Kosuke Heki (Japan)

Members:
- *M. Rothacher (Switzerland)*
- *G. Blewitt (USA)*
- *T. Gruber (Germany)*
- *J. Chen (USA)*
- *J. Ferrandiz (Spain)*
- *J. Wickert (Germany)*
- *P. Wielgosz (Poland)*
- *Y. Tanaka (Japan)*
- *M. Crespi (Italy)*
- *B. Heck (Germany)*
- *D. Melgar (USA)*
- *D. Chambers (USA)*
- *E. Forootan (UK/Germany)*

Purpose and Scope

The GGOS Science Panel is a multi-disciplinary group of experts representing the geodetic and relevant geophysical communities that provides scientific advice to GGOS in order to help focus and prioritize its scientific goals. The Chair of the Science Panel is a member of the Coordinating Board and a permanent guest at meetings of the Executive Committee. This close working relationship between the Science Panel and the governance entities of GGOS ensures that the scientific expertise and advice required by GGOS is readily available.

Activities and Actions

The Science Panel provides scientific support to GGOS. During the 2019-2021 period, this support included participation in Consortium, Coordinating Board, and Executive Committee meetings and conference calls.

The Science Panel has been actively promoting the goals of GGOS by helping to organize GGOS sessions at major scientific conferences. During the 2019-2021 period, GGOS sessions have been organized at:

- 2019 American Geophysical Union Fall Meeting in San Francisco
- 2020 American Geophysical Union Fall Meeting (virtual conference)
- 2020 European Geosciences Union General Assembly (virtual conference)
- 2021 European Geosciences Union General Assembly (virtual conference)
- 2020 Japan Geophysical Union – American Geophysical Union Joint Meeting in Chiba, Japan (virtual conference)

As a future session, the Science Panel proposed a GGOS session in the 2021 December American Geophysical Union Fall Meeting (hybrid meeting in New Orleans). Owing to the COVID19 pandemic, most international conferences in 2020 and 2021 were held as virtual online meetings. This situation is anticipated to continue until the condition recovers to the pre-2019 status.

In 2021, the Science Panel cooperated in the effort to renew the GGOS website, being led by the GGOS Coordinating Office and the GGOS Bureau of Products and Standards, specifically in reviewing the GGOS product page descriptions.

Objectives and Planned Efforts for 2021-2023 and Beyond

During the next two years the Science Panel will continue to participate in Consortium, Coordinating Board, and Executive Committee meetings and conference calls. In addition, the Science Panel will continue to help organize GGOS sessions at conferences and symposia including:

- American Geophysical Union Fall Meetings
- Asia Oceania Geosciences Society Annual Meetings
- European Geosciences Union General Assemblies
- International Association of Geodesy General and Scientific Assemblies

The next Unified Analysis Workshop is planned to be held in Munich, Germany during 05-08 October 2021, but the workshop may be postponed considering the COVID19 situation in Europe and the world. The Science Panel will also continue to organize topical science workshops in order to determine the requirements that different scientific disciplines have for geodetic data and products.

With the GGOS Bureau of Products and Standards, the Science Panel will help conduct a Gap Analysis to identify the gap between the data and products provided by the IAG and the needs of the user community. As part of this analysis, a list of Essential Geodetic Variables (EGVs) will be compiled along with observational requirements on those variables. This list of EGVs and their observational requirements can then be used to determine requirements on derived products like the terrestrial reference frame. Activities related to EGV will continue in the committee on EGV established in 2019, which includes the whole Science Panel members.

GGOS Bureau of Networks and Observations

Prepared by Michael Pearlman, Erricos C. Pavlis, Frank Lemoine, Daniela Thaller, Benjamin Männel, Roland Pail, C.K. Shum, Nick Brown, Ryan Hippenstiel

Membership

Standing Committees affiliated with this Bureau:

- **GGOS Standing Committee on Satellite Missions**
- **GGOS Standing Committee on Data and Information Systems**
- **GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)**
- **IERS Working Group on Survey and Co-location**

Associated Members and Representatives:

- Director (Mike Pearlman/CfA USA)
- Secretary (Claudia Carabajal/SSAI NASA USA)
- Analysis Specialist (Erricos Pavlis/UMBC USA)
- IERS Representative (Ryan Hippenstiel/ NOAA USA)
- Representatives from each of the member Services:
  - IGS (Allison Craddock/JPL CalTech USA, Michael Moore/GA Australia)
  - ILRS (Toshi Otsubo/Hitotsubashi U. Japan, Jean-Marie Torre/ OCA France)
  - IDS (Jérôme Saunier/IGN France, Pascale Ferrage/CNES France)
  - IVS (Hayo Hase/BKG Germany, Dirk Behrend/NASA USA)
  - IGFS (Riccardo Barzaghi/PM Italy, George Vergos/UT Greece)
  - PSMSL (Elizabeth Bradshaw/BODC UK, Lesley Rickards/ BODC UK)
- Representatives from each of the member Standing Committees:
  - PLATO (Daniela Thaller/BKG Germany, Benjamin Maennel/GFZ Germany)
  - Data and Information Systems (Nick Brown/GA Australia)
  - Satellite Missions (Roland Pail/TUM Germany, C.K. Shum/OSU USA)
  - IERS WG on Survey Ties and Co-location (Ryan Hippenstiel/ NOAA USA)

Purpose and Scope

- Advocate for new and increased network participation, encouraging formation of new partnerships to develop new sites;
- Hold annual meetings of the Services and Standing Committees/Working Groups to share and discuss status plans, progress;
- Give talks and posters at public meetings to help familiarize the community with GGOS activities;
- Encourage integration of ground observation networks within the GGOS affiliated Network;
- Work with the UN GGIM and its affiliates to develop a plan for the implementation of the IAG geodetic network to satisfy the IAG requirement for the ITRF

Activities

- Participated and gave talks/posters on the BN&O and the ILRS at the AGU, EGU, IAG, JpGU-AGU, etc.
- The BN&O has been advocating for enhanced network infrastructure for Latin America, and participated and gave talks on the GGOS Bureau of Networks and Observations at;

- IUGG meeting "Implementation of the Global Reference Frame (GGRF) in Latin America" in in Buenos Aires, September 16 - 20, 2019;
- SIRGAS meeting in Rio de Janeiro, November 12 – 14, 2019;
- Unified Analysis Workshop in Paris, October 2 – 4, 2019;

- Met with representative from existing and planned stations in Latin America to discuss strategies, station details, equipment, etc.
- Supported new and vulnerable stations and analysis centers with letters of support and documentation;
- New SLR and VGOS stations have recently become active and others are scheduled to become active over the next few years; we have been disappointed by the schedule delays in many stations so we are now taking a closer look at deployment schedules to try to figure out what is realistic and what kind performance we can reasonably expect; from that we can estimate the expected quality of our data products including the Reference Frame.
- Worked with the IGFS define the gravity field measurement configuration at GGOS network core and co-location sites; encourage the cooperation of the IGS and DORIS with PSMSL to enhance the geodetic link of the tide gauges to the reference frame;
- A Memorandum of Cooperation had been established with ROSCOSMOS and the ILRS to enhance cooperation and data diagnosis issues: this may provide a vehicle for broader cooperation; the Russians have been regular participants in ILRS activities, we believe that are desirous of formally joining the GGOS network;
- The GGOS "Site Requirements for GGOS Core Sites" document (with the IAG Services) should be updated to include the requirements for the gravity field with the guidance of the IGFS;

Outcomes and Future Plans

- Continue the tasks above
- Bureau Call for Participation in the "Global Geodetic Core Network: Foundation for Monitoring the Earth System"; work with new potential groups interested in participating; discussions are underway with the Russian SLR network; they participate in ILRS and VLBI activities, but have yet to join the GGOS network; close with the Russians;
- Project network status 5 and 10 years ahead to anticipate data product quality especially the ITRF;
- Work with the IAG and the UN GGIM to develop a plan for the IAG Network to satisfy the ITRF requirements;
- The Standing Committees/Working Groups will each continue their tasks (see below)

Websites:

https://ggos.org/about/org/bureau/bno/

Presentations and Posters

Pearlman, et al., *Update on the Activities of the GGOS Bureau of Networks and Observation,* AGU Fall virtual meeting, December 14, 2018.

..

M. Pearlman, D. Behrend, A. Craddock, C. Noll, E. Pavlis, J. Saunier, A. Matthews, R. Barzaghi,

D. Thaller, B. Maennel, S. Bergstrand, J. Müller, "*GGOS: Current Activities and Plans of the*

*Bureau of Netw*orks and Observations", Abstract No. EGU2019-6181, presented at the European Geosciences Union General Assembly, Vienna, Austria, April 07-12, 2019.

Pearlman et al., *Status and Plans for the GGOS Bureau of Networks and Observations*, IUGG Meeting, Montreal Convention Center, July 15, 2019.

Pearlman, M., *GGOS Bureau of Networks and Observations,* presented at the IUGG, Implementation of the Global Reference Frame (GGRF) in Latin America, Buenos Aires, Argentina, September 16 – 20, 2019.

Pearlman, M., C. Noll, and E. Pavlis, *GGOS Bureau of networks and Observations*, GGOS Days 2019, October 5 – 7, 2019.

Pearlman, M. and Noll, C., *GGOS Bureau of Networks and Observations,* GGOS Days 2019 Meeting, Rio de Janiero, Brazil, November 13 – 14, 2019.

Pearlman, M., et al., "*Current Activities and Plans of the Bureau of Networks and Observations*" *(poster)*, AGU Fall virtual meeting, December 1 – 17, 2020.

GGOS Standing Committee on Performance Simulations & Architectural Trade-Offs (PLATO)

(Joint WG with IAG Commission 1)

Chair: Daniela Thaller (Germany)
Vice-Chair: Benjamin Männel (Germany)

Contributing Institutions (as of May 2021):

- R. Dach, F. Andritsch (AIUB, Switzerland)
- D. Thaller (BKG, Germany)
- M. Bloßfeld, A. Kehm (DGFI-TU Munich, Germany)
- M. Rothacher, I. Herrera Pinzón (ETH Zürich, Switzerland)
- B. Männel, S. Glaser (GFZ/TU Berlin, Germany)
- J. Müller, L. Biskupek (IfE University Hannover, Germany))
- D. Coulot, A. Pollet (IGN, France)
- R. Gross (JPL, USA)
- E. Pavlis (NASA GSFC/JCET, USA)
- E. Mysen, G. Hjelle (NMA, Norway)
- J. Böhm (TU Vienna, Austria)

Purpose and Scope

- Develop optimal methods of deploying next generation stations, and estimate the dependence of reference frame products on ground station architectures
- Estimate improvement in the reference frame products as co-located and core stations are added to the network
- Estimate the dependence of the reference frame products on the quality and number of the site ties and the space ties
- Estimate the improvement in the reference frame products as other satellites are added, e.g., cannonball satellites, LEO, GNSS constellations
- Estimate the improvement in the reference frame products as co-locations in space are added, e.g., use co-locations on GNSS and LEO satellites, add special co-location satellites (GRASP, E-GRASP/Eratosthenes, NanoX, etc.)
- Estimate the improvement in the reference frame products as new observation types and concepts are added, e.g., inter-satellite links

Achievements during the reporting time span:

- Several projects related to simulation studies became funded and even extended to a second phase at various institutions (e.g., GFZ, DGFI-TUM, TU Vienna, BKG)s
- Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn, EPOS-OC)
- A concept for carrying out coordinated simulations and adjacent analysis tests was developed within the group. The start for this activity was delayed due to the pandemic situation.
- Simulations for improved global SLR station networks were carried out (Glaser et al. 2019, Kehm et al. 2019).
- Simulations of optimal locations for an additional VGOS station were carried out, with special focus on its contribution to EOP determination (Schartner et al., 2020). A location in South America is most beneficial.
- Simulations and analysis of VLBI tracking data of Galileo satellites are carried out to assess the possibilities for improving dUT (Wolf et al. 2021).
- The benefit of using a local time transfer system for short VLBI baseline analysis was demonstrated.
- Studies for combined GNSS-Rapid and VLBI Intensives showed that improved ERPs with low latency can be derived (Hellmers et al., 2019).
- Studies on the quality of GNSS-based scale by adding LEOs to an integrated processing or by using Galileo data were carried out. A correction to the satellite antenna phase center offset (PCO) in nadir direction of approx. -200mm was found for GPS.
- Studies on the potential of SLR Short baseline observations (e.g. at Wettzell) for monitoring the terrestrial local ties were carried out in order to identify technique-specific systematic error sources.
- The impact of the local ties (LT) on the reference frame products were studied regarding different stochastic models of the LT, selection of the LT, and the impact of systematically wrong LT (Glaser et al., 2019).
- Studies on the impact of adding the LLR data in infra-red to reference frame products were carried out by IfE, Uni Hannover.
- Simulation capabilities for DORIS have been developed by GFZ.
- Studies on future GNSS constellations were carried out (Glaser et al., 2020).
- Consistent estimation of TRF+CRF+EOP started along with the VLBI reprocessing activities related to ITRF2020 generation.
- Presentations were given at IAG Assembly (July 2019), annual conferences of EGU and AGU as well as meetings of IAG Services.

Future Plans

- Improved analysis methods for reference frame products will be developed with the focus of including all existing data (especially to satellites not yet included in standard TRF products) and all available co-locations
- Simulations performed by PLATO members showed impressively the benefits of a dedicated satellite mission as co-location in space. Therefore, we recommend to strive by all means for a satellite mission dedicated to co-location in space.
- A coordinated analysis campaign with exchanged simulated observations was re-started in May 2021 in order to get an estimate about the comparability of the simulation studies.
- A consistently estimated IVS product for TRF+CRF+EOP will be generated for the first time along with the IVS activities related to ITRF2020.
- Simulations of network projections will be carried out if new potential stations come up.
- Status reports will be given at IUGG General Assembly (2023).
- A dedicated session covering the PLATO topics will be initiated for EGU General Assemblies.
- Annual meetings are foreseen in conjunction with EGU General Assembly or virtually.

Publications

- Glaser S, König R, Neumayer K H, Balidakis K, Schuh H (2019) Future SLR station networks in the framework of simulated multi-technique terrestrial reference frames, Journal of Geodesy doi:10.1007/s00190-019-01256-8
- Glaser S, König R, Neumayer K H, Nilsson T, Heinkelmann R, Flechtner F, Schuh H (2019) On the impact of local ties on the datum realization of global terrestrial reference frames, Journal of Geodesy, doi:10.1007/s00190-018-1189-0
- Glaser S, Michalak G, Männel B, König R, Neumayer K H, Schuh H (2020) Reference system origin and scale realization within the future GNSS constellation "Kepler", Journal of Geodesy, doi: 10.1007/s00190-020-01441-0
- Hellmers, H., D. Thaller, M. Bloßfeld, A. Kehm, A. Girdiuk (2019): Combination of VLBI Intensive Sessions with GNSS for generating Low-latency Earth Rotation Parameters. Advances in Geosciences, 50:49-56. Doi: 10.519/adgeo-50-49-2019
- Herrera Pinzón, I. & Rothacher, M. J Geod (2018) 92: 1079. https://doi.org/10.1007/s00190-017-1108-9
- Kehm A., Bloßfeld M., König P., Seitz F. (2019): Future TRFs and GGOS – where to put the next SLR station? Advances in Geosciences, 50, 17–25, DOI 10.5194/adgeo-50-17-2019
- Männel B. et al. (2018) Recent Activities of the GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO). In: Freymueller J., Sánchez L. (eds) International Symposium on Advancing Geodesy in a Changing World. International Association of Geodesy Symposia, vol 149. Springer, Cham, doi:10.1007/1345_2018_30
- Michalak G, Glaser S, Neumayer K H, König R (2021) Precise orbit and Earth parameter determination supported by LEO satellites, inter-satellite links and synchronized clocks of a future GNSS, Advances in Space Research, doi:10.1016/j.asr.2021.03.008
- M. Schartner, J. Böhm, A. Nothnagel (2020): Optimal antenna locations of the VLBI Global Observing System for the estimation of Earth orientation parameters. Earth Planets and Space, 72 (2020), 87; S. 1 – 14

GGOS Standing Committee on Satellite Missions (CSM)

Chair: Roland Pail (Germany)
Vice-Chair: C.K. Shum (USA)

Members

CSM has quite an open team of members, associate members and guests to work on the various CSM tasks and to provide material for the website, presentation material, and other documentation. CSM traditionally has about one meeting per year, although the pandemic has precluded and will likely prohibit in the near future any such meetings. Therefore, the main work is and will accomplished via email exchanges. Additional members will be added in the near future.

Purpose and Scope

The Committee on Satellite Missions (CSM) has been set-up as an international panel of experts, with consultants of national and international space agencies.

The purpose and scope of CSM is the information exchange with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals. New space missions shall be advocated and supported, if appropriate.

Satellite missions are a prerequisite for realizing a global reference for any kind of Earth observation. They are the key for monitoring change processes in the Earth system on a global scale with high temporal and spatial resolution. Therefore, beyond purely scientific objectives they meet a number of societal challenges, and they are an integral part of the GGOS infrastructure and essential to realize the GGOS goals. The role of CSM is to monitor the availability of satellite infrastructure, to propose and to advocate new missions or mission concepts, especially in case that a gap in the infrastructure is identified.

Activities

Improve coordination and information exchange with the missions for better ground-based network response to mission requirements and space-segment adequacy for the realization of GGOS goals, including:

- Advocate, coordinate, and exchange information with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals;
- Assess current and near-future satellite mission infrastructures and their relevance towards achieving GGOS 2020 goals;
- Support proposals for new mission concepts and advocate for needed missions;
- Interfacing and outreach with other components of the Bureau; especially with the ground networks component, the GGOS Performance Simulations and Architectural Trade Offs (PLATO) activities, as well as with the Bureau of Standards and Products.

Future Activities and Objectives

- Continue the planned activities, i.e., updating the two central lists, supporting future satellite missions, etc.;
- Work with the Coordinating Office to set up and maintain a Satellite Missions Committee section on the GGOS website;
- Evaluate the contribution of current and near-term satellite missions to the GGOS 2020 goals;
- Work with GGOS Executive Committee, Focus Areas, and data product development activities (e.g., ITRF) to advocate for new missions to support GGOS goals;
- Support the Executive Committee and the Science Committee in the GGOS Interface with space agencies;
- Finalize and publish (outreach) of Science and User Requirements Documents for future gravity field missions.
- Increase the exchange and collaboration with PLATO; set up a more formal procedure of collaboration; discuss needs and run simulations to study the impact of future satellite missions, identify gaps for fulfilling the GGOS goals, etc.;
- Investigate possible collaborations with commercial satellite companies, e.g., Spire Global, Inc., PlanetIQ, GeoOptics, with launched Cubesat constellations, on GGOS research and applications including GNSS occultation, and bistatic radar reflectometry.

Website

Website will be built or improved.

Publications and Presentations

Pail, R.; IUGG, Writing Team: Observing Mass Transport to Understand Global Change and Benefit Society: Science and User Needs, An international multi-disciplinary initiative for IUGG; in: Pail, R. (eds.) Deutsche Geodätische Kommission der Bayerischen Akademie der Wissenschaften, Reihe B, Vol. 2015, Heft 320, Verlag der Bayerischen Akademie der Wissenschaften in Kommission beim Verlag C.H. Beck.

GGOS Standing Committee on Data and Information Systems

Chair: Nicholas Brown (GA Austria)
Vice-Chair: Sandra Blevins (NASA USA)

Purpose and Scope

The Committee on Data and Information had two GGOS objective areas:

- Development and implementation of a portal;
- Development and implementation of a metadata scheme

Near term Metadata activity (NASA CDDIS)

CDDIS continues to add new data and derived product collections and further populate collection-level metadata stored in the Earth Observation System Data and Information System (EOSDIS) Common Metadata Repository (CMR). CDDIS is an EOSDIS Distributed Active Archive Centers (DAACs) and thus utilizes the EOSDIS infrastructure to manage collection and granule level metadata describing CDDIS archive holdings; these metadata include 120 published DOIs representing DORIS, GNSS, and SLR data and derived product collections archived at the CDDIS archive. Since the AGU Fall Meeting 2019 the CDDIS actively participates in the GGOS DOI Working Group, sharing NASA Earth Science Data and Information System (ESDIS) DOI methods and best practices with the greater Geodesy community.

Longer-Term Metadata activity (Nick Brown/Geoscience Australia)

Development of a Geodesy Markup Language (GeodesyML), for the GNSS community; potential for expansion to the other space geodesy techniques and GGOS. The current study is identifying metadata standards and requirements, assessing critical gaps and the how these might be filled, what changes are needed in the current standards, and who are the key people who should work on it (more comprehensive scheme). The schema that would be used by its elements for standardized metadata communication, archiving, and retrieval. First applications would be the automated distribution of up-to-date station configuration and operational information, data archives and catalogues, and procedures and central bureau communication. One particular plan of great interest is a site metadata schema underway within the IGS Data Center Working Group. This work is being done in collaboration with the IGS, UNAVCO, SIO, CDDIS, and other GNSS data centers. The current activity is toward a means of exchange of IGS site log metadata utilizing machine-to-machine methods, such as XML and web services, but it is expected that this will be expanded to the other Services to help manage site related metadata and to other data related products and information. Schema for the metadata should follow international standards, like ISO 19xxx or DIF, but should be extendable for technique-specific information, which would then be accessible through the GGOS Portal.

Activities and Actions

Activities underway at CDDIS:

1. Complete collection level metadata related to CDDIS data and derived product holdings in the EOSDIS Common Metadata Repository (CMR)
2. Continue to re-ingest CDDIS data and derived product holdings in order to extract granule level metadata linked to these new collection level records

Activities underway in Geodesy Markup Language (GeodesyML) System

1. Review and document the metadata and standards requirements of precise positioning users in expected high use sectors (e.g. precision agriculture, intelligent transport, marine, location-based services etc.).
2. Assess and document the critical gaps in standards which restrict how Findable Accessible Interoperable and Reusable (FAIR) precise positioning data is for the expected high use sectors.
3. Record use cases of standards being applied well and the benefits it provides to users.
4. Review the "use cases" of geodetic data developed by Geoscience Australia and the IGS Data Center Working Group. (https://drive.google.com/drive/folders/1L792ImLktAiAbmhX9WZhvHrXB3BMD00G?usp=sharing) and document what work and time would be required to ensure these use cases can be met in international standards. This could be:
   - Identify which gaps can be filled by GeodesyML
   - Identify which components of GeodesyML would be better, handled by / integrated with, existing standards (such as TimeSeriesML, SensorML, Observations and Measurements) where possible.
   - Identify which components of already existing international geospatial infrastructure can be approached (such as the European Inspire initiative)
   - Advise on who we should engage with from the OGC/ISO community to facilitate a change to a standard to meet our requirements.
5. Work with Project Partners to develop and test other use cases (e.g. integration of geodetic data with geophysics data (e.g. tilt meters), Intelligent Transport Sector data, mobile applications). Then, document what work and time would be required to ensure these use cases can be met in international standards.
6. Provide advice on how to best engage with the right communities to learn from their experiences, test their tools and influence the development of required standards.

Future Activities and Objectives

1. Working with the IGS Infrastructure Committee, complete the development of the metadata system for GNSS (IAG) and then expand its role to the other IAG Services (IVS, ILRS, IDS, IGFS, etc.).

IERS Working Group on Site Survey and Co-location

Chair: Ryan Hippenstiel (NOAA USA)
Co-Chair: Sten Bergstrand (RISE Sweden)

Members: (Member list will be updated as WG develops and confirmation is received.)

- Zuheir Altamimi (IGN, France)
- Sten Bergstrand (BIPM, France)
- Steven Breidenbach (NOAA/NGS, USA)
- Benjamin Erickson (NOAA/NGS, USA)
- Cornelia Eschelbach (FRA UAS, Germany)
- Kendall Fancher (NOAA/NGS, USA)
- Charles Geoghegan (NOAA/NGS, USA)
- Rudiger Haas (Chalmers, Sweden)
- Ryan Hippenstiel (NOAA/NGS, USA)
- Christopher Holst (Technische Universität München, Germany)
- Kevin Jordan (NOAA/NGS, USA)
- Jack McCubbine (GA, Australia)
- Damien Pesce (IGN, France)

- Jerome Saunier (IGN, France)
- Elena Martínez Sánchez, (Observatorio de Yebes, Spain)
- Daniela Thaller, (BKG, Germany)

Correspondent Members
- Xavier Collilieux (IGN, France)
- Mike Pearlman (Harvard/GGOS, USA)
- Robert Heinkelmann, (GFZ, Germany)

Purpose and Scope

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation. Our group has a new set of terms and has received confirmation of new participants in the group. We would continue to encourage participation from any agency or community that is conducting research, improving protocols, or completing field surveys of local ties as sites with various space geodesy techniques present. Our group has continued to share improved protocols, technologies, and instrumentation to provide the most accurate tie measurements possible for all sites around the world. We reminded participants to share their contributions of local tie data for inclusion into ITRF2020 and many were submitted.

Activities during the period 2019 - 2021

Improvements have been made to standardize report and data submissions of local tie surveys to provide consistency across all agencies. Survey data has recently been reported with new standards in place.

The group is continuing to explore methodologies to measure and quantify antenna deformation. Research and continued field tests using laser scanning and terrestrial inSAR have been discussed. Members completed and documented work researching site-dependent GNSS antenna calibrations to account for systematic errors and biases.

Measurements were collected at the Zeppelin Observatory (Svalbard, Norway) and Hartebeesthoek has been reprocessed (Muller et al., 2020). The latter was assisted by updating of local software to allow estimating VLBI and SLR references points from raw survey data into one single processing.

The US National Geodetic Survey conducted an IERS local site survey at the National Radio Astronomy Observatory in Maui (GNSS and SLR), the Table Mountain Geophysical Observatory in Colorado (new GNSS, gravity), Midway Naval Research Laboratory's OTF in Virginia (GNSS and SLR), and the International Earth Rotation and Reference Systems Service (IERS) Mauna Kea site (VLBA). Surveys were paused in the spring of 2020 due to the COVID pandemic and have not yet resumed fully. It is hopeful that recon and survey efforts will begin again in the fall of 2021.

NGS fully implemented the use of an absolute laser tracking system (Leica AT402) into all completed tie surveys, enhancing precision of terrestrial observations. Progress was made on technical memorandum documenting current NGS procedures which will be released and reflect upon IERS TN39.

NGS has developed deflection of vertical (DoV) measurement capabilities utilizing a robotic total station and camera, and will continue testing equipment in 2021 for hopeful deployment on upcoming local tie surveys.
https://www.euramet.org/research-innovation/search-research-projects/details/project/large-scale-dimensional-measurements-for-geodesy/

References/Publications

Eschelbach, C., Lösler, M., Haas, R., Greiwe (2020) A.: Untersuchung von Hauptreflektordeformationen an VGOS-Teleskopen mittels UAS. In: Wunderlich, T.A. (Eds.): Ingenieurvermessung 20: Beiträge zum 19. Internationalen Ingenieurvermessungskurs, Wichmann, pp. 411-424, ISBN: 978-3-87907-672-7

Eschelbach, C., Lösler, M., Haas, R., Fath, H. (2019) Extension and Optimization of the Local Geodetic Network at the Onsala Space Observatory. In: Proceedings of the 10th IVS General Meeting, Svalbard, pp. 27-31, NASA/CP-2019-219039.

Fancher, K., Hippenstiel, R. (2019) US National Geodetic Survey - Recent and Planned Local Site Survey Activites. Proceedings of the Unified Analysis Workshop 2019. http://ggos.org/media/filer_public/ff/67/ ff679767-62ec-4065-acfc-3394ae85d573/uaw_sitesurvey_1- hippenstiel_usnationalgeodeticsurvey.pdf

Lösler M., Eschelbach C., Riepl S., Schüler T. (2019) A Modified Approach for Process-Integrated Reference Point Determination. Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, 17-19 March 2019, Las Palmas de Gran Canaria, Spain, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, :172-176 DOI: 10.7419/162.08.2019

Lösler, M., Haas, R., Eschelbach, C., Greiwe, A. (2019) Gravitational Deformation of Ring-Focus Antennas for VGOS - First Investigations at the Onsala Twin Telescopes Project. Journal of Geodesy, Vol. 93(10), pp. 2069-2087, DOI: 10.1007/s00190-019-01302-5

Mähler, S., Klügel, T., Lösler, M., Schüler, T., Plötz, C. (2019) Permanent Reference Point Monitoring of the TWIN Radio Telescopes at the Geodetic Observatory Wettzell. In: Proceedings of the 10th IVS General Meeting, Svalbard, pp. 251-255. NASA/CP-2019-219039

Pesce, D., Saunier J. (2019) IGN Recent and Planned Local Site Survey Activities & Contribution to the EURAMET GeoMetre Project. Proceedings of the Unified Analysis Workshop 2019. http://ggos.org/ media/filer_public/9f/b6/9fb60a43-3d60-4218-9f48-89ac81073b79/ uaw_sitesurvey_2-saunier_ignrecentactivities.pdf

Co-location survey online reports http://itrf.ign.fr/local_surveys.php and https://www.ngs.noaa.gov/corbin/iss/:

- Erickson, B., Breidenbach, S., Jordan, K. Maui co-location survey, June 2019
- Jordan, K., Hippenstiel, R., Erickson, B., Fancher, K. Stafford co-location survey, October 2019
- Jordan, K., Hippenstiel, R., Fancher, K. Table Mountain co-location survey, October 2019
- Jordan, K., Hippenstiel, R., May, J. Mauna Kea co-location survey, October 2019
- Muller J.-M., Pesce D., Collilieux X., 2014 Hartebeesthoek co-location survey reprocessing report, dec 2020

GGOS Bureau of Products and Standards

Director: Detlef Angermann (Germany)
Vice Director: Thomas Gruber (Germany)

Members

- *Michael Gerstl (Germany)*
- *Robert Heinkelmann (Germany)*
- *Urs Hugentobler (Germany)*
- *Laura Sánchez (Germany)*
- *Peter Steigenberger (Germany)*

GGOS entities associated to the BPS:

- *Committee "**Contributions to Earth System Modelling**", Chair: Maik Thomas (Germany)*
- *Committee "**Definition of Essential Geodetic Variables (EGV)**", Chair: Richard Gross (USA)*
- *Working Group "**Towards a consistent set of parameters for the definition of a new GRS**", Chair: Urs Marti (Switzerland)*

The Bureau of Products and Standards (BPS) is chaired and operated by the Technical University of Munich. The BPS staff members are Detlef Angermann, Thomas Gruber, Michael Gerstl, Urs Hugentobler and Laura Sánchez (all from Technical University Munich), as well as Robert Heinkelmann (GFZ German Research Centre for Geosciences Potsdam) and Peter Steigenberger (German Aerospace Centre (DLR), Oberpfaffenhofen). The Bureau comprises the staff members, the chairs of the associated GGOS components as well as representatives of the IAG Services and other entities. The present status of the associated members as BPS representatives is summarized in Table **X.1**.

***Tab. X.1**: Representatives of IAG Services and other entities involved in standards and geodetic products (status: May 2021)*

R. Heinkelmann, Germany	International Earth Rotation and Reference Systems Service (IERS)
N. Stamatakos, USA	International Earth Rotation and Reference Systems Service (IERS)
U. Hugentobler, Germany	International GNSS Service (IGS)
E. Pavlis, USA	International Laser Ranging Service (ILRS)
J. Gipson, USA	International VLBI Service for Geodesy and Astrometry (IVS)
P. Štěpánek, Czech Republic	International DORIS Service (IDS)
R. Barzaghi, Italy	International Gravity Field Service (IGFS)
S. Bonvalot, France	Bureau Gravimétrique International (BGI)
M. Reguzzoni, Italy	International Service for the Geoid (ISG)
E. S. Ince, Germany	International for Global Earth Models (ICGEM)
K. M. Kelly, Germany	International Digital Elevation Model Service (IDEMS)
H. Wzointek, Germany	International Geodynamics and Earth Tide Service (IGETS)
J. L. Hilton, USA	IAU Commission A3 Representative
M. Craymer, USA	Chair of Control Body for ISO Geodetic Registry Network
L. Hothem, USA	Vice-Chair of Control Body for ISO Geodetic Registry Network
S. Rózsa, Hungary	IAG Communication and Outreach Branch
D. Angermann, Germany	IAG Representative to ISO/TC211
J. Kusche, Germany	Representative of gravity community

Overview

The Bureau of Products and Standards (BPS) is a key component of IAG's Global Geodetic Observing System (GGOS). It supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth. In order to fully benefit from the ongoing technological improvements of the geodetic observing systems, it is essential that the analysis of the precise observations is based on the definition and application of common standards and conventions. This is an important requirement for reliably monitoring global change phenomena (e.g., global sea level rise) and for providing the metrological basis for Earth system sciences (Fig. X.1).

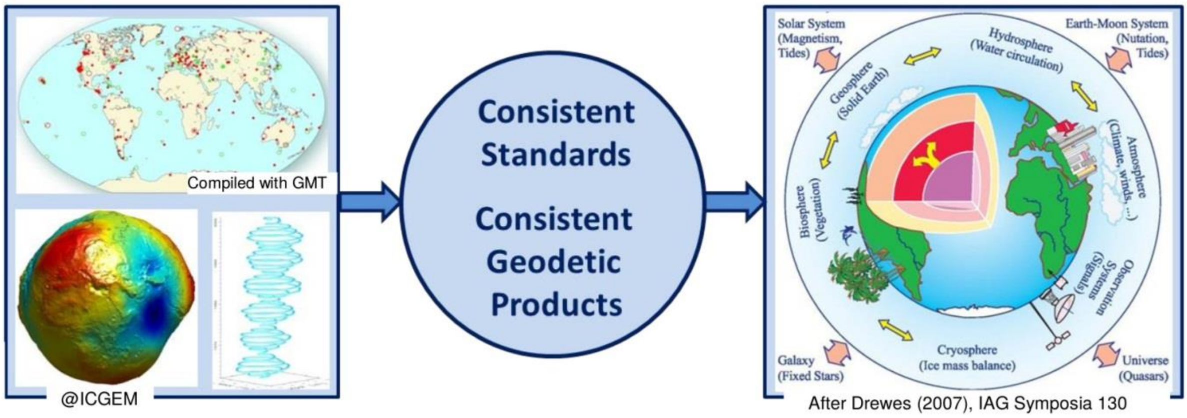


***Fig. X.1**: The integration of the "three pillars" Earth's geometry, rotation and gravity field requires unified standards to obtain consistent geodetic products as the basis for Earth system research and for precisely quantifying global change phenomena.*

Objectives

A key objective of the BPS is to keep track of adopted geodetic standards and conventions across all IAG components as a fundamental basis for the generation of consistent geometric and gravimetric products. The work is primarily build on the IAG Service activities in the field of data analysis and combinations. The BPS acts as contact and coordinating point regarding homogenization of standards and IAG products. Moreover, the BPS interacts with external stakeholders that are involved in standards and conventions, such as the International Organization for Standardization (ISO), the Committee on Data for Science and Technology (CODATA), the International Astronomical Union (IAU), the UN GGIM Subcommittee on Geodesy (SCoG) and the newly established Global Geodetic Centre of Excellence (GGCE).

The objectives of the BPS may be divided into two major topics:

- **Standards**: A key objective is the compilation of an inventory regarding standards, constants, resolutions and conventions adopted by IAG and its components. This includes an assessment of the present status, the identification of gaps and shortcomings concerning geodetic standards and the generation of the IAG products, as well as the provision of recommendations. It is obvious that such an inventory needs to be regularly updated, since the IAG standards and products are continuously evolving. The BPS shall also propose the adoption of new standards where necessary and propagate standards and conventions to the wider scientific community promoting their use. In this context, the BPS recommends the development of a new Geodetic Reference System GRS20XX based on the best estimates of the major parameters related to a geocentric level ellipsoid.

- **Products**: The BPS shall take over a coordinating role regarding the homogenization of standards and geodetic products. The present status regarding IAG Service products shall be evaluated, including analysis and combination procedures, accuracy assessment with respect to GGOS requirements, documentation and metadata information for IAG products. The Bureau shall initiate steps to identify user needs and requirements for geodetic products and shall contribute to develop new and integrated products. The BPS shall also contribute to the development of the GGOS Portal (as central access point for geodetic products), to ensure interoperability with IAG Service data products and external portals (e.g., GEO, EOSDIS, EPOS, GFZ Data Services).

Activities

According to its charter, the BPS has the task to keep track of adopted standards across all IAG components and to evaluate products of IAG with respect to the adequate use of standards and conventions. Based on this general task description, a major activity of the BPS was the compilation of an inventory regarding standards, constants, resolutions and conventions adopted and used by IAG and its components for the generation of IAG products.

Updated version of the BPS inventory

In 2019 and 2020, the second version of the inventory has been prepared for publication in the Geodesist’s Handbook 2020 (Angermann et al., 2020). In this updated version of the inventory the general structure of the original document published in the Geodesist’s Handbook 2016 is largely kept, whereas the contents of the individual sections has been updated to take into account the latest developments.

The updates in the field of standards and conventions comprise the newly released ISO standards by ISO/TC211 covering geographic information and geomatics, the activities of the GGRF Working Group “Data Sharing and Development of Geodetic Standards” within the UN-GGIM Subcommittee on Geodesy, the update of the IERS Conventions initiated by the IERS Conventions Center, and the recently adopted resolutions by IAG, IUGG and IAU that are relevant for geodetic standards and products. In the framework of the update of the IERS Conventions, the director of the BPS has been nominated as Chapter Expert for Chapter 1 “General definitions and numerical standards”.

At the end of 2019, a new GGOS Working Group “Towards a consistent set of parameters for the definition of a new GRS” was established as a component of the BPS to solve open problems regarding numerical standards and open issues related to tide and time systems. The fact that various definitions are in use within the geodetic community is a potential source for inconsistencies and even errors of geodetic products. The BPS recommends to resolve these inconsistencies and to develop a new Geodetic Reference System.

Product-based review of standards and conventions

The second version of the inventory also provides an update regarding IAG products, addressing the following major topics (see Angermann et al., 2020):

- Celestial reference systems and frames
- Terrestrial reference systems and frames
- Earth orientation parameters
- GNSS satellite orbits
- Gravity and geoid
- Height systems and their realizations

New versions of IERS products have been released for the celestial and terrestrial reference frame as well as for the EOP, namely ICRF3, ITRF2014 and EOP 14C04. Although a significant progress has been achieved compared to previous realizations, there are still some deficiencies and open problems that are addressed in this inventory. Recommendations are provided for each product to further improve their accuracy and consistency. Concerning GNSS satellite orbits, the modelling has been improved and some missing information has been provided by the satellite operators, but there are still some remaining deficiencies. A remarkable progress has been achieved in the field of gravity and geoid related data and products, including the development of a dedicated data and products portal based on online applications for the creation of metadata for gravity and geoid data. Also the latest developments and achievements in the field of height systems and their realizations are reported (for details see the Report of the GGOS Focus Area "Unified Height System").

BPS contributions to the new GGOS website

The BPS representation at the GGOS website has been redesigned and updated, including the two Committees "Contributions to Earth System Modelling" and "Definition of Essential Geodetic Variables (EGVs)" and the Working Group "Towards a consistent set of parameters for the definition of a new GRS".

The BPS also contributed to the representation of geodetic products at the GGOS website. The GGOS website should serve as an "entrance door" to geodetic products to satisfy different user needs and communities (e.g., geodesists, geophysicists, other geosciences and further customers, …) in order to make geodesy more visible to other disciplines and to society.

Two classifications for the geodetic products have been implemented at the GGOS website:

- Option 1 "Geodetic themes": Reference frames, geometry, Earth orientation parameters, gravity field, positioning and applications.
- Option 2: "Earth system components and space": Outer and near space, atmosphere, hydrosphere, oceans, cryosphere, solid Earth.

Option 1 provides the classical geodetic view, whereas option 2 should also attract users from other disciplines. So far, about 25 product descriptions have been prepared by the BPS members, including valuable contributions from the IAG Services and several individual persons. The product descriptions provide an overview and easy understandable information on the products, including figures. Furthermore, the data sources (i.e., the links to the IAG Services and other data providers) are given for each product, including selected references. The products have been reviewed by the members of the GGOS Science Panel, coordinated by its chair Kosuke Heki. The product descriptions have been implemented at the GGOS website by Martin Sehnal, the Director of the GGOS Coordinating Office. All the above mentioned contributions are gratefully acknowledged by the BPS.

New BPS Implementation Plan 2020-2022

In 2020, the Implementation Plan for the Bureau of Products and Standards has been revised and updated for the years 2020 to 2022. The major changes were an update of the task descriptions of the BPS and the interactions with other entities involved in standards and conventions, such as the IAU, ISO and the UN-GGIM Subcommittee on Geodesy and its newly established Global Geodetic Centre of Excellence (GGCE).The activities of the BPS are divided into the three main categories: Coordination activities, specific tasks of the BPS and outreach activities. An overview and schedule of the BPS activities is provided in Fig. **X.2**.

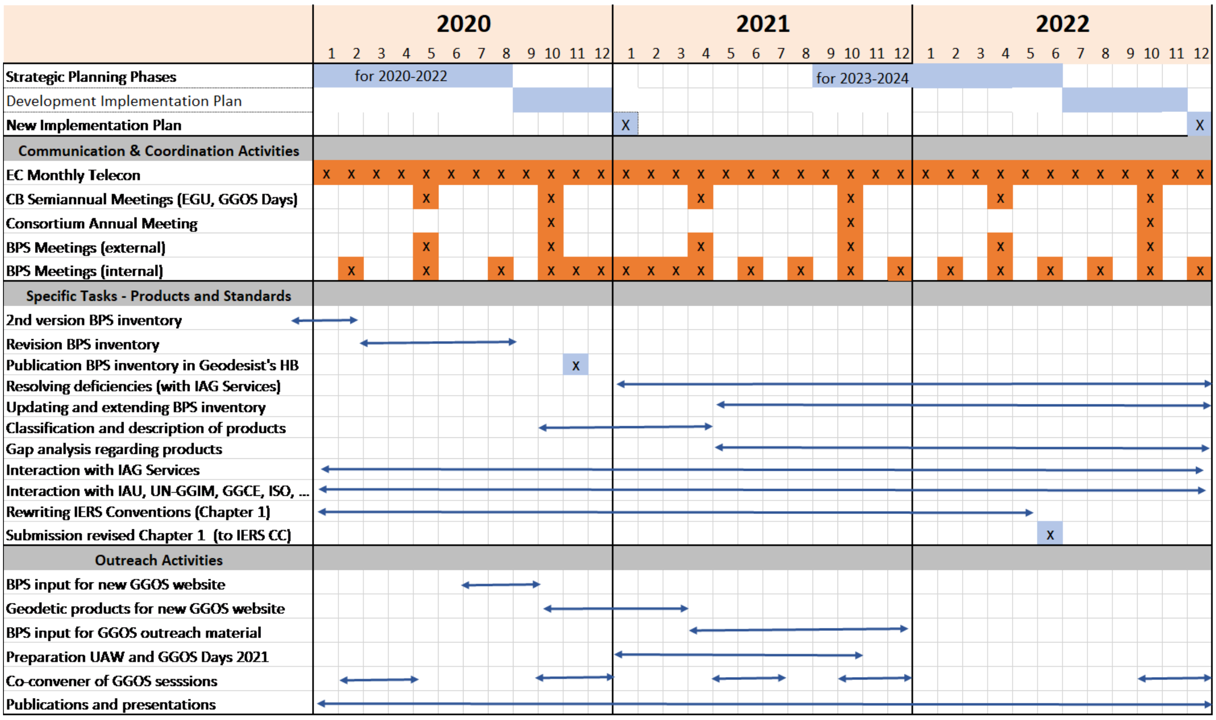


Fig. X.2: Overview and schedule of BPS activities

Selected publications:

- Angermann D, Gruber T, Gerstl M, Heinkelmann R, Hugentobler U, Sánchez L, Steigenberger P (2020): GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products. In: Drewes H, Kuglitsch F, Adám J, Rozsa S (Eds.) The Geodesist's Handbook 2020,Journal of Geodesy, https://doi.org/10.1007/s00190-020-01434-z.
- Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sanchez L., Steigenberger P. (2019): GGOS Bureau of Products and Standards. In: Drewes H., Kuglitsch F. (Eds.), Report of the IAG Vol. 41 - Travaux de l'AIG 41, 2015-2019.

GGOS Committee on Earth System Modeling

Chair: Maik Thomas (Germany)

Role

The GGOS Committee on "Earth System Modeling" tends to promote the development of physically consistent modular Earth system modeling tools that are simultaneously applicable to all geodetic parameter types (i.e., Earth rotation, gravity field and surface geometry) and observation techniques. Hereby, the committee contributes to:

- The interpretation of geodetic monitoring data and, thus, to a deeper understanding of processes responsible for the observed variations;
- The establishment of a link between the geodetic products delivered by GGOS and numerical process models;
- A consistent combination and integration of observed geodetic parameters derived from various monitoring systems and techniques;
- The utilization of geodetic products for the interdisciplinary scientific community.

Objectives

The long-term goal is the development of a physically consistent modular numerical Earth system model for homogeneous processing, interpretation and prediction of geodetic parameters with interfaces allowing the introduction of constraints provided by geodetic time series of global surface processes, rotation parameters and gravity variations. This ultimate goal implicates the following objectives:

- Development of Earth system model components considering interactions and relationships between surface deformation, Earth rotation and gravity field variations as well as interactions and physical fluxes between relevant compartments of the Earth system;
- Promotion of homogeneous processing of geodetic monitoring data (de-aliasing, reduction) by process modeling to improve analyses of geodetic parameter sets;
- Contributions to the interpretation of geodetic parameters derived from different observation techniques by developing strategies to separate underlying physical processes;
- Contributions to the integration of geodetic observations based on different techniques in order to promote validation and consistency tests of various geodetic products.

Activities

The activities of the committee mainly concentrated on systematic comparisons of different stand-alone and coupled model approaches as well as on the development of model interfaces and algorithms for data assimilation.

- Implementation of interfaces to geodetic monitoring data based on Kalman and particle filter approaches in order to constrain and improve stand-alone model approaches and to prove consistency of various geodetic monitoring products;

- Implementation and evaluation of various numerical approaches with different complexities for the consideration of self-attraction and loading in ocean general circulation models;
- Combination of neural network modules with stand-alone models as a basis for further studies on the applicability of artificial intelligence for downscaling purposes.
- Feasibility studies for the provision of error and uncertainty estimates of model predictions of geodetic parameters (Earth rotation, gravity field, surface deformation) due to imperfect model physics, initialization, and external forcing.

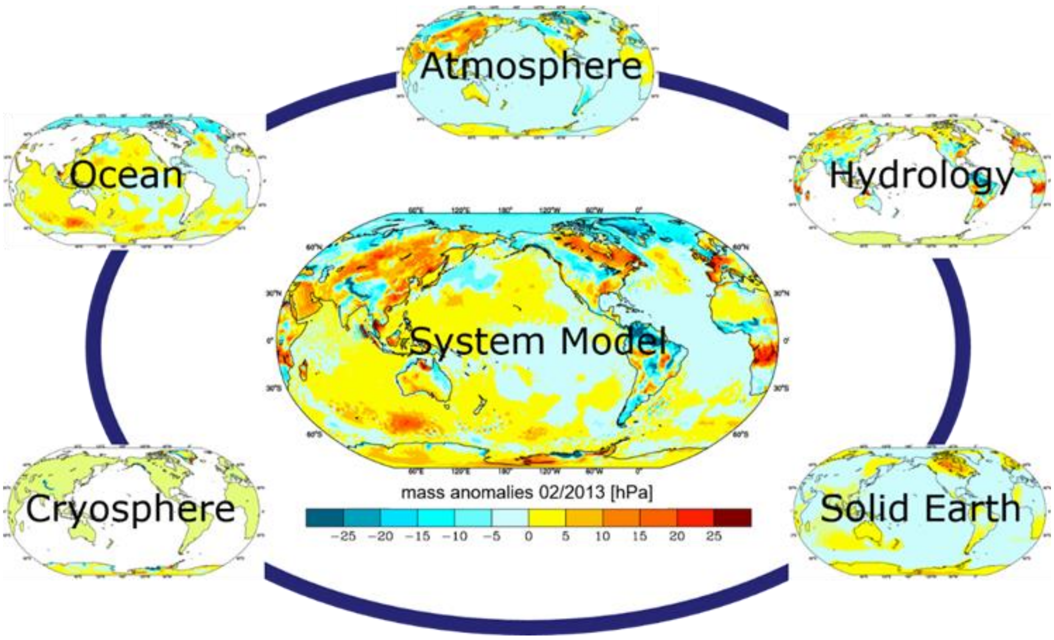


Fig. X.3: *Simulated mass anomalies in a modular system model approach.*

Selected publications:

- Boergens, E., Dobslaw, H., Dill, R., Thomas, M., Dahle, C., Flechtner, F.: Modelling spatial covariances for terrestrial water storage variations verified with synthetic GRACE-FO data. GEM - International Journal on Geomathematics, 11, 24, 2020.
- Irrgang, C., Dill, R., Boergens, E., Saynisch-Wagner, J., Thomas, M.: Self-validating deep learning for recovering terrestrial water storage from gravity and altimetry measurements. Geophysical Research Letters, 47, 17, e2020GL089258, 2020.

Committee on Essential Geodetic Variables

Chair: Richard Gross (USA)

The GGOS BPS Committee on Essential Geodetic Variables was established in 2018 in order to define a list of Essential Geodetic Variables and to assign requirements to them. Essential Geodetic Variables (EGVs) are observed variables that are crucial (essential) to characterizing the geodetic properties of the Earth and that are key to sustainable geodetic observations. Examples of EGVs might be the positions of reference objects (ground stations, radio sources), Earth orientation parameters, ground- and space-based gravity measurements, etc. Once a list of EGVs has been determined, requirements can be assigned to them. Examples of requirements might be accuracy, spatial and temporal resolution, latency, etc. These requirements on the EGVs can then be used to assign requirements to EGV-dependent products like the terrestrial and celestial reference frames. The EGV requirements can also be used to derive requirements on the observing systems that are used to observe the EGVs. And the list of EGVs can serve as the basis for a gap analysis to identify observations needed to fully characterize the geodetic properties of the Earth. During GGOS Days 2017 it was agreed that a Committee within the GGOS Bureau of Products and Standards should be established in order to define the list of Essential Geodetic Variables and to assign requirements to them. This Committee was subsequently established in 2018 and consists of representatives of the IAG Services, Commissions, Inter-Commission Committees, and GGOS Focus Areas.

Tasks

The tasks of the Committee on Essential Geodetic Variables are to:

- Develop criteria for choosing from the set of all geodetic variables those that are considered essential
- Develop a scheme for classifying EGVs
- Within each class, define a list of EGVs
- Assign requirements to each EGV
- Document each EGV including its requirements, techniques by which it is observed, and point-of-contact for further information about the EGV
- Perform a gap analysis to identify potential new EGVs
- Define a list of geodetic products that depend on each EGV
- Assign requirements to the EGV-dependent products
- Hold workshops to engage the geodetic community in the process of defining EGVs, determining their dependent products, and assigning requirements to them

Activities

- A meeting of the Committee on Essential Geodetic Variables was held on 14 July 2019 in Montreal in conjunction with the 27th General Assembly of the IUGG. At the meeting, defining characteristics of essential geodetic variables were discussed.

Members

Committee on EGVs

GGOS
Detlef Angermann (Germany)
Richard Gross, Chair (USA)
Harald Schuh (Germany)

GGOS Focus Area
Unified Height System
Laura Sanchez (Germany)

GGOS Focus Area
Geohazards
Diego Melgar (USA)

GGOS Focus Area
Space Weather
Ehsan Forootan (UK)

IAG Commission 1
Markus Rothacher (Switzerland)
Geoffrey Blewitt (USA)

IAG Commission 2
Kosuke Heki (Japan)
Thomas Gruber (Germany)

IAG Commission 3
Jianli Chen (USA)
Jose Ferrandiz (Spain)

IAG Commission 4
Jens Wickert (Germany)
Pawel Wielgosz (Poland)

IAG ICC Theory
Yoshiyuki Tanaka (Japan)
Mattia Crespi (Italy)

IAG ICC Climate
Annette Eicker (Germany)

IAG Project Quantum
Jürgen Müller (Germany)

IERS
Tom Herring (USA)

IGS
Tom Herring (USA)
Michael Moore (Australia)

ILRS
Erricos Pavlis (USA)
Jürgen Müller (Germany)

IVS
John Gipson (USA)
Johannes Böhm (Austria)

IDS
Laurent Soudarin (France)
Jean-Michel Lemoine (France)

IGFS
Urs Marti (Switzerland)
Georgios Vergos (Greece)

BGI
Sylvain Bonvalot (France)

ICGEM
E. Sinem Ince (Germany)

ISG
Jianliang Huang (Canada)

IGETS
Hartmut Wziontek (Germany)
Jean-Paul Boy (France)

IDEMS
Christian Hirt (Germany)
Michael Kuhn (Australia)

PSMSL
Svetlana Jevrejeva (UK)

Other
Srinivas Bettadpur (UTCSR)
Johannes Bouman (BKG)
Don Chambers (USA)

Total: 38

Working Group "Towards a consistent set of parameters for the definition of a new GRS"

Chair: Urs Marti (Switzerland)

Terms of Reference

The Geodetic Reference System 1980 GRS80 is still the conventional system for most applications in Geodesy and other Earth sciences. It was defined through the four parameters a (semi-major axis), J2 (Dynamical Form Factor), GM (geocentric Gravitational Constant) and ω (Angular Rotation Velocity). It represents the scientific status of the 1970ies and in its concept, the tidal systems and relativistic theories are not considered. Since its adaptation, various inconsistencies have been introduced into geodetic standards and applications, such as new values for GM or a in the IERS conventions. In 2015, a conventional value for the gravitational potential at sea level W0 was adopted in an IAG resolution, which is in contradiction to the definition of GRS80.

This WG will publish a new set of defining parameters for a modern GRS based on todays knowledge and calculate all the necessary derived parameters in a consistent way. It will study the necessity to work towards an IAG resolution to replace GRS80 as the conventional system and provide transformation procedures between the two systems. It will study as well the necessity to define and adopt a conventional global gravity field model for standard applications in geodesy, navigation and related topics.

This JWG is assigned to the GGOS Bureau of Products and Standards (BPS) and works together with representatives of IAG Commissions 1 and 2, the Inter-Commission-Committee on Theory (ICCT), the International Gravity Field Service (IGFS), the International Earth Rotation and Reference Systems Service (IERS) and the Committee on Essential Geodetic Variables (EGV).

This JWG will focus its activities on the coordination of the geometric reference frame, the global height system, the global gravity network and their temporal changes. The application of Earth orientation parameters and tidal models and the underlying standard and reference models has to be brought into consistency.

Objectives and activities

The main objectives and activities of this working group are:

- Calculate consistent parameters of a new mean Earth ellipsoid and derived quantities
- Study the necessity to replace the global reference system GRS80 as the conventional system
- Advance the realization of a conventional global reference gravity field model (combined and satellite only)
- Assist the working group for establishing the International Height Reference System (IHRS) in the realization
- Integrating and combining the global gravity network with other techniques
- Study the influence of earth orientation parameters, tidal models and relativistic effects on the realization of a consistent global reference frame in geometry, height and gravity
- Foster the free exchange of geodetic data and products

Members

Urs Marti (Switzerland), Chair
Detlef Angermann (Germany), Chair of GGOS BPS, IERS
Richard Gross (USA) IAG Vice President, Committee on EGV
Ilya Oshchepkov (Russia), GRS, Gravity Networks and Height Systems
Christopher Kotsakis (Greece), Commission 1
Jonas Ågren (Sweden), Commission 2
Ulrich Meyer (Switzerland) COST-G
Riccardo Barzaghi (Italy), IGFS
Jaakko Mäkinen (Finland), Tidal Systems
Pavel Novak (Czech Republic), ICCT
Laura Sánchez (Germany), IHRF
Hartmut Wziontek (Germany), IGRF
John Nolton (USA), GRS
Robert Heinkelmann (Germany), IAU
Sergei Kopeikin (USA), relativistic effects
Erricos Pavlis (USA), ILRS

Focus Area "Unified Height System"

Lead: Laura Sánchez (Germany)

With contributions from: *H.A. Abd-Elmotaal (Egypt), J. Ågren (Sweden), H. Denker (Germany), W. Featherstone (Australia), R. Forsberg (Denmark), V.N. Grigoriadis (Greece), T. Gruber (Germany), G. Guimarães (Brazil), J. Huang (Canada), T. Jiang (China), Q. Liu (Germany), J. Mäkinnen (Finland), U. Marti (Switzerland), K. Matsuo (Japan), P. Novák (Czech Republic), I. Oshchepkov (Russia), D. Smith (USA), M. Varga (Croatia), G. Vergos (Greece), M. Véronneau (Canada), Y. Wang (USA), K. Ahlgren (USA), R. Winefield (New Zealand), M. Amos (New Zealand), D. Avalos (Mexico), M. Bilker-Koivula (Finnland), D. Blitzkow (Brazil), S. Claessens (Australia), X. Collilieux (France), M. Filmer (Australia), A.C.O.C. Matos (Brazil), J. McCubbine (Australia), R. Pail (Germany), D. Roman (USA), C. Tocho (Argentina), E. Antokoletz (Argentina), H. Wziontek (Germany).*

The GGOS Focus Area "Unified Height System" (GGOS-FA-UHS, formerly Theme 1) was established at the 2010 GGOS Planning Meeting (February 1 - 3, Miami, Florida, USA) to lead and coordinate the efforts required for the establishment of a global unified height system that serves as a basis for the standardisation of height systems worldwide. Starting point was the results delivered by the IAG Inter-Commission Project 1.2 Vertical Reference Frames (IAG-ICP1.2-VRF), which was operative from 2003 to 2011. During the 2011-2015 term, different discussions focussed on the best possible definition of a global unified vertical reference system resulted in the IAG resolution for the Definition and realisation of an International Height Reference System (IHRS) that was approved during the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague, Czech Republic. In the term 2015-2019, actions dedicated to investigate the best strategy for the realisation of the IHRS (i.e., the establishment of the International Height Reference Frame – IHRF) were undertaken. In particular, a preliminary station selection for the IHRF reference network was achieved and different computation procedures for the determination of potential values as IHRS coordinates were evaluated. For the present term, 2019-2023, the objectives of the GGOS-FA-UHS are (i) to compile detailed standards, conventions, and guidelines to support a consistent determination of the IHRF at global, regional and national levels; (ii) to coordinate with regional/national experts in gravity field modelling the computation of a first IHRF solution; and (iii) to design an operational infrastructure that ensures the long-term sustainability and reliability of the IHRS/IHRF. This infrastructure should operate under the responsibility of the International Gravity Field Service (IGFS).

Networking within the IAG

The implementation of a global reference system for physical heights as the IHRS is a big challenge and requires the support of a wide scientific community. Thus, the installation of the IHRS/IHRF is only possible within a global and structured organisation like the IAG. Presently, following entities are contributing to achieve the goals of the GGO-FA-UHS:

- GGOS-FA-UHS and IGFS working group *Implementation of the International Height Reference Frame (IHRF)*, chairs L Sánchez (Germany) and R Barzaghi (Italy).
- ICCT joint study group *Geoid/quasi-geoid modelling for realization of the geopotential height datum*, chairs: J Huang (Canada), YM Wang (USA).
- IAG SC 2.2: *Methodology for geoid and physical height systems*, chairs: G. Vergos (Greece), Rossen S. Grebenitcharsky (Saudi Arabia).
- IAG Commission 2.2 working group *Error assessment of the 1 cm geoid experiment*, chairs: T Jiang (China), V Grigoriadis (Greece).

- IAG Commission 2 joint working group *On the realization of the International Gravity Reference Frame*, chairs: H. Wziontek (Germany), S. Bonvalot (France)
- GGOS-BPS working group *Towards a consistent set of parameters for a new GRS*, chair U Martí (Switzerland)
- *International Gravity Field Service* – IGFS, chair: R, Barzaghi (Italy), vice-chair: G. Vergos (Greece).

Advances in the establishment of the IHRF

To move forwards in the realisation of the IHRS, we currently concentrate on four primary aspects: (1) specific standards and conventions that ensure consistency between the IHRS definition and the IHRF coordinates; (2) a global reference network for the IHRF; (3) the determination of IHRF coordinates at the reference stations; and (4) an operational infrastructure to guarantee a reliable and long-term sustainability of the IHRS/IHRF (see a detailed discussion of these four aspects in Sánchez et al. 2021).

Standards and conventions for the IHRS/IHRF

The IHRS is a gravity potential-based reference system: the vertical coordinates are geopotential numbers [$C(P) = W_0 - W(P)$] referring to an equipotential surface of the Earth's gravity field realised by the IAG conventional value W_0 = 62 636 853.4 m^2s^{-2}. The spatial reference of the position P for the potential $W(P) = W(X)$ is given by the coordinates **X** referring to the ITRS/ITRF. Geopotential numbers are defined as the primary vertical coordinate as they can be converted to any type of physical heights (orthometric or normal heights). As the reference value W_0 is constant and conventionally adopted, the IHRS essentially materialises the combination of a geometric component given by the coordinate vector **X** in the ITRS/ITRF and a physical component given by the determination of potential values W at **X**. To be compatible with the ITRF, the accuracy of the IHRF geopotential numbers and their variation with time should be at least $\pm 3\times 10^{-2}$ m^2s^{-2} (equivalent to $\approx \pm 3$ mm in height) and $\pm 3\times 10^{-3}$ $m^2s^{-2}a^{-1}$ ($\approx \pm 0.3$ mm a^{-1}), respectively. However, for the moment, the goal is to reach $\pm 1\times 10^{-1}$ m^2s^{-2} (about 1 cm) in the static component.

The most pragmatic way to determine potential values W(P) would be to introduce the ITRF coordinates of any point into the harmonic expansion equation representing a global gravity model (GGM) of high degree (up to degree 2190 or higher). These models could provide potential values with accuracies of around ± 0.2 m^2s^{-2} (equivalent to ± 2 cm in height) in regions with flat and moderate terrains when dense and consistent gravity data are used in the computation of the GGM. If no regional gravity data are available to be included in the GGM, the best possible mean accuracy offered by these models would be around ± 2.0 m^2s^{-2} (± 0.2 m), or even worse (up to ± 10 m^2s^{-2} or ± 1 m) in regions with strong topography gradients. To increase this accuracy, the values W(P) could be determined from gravity field observables applying appropriate modelling strategies, which in general correspond to geoid or quasi-geoid computation methods. In the geoid/quasi-geoid computation, the primary functional to be determined is the disturbing potential $T = W - U$. If the disturbing potential T(P) is known, the determination of station potential values W(P) is straightforward. However, the determination of the disturbing potential relies not only on the available gravity data but also on the gravity field modelling approaches. This includes different methods for the handling of terrain effects, the filtering and combination of surface gravity data, the treatment of long-wavelength errors, the mathematical formulations to invert and to integrate gravity and terrain observations, etc. Since there are so many parameter choices when handling the gravity and terrain data, the obtained potential values inevitably vary from computation to computation. Thus, different groups can generate quite different results from the same input data. Nevertheless, to define only one standard procedure for the computation of potential values is unsuitable as different data availability and different data quality exist around the world, and additionally, regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.). On the other hand, a centralised computation of the IHRF coordinates (like in the ITRF) also poses a problem due to the restricted accessibility to terrestrial gravity data.

In order to get as similar and compatible results as possible, we complied a set of basic standards covering general constants, reference ellipsoid, mass centre convention, zero-degree correction to realise the vertical datum defined by the conventional W_0 value, standardised formulas for the conversion of potential coordinates between different permanent tide systems, and a standardised procedure to recover potential values from existing regional/national geoid or quasi-geoid models. The latter is of particular importance as (1) the regional geoid/quasi-geoid models include surface gravity data sets that are not always available for the determination of GGM, (2) the regional models can assimilate new regional/local gravity surveys very quickly, and (3) national/regional experts on gravity field modelling have the best possible knowledge about the local conditions (topography, data distribution, geophysical corrections, validation data, etc.) to be considered in the computation of the geoid/quasi-geoid, or more precisely, in the determination of the disturbing potential T in their countries/regions.

Global reference network of the IHRF

The main criteria for the selection of IHRF reference stations were defined as:

- GNSS continuously operating reference stations to detect reference frame deformations (with preference for stations belonging to the ITRF and the regional reference frames like SIRGAS, EPN, APREF, etc.);
- Co-location with fundamental geodetic observatories to ensure a consistent connection between geometric coordinates, potential and gravity values, and reference clocks;
- Co-location with reference stations of the International Gravity Reference Frame (IGRF) to integrate the gravity and physical height reference frames;
- Co-location with reference tide gauges and connection to the national levelling networks to facilitate the vertical datum unification;
- Availability of terrestrial gravity data around the IHRS reference stations as main requirement for high-resolution gravity field modelling (i.e., precise estimation of potential values).

Based on this criteria, a preliminary station selection for the IHRF was initiated in 2016. This selection was based on a global network with worldwide distribution, including a core network (to ensure sustainability and long-term stability of the reference frame) and regional/national densifications (to provide local accessibility to the global frame). The core network includes fundamental geodetic observatories, ITRF sites with more than two space geodetic techniques, IGRF reference stations and selected IGS reference stations to ensure a global coverage as homogeneous as possible. During 2017-2018, regional and national experts were asked to evaluate whether the preliminary selected sites are suitable to be included in the IHRF (availability of gravity data or possibilities to survey them); and to propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries. After the feedback from the regional/national experts, the first approximation to the IHRF reference network was completed in 2019. This network comprises about 170 stations (Fig. x1) and currently, it is regularly refined in agreement with changes/updates of other geodetic reference frames (ITRF and IGRF and their densifications).

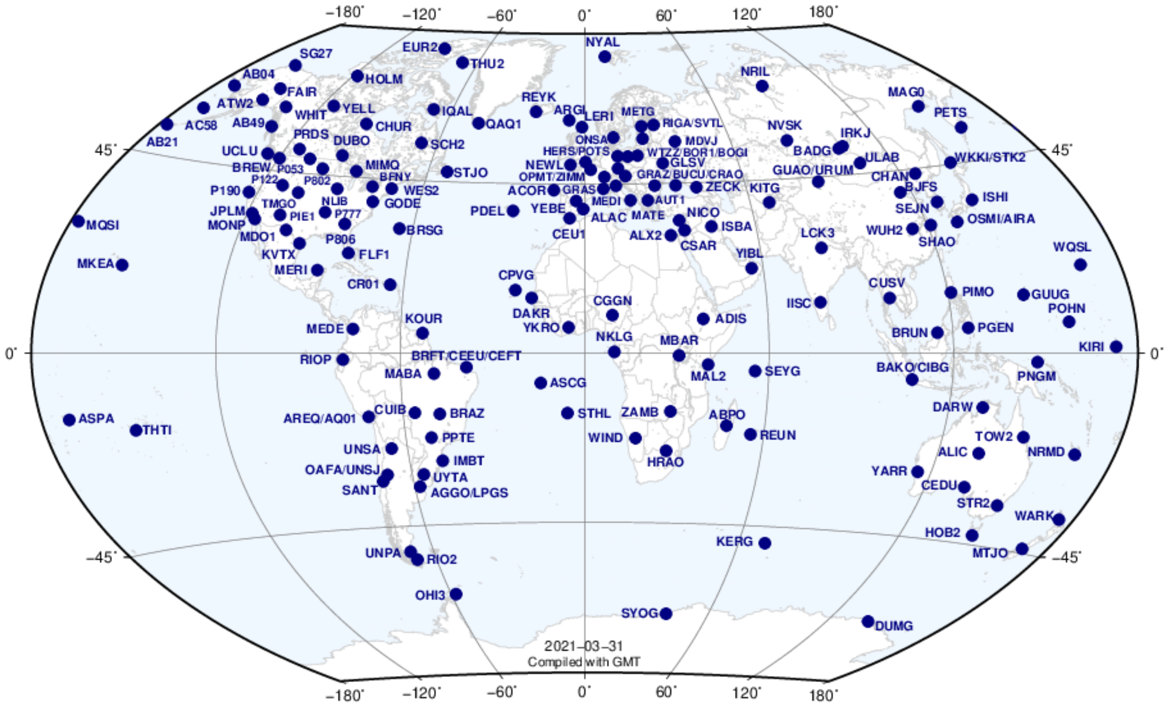


Fig. x1 IHRF reference network (latest update in March 2021)

Determination of IHRF coordinates

A key activity in this regard was the evaluation of different methodologies for the determination of potential values as IHRS/IHRF reference coordinates within the so-called Colorado experiment. This experiment aimed at computing geoid, quasi-geoid and potential values using the same input data and the own methodologies of colleagues involved in the gravity field modelling. About 40 colleagues grouped in fourteen international computation groups contributed to this initiative. The Colorado experiment started at the IAG/IASPEI Scientific Assembly (Aug 2017, Kobe). First results were discussed at the GGHS2018 Symposium (Sep 2018, Copenhagen). A second computation was ready for the EGU2019 (Apr 2019, Vienna) and some refinements (third computation) were delivered in Jun 2019. The results were extensively discussed at the IUGG2019, Symposium G02: Static Gravity Field and Height Systems (July 2019, Montreal). At present, a special issue on Reference Systems in Physical Geodesy to be published in the Journal of Geodesy is preparation. This special issue includes the scientific description of the individual solutions contributing to the Colorado experiment as well as key contributions for the establishment of the IHRS/IHRF and the IGRS/IGRF.

Based on the efforts of the previous term 2015-2019, in particular, the outcomes of the Colorado experiment, we classified the computation of potential values in three main scenarios:

a) Regions without (or with very few) surface gravity data,
   - The only option to determine potential values is the use of GGM of high resolution
   - Expected mean accuracy values around the ±4.0 m^2s^{-2} (±40.0 cm in terms of height) level or even worse in regions with strong topography gradients
   - It could be improved for instance to the ±1.0 m^2s^{-2} (±10.0 cm) level if new and better surface gravity data are included in the GGMs.
   - To avoid multiple potential values provided by different GGM-HRs at the same point, it is necessary to select one GGM-HR as reference model.

b) Regions with some surface gravity data, but with poor data coverage or unknown data quality,
   - The reliability of the existing (quasi-)geoid models is poor
   - Additional gravity surveys around the IHRF stations would help to increase the accuracy of the geopotential numbers computed at those specific stations.

c) Regions with good surface gravity data coverage and quality.
   - Potential values may be inferred from precise geoid/quasi-geoid regional models.

Using this classification, we started in the beginning of 2021 the computation of a first solution for the IHRF. As an initial action, a short description of the “step by step” to infer IHRF potential values from local/regional geoid/quasi-geoid models was prepared. It is based on the IHRS paper published by Sánchez et al. (2021) and was distributed to the members of the working group *Implementation of the International Height Reference Frame (IHRF)*, so that they can compute potential values at the IHRF stations located in their countries using their present/latest geoid/quasi-geoid models. This activity is supported by about 40 colleagues from Canada, Mexico, USA, Germany, Italy, Switzerland, Austria, Sweden, Finland, Australia, Japan, China, South America, Russia, and Africa. Complementary, the ISG and the IGFS are evaluating the quality and documentation of the different regional models available at the Geoid Repository of ISG in order to identify which models can be used to infer potential values. This action is useful for the IHRF computation in areas underrepresented in the working group.

Simultaneously, we are computing potential values for all the IHRF stations (Fig. x1) using GGM extended with topography-based synthetic gravity signals, reaching resolutions up to degree ~ 80000 … ~ 90000. As mentioned, this would be the only option available in those regions where no geoid/quasi-geoid models are available. At the end, we will have different potential values for the same points. The agreement of the different GGM and the models stored by ISG with the own computations performed by the colleagues of the working group will allow us to decide which GGM+topography models perform better. Our goal in this regard is to present the first results at the next IAG2021 Scientific Assembly in Beijing, China.

Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF

An IHRS/IHRF objective is to support the monitoring and analysis of Earth’s system changes. The more accurate the IHRS/IHRF is, the more phenomena can be identified and modelled. Thus, the IHRS/IHRF must provide vertical coordinates and their changes with time as accurately as possible. As many global change phenomena occur at different scales, the global frame should be extended to regional and local levels to guarantee consistency in the observation, detection, and modelling of their effects. From this perspective, we are proposing the establishment of an operational infrastructure within the IGFS that takes care of (cf. Sánchez et al. 2021):

a) Maintenance of the IHRF reference network in accordance with the GGOS-BNO and the coordinators of the reference networks for the ITRF, IGRF and their regional densifications. This activity should be faced by the IHRF reference network coordination (see blue boxes in Fig. x2).
b) Maintenance of a catalogue with the conventions and standards needed for the IHRF. This should consider a harmonisation with the conventions and standards kept by the GGOS-BPO, the IERS Conventions (for the determination of the ITRF), and the standards applied in the IGRF and the global gravity field modelling. This task should be carried out by the IHRF conventions’ coordination (see pink boxes in Fig. x2).
c) The national/regional agencies/entities contributing to the realisation of the IHRF in their regions may be declared as IHRF national/regional computation centres (dark blue

box in Fig. x2). The input data would then be provided by existing IAG gravity field services and local data centres; e.g., GGM are provided by ICGEM and surface gravity data are provided by the Bureau Gravimétrique International (BGI) and refined/complemented with gravity data available at local data centres. In a similar way, one can proceed with digital elevation models (see violet box in Fig. x2).

d) In an ideal data flow scheme, the national/regional IHRF computation centres would provide the IGFS with the following products (cyan box in Fig. x2): potential values at the IHRF reference stations; vertical datum unification parameters (to transform the existing local height systems to the IHRF); mean gravity anomalies or disturbances (without violating data confidentiality but contributing to the determination of improved GGMs); and regional geoid/quasi-geoid models of high resolution. The mean gravity anomalies (or disturbances) and the geoid/quasi-geoid models would be then managed by BGI and ISG. For the combination of the regional/national solutions, validation, storage, management, and servicing of potential values at IHRF stations and vertical datum parameters, the IGFS would have to establish a new element, which could be called IHRF product centre (see magenta boxes in Fig. x2).

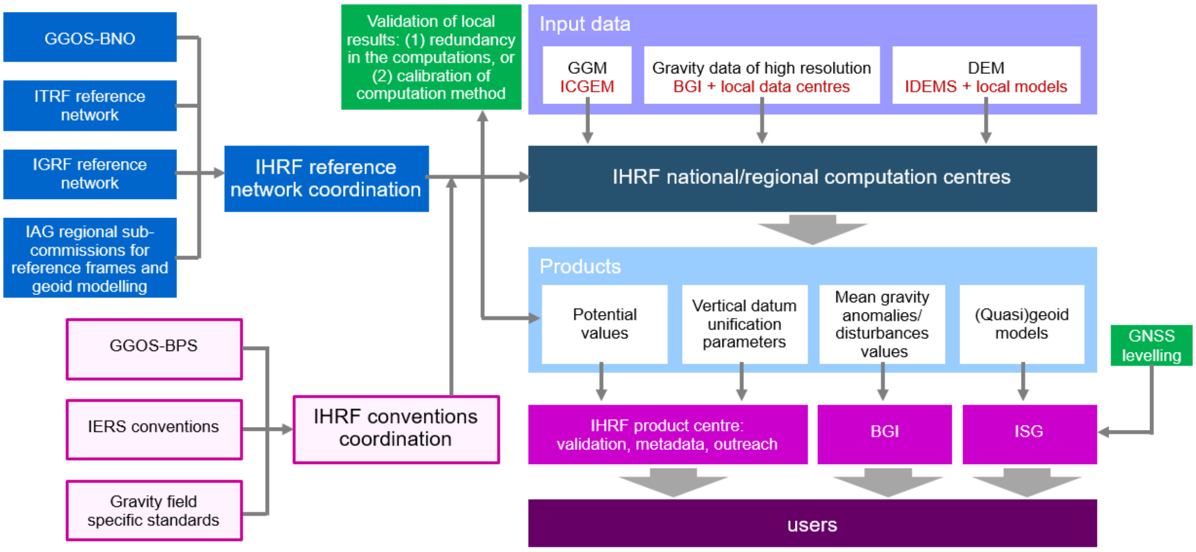


Fig. x2 Proposal for an IHRF operational infrastructure within the IGFS (taken from Sánchez et al., 2021)

Further activities

In addition to the actions oriented to the establishment of the IHRF, following activities are reported since July 2019:

a) Preparation of the Journal of Geodesy Special Issue *Reference Systems in Physical Geodesy* with
   - detailed description, comparison and evaluation of fourteen different approaches for the determination of the geoid/quasi-geoid within the Colorado experiment,
   - an initial strategy for the establishment of the IHRF, and
   - contributions about the establishment of the IGRS/IGRF.
   - Guest editors: L Sánchez, H Wziontek, YM Wang, G Vergos, L Timmen
   - Paper submission from Oct 25, 2019 to May 31, 2020
   - 23 papers submitted: 15 published, 2 rejected, 6 under revision/correction (as of May, 2021)

b) Contribution to the GGOS-BPS inventory with issues related to physical heights

c) Preparation of new texts and graphics for the new GGOS Website

d) Preparation of a joint session on Vertical Reference Systems for the IAG2021 Scientific Assembly together with the IAG Commissions 1 and 2, ICCT, and the project Quantum Geodesy (QuGe)
e) Presentations at: EGU2021 (virtual meeting, Apr 2021), Latin American Regional School on Geodesy (virtual meeting, March 2021), Symposium SIRGAS2020 (virtual meeting, Nov 2020), GGOS Days 2020 (virtual meeting, Oct 2020), SIRGAS webinar on the IHRF (virtual meeting, July 2020), EGU2020 (virtual meeting, May 2020), Symposium SIRGAS2019 (Rio de Janeiro – Brazil, Nov 2019), GGOS Days 2019 (Rio de Janeiro – Brazil, Nov 2019), GGOS-IERS Unified Analysis Workshop (Paris – France, Oct 2019), IUGG Workshop for the implementation the UN-GGRF in Latin America (Buenos Aires – Argentina, Sep 2019).

Selected publications

Abd-Elmotaal H and Kühtreiber N (2020) Direct Harmonic Analysis for the Ellipsoidal Topographic Potential with Global and Local Validation. Surveys in Geophysics, DOI: 10.1007/s10712-020-09614-4.

Claessens SJ, Filmer MS (2020) Towards an International Height Reference System: insights from the Colorado experiment using AUSGeoid computation methods, J Geod, 94: 52, https://doi.org/10.1007/s00190-020-01379-3, Special Issue on Reference Systems in Physical Geodesy.

Grigoriadis VN, Vergos GS, Barzaghi R, Carrion D, Koç O (2021) Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment, submitted to J Geod, Special Issue on Reference Systems in Physical Geodesy.

Işık MS, Erol B, Erol S and Sakil FF (2021) High-Resolution Geoid Modeling Using Least Squares Modification of Stokes and Hotine Formulas in Colorado, J Geod 95, 49 (2021). https://doi.org/10.1007/s00190-021-01501-z.

Jiang T, Dang YM, Zhang CY (2020) Gravimetric geoid modeling from the combination of satellite gravity model, terrestrial and airborne gravity data: a case study in the mountainous area, Colorado. Earth Planets and Space 72, 189. https://doi.org/10.1186/s40623-020-01287-y.

Liu Q, Schmidt M, Sánchez L, Willberg M (2020) Regional gravity field refinement for (quasi-)geoid determination based on spherical radial basis functions in Colorado. J Geod 94-99, https://doi.org/10.1007/s00190-020-01431-2.

Mäkinen J (2021) The permanent tide and the International Height Reference System IHRS, submitted to J Geod, Special Issue on Reference Systems in Physical Geodesy.

Matsuo K and Forsberg R (2021) Gravimetric geoid and quasigeoid computation over Colorado based on the Remove–Compute–Restore Stokes-Helmert scheme, submitted to J Geod, Special Issue on Reference Systems in Physical Geodesy.

Sánchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Pail R, Barzaghi R, Vergos GS, Ahlgren K, Liu Q (2021) Strategy for the realisation of the International Height Reference System (IHRS). J Geod, 95(3), 10.1007/s00190-021-01481-0.

Sánchez L, Barzaghi R (2020) Activities and plans of the GGOS Focus Area Unified Height System, EGU General Assembly 2020, EGU2020-8625, https://doi.org/10.5194/egusphere-egu2020-8625.

Tocho CN, Antokoletz ED, Piñón DA (2020) Towards the Realization of the International Height Reference Frame (IHRF) in Argentina. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2020_93.

Varga M, Pitoňák M, Novák P, Bašić T (2021) Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA, J Geod, 95, 53, https://doi.org/10.1007/s00190-021-01494-9.

Wang YM, Li X, Ahlgren K, Krcmaric J (2020) Colorado geoid modeling at the US National Geodetic Survey, J Geod 94, 106, https://doi.org/10.1007/s00190-020-01429-w.

Willberg M, Zingerle P, Pail R (2020) Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment. J Geod 94, 75 https://doi.org/10.1007/s00190-020-01396-2.

Willberg, M., Zingerle, P. & Pail, R. (2019) Residual least-squares collocation: use of covariance matrices from high-resolution global geopotential models. J Geod 93, 1739–1757. https://doi.org/10.1007/s00190-019-01279-1.

GGOS Geohazards Focus Area

Chair: John LaBrecque (USA)
Geohazards Focus Area Representative to GGOS Science Panel: Dr. Philippe Lognonne

Background:

The GGOS Geohazards Focus Area (GFA) is applying geodetic science, technology, and infrastructure to mitigate natural hazards and improve disaster response. Following the devastating losses of the past two decades and the apparent short comings of available early warning systems the Geohazards Focus Area (GFA) determined to apply geodetic techniques upon the improvement of tsunami warning. The publication of significant advances in real-time technology and analysis laid a compelling case for the implementation of this geodetic capability.

The GFA formally began its first initiative with the April 1, 2016 release of a Call for Participation (CfP) to the GNSS augmentation to the Tsunami Early Warning Systems (GTEWS) (http://kb.igs.org/hc/en-us/articles/218259648-Call-for-Participation-GNSS-Augmentation-to-the-Tsunami-Early-Warning-System). The GTEWS CfP identifies the formal recommendations by the IGS, IUGG, IOC, and the APSG that support the CfP. The GTEWS Initiative seeks to advance and implement the Resolution #4 of the IUGG 2015 General Assembly. The GTEWS Initiative builds upon the benefits of the IGS Real Time Service (GPSRT) and the Multi-GNSS Experiment (MGEX) within the context of the UN-GGIM program.

The GATEW CfP called upon the community of agencies and institutions to join the GATEW working group to support and promote GNSS Augmentation to Tsunami Early Warning system as recommended by Resolution #4 of the 2015 IUGG General Assembly. The membership has grown to 18 institutions from 12 nations with the recent addition of the Indian National Centre for Ocean Information Services (INCOIS),

The GTEWS CfP was distributed to the Earth science and disaster management agencies and institutions of more than 16 countries. The UN-GGIM-AP Secretariat distributed the GGOS GTEWS CfP to the UN-GGIM membership. The GTEWS working group currently comprises 17 agencies and institutions from 11 countries. The agencies and institutions of the GTEWS working group are actively involved in the development of GNSS infrastructure, analysis, and disaster preparedness. The GTEWS working group is a catalyst and motivating force for the definition of requirements, identification of resources, and for the encouragement of international cooperation in the establishment, advancement, and utilization of GNSS for Tsunami Early Warning. The GTEWS CfP and registration to the GTEWS working group remains open and relevant organizations are encouraged to participate.

Resolution 4: Real-Time GNSS Augmentation of the Tsunami Early Warning System (http://www.iugg.org/resolutions/IUGGResolutions2015.pdf):

The International Union of Geodesy and Geophysics

Considering

- That large populations may be impacted by tsunamis generated by megathrust earthquakes,
- That among existing global real-time observational infrastructure, the Global Navigation Satellite Systems (GNSS) can enhance the existing tsunami early warning systems,

Acknowledging

- The need to coordinate with the UNESCO Intergovernmental Oceanographic Commission (IOC) and the established intergovernmental coordination framework to define GNSS network requirements, data sharing agreements and a roadmap for the development and integration of the GNSS tsunami early warning augmentation.

Urges

- Operational agencies to exploit fully the real-time GNSS capability to augment and improve the accuracy and timeliness of their early warning systems,
- That the GNSS real-time infrastructure be strengthened,
- That appropriate agreements be established for the sharing of real-time GNSS data within the tsunami early warning systems,
- Continued support for analysis and production of operational warning products,

Resolves

- To engage with IUGG member states to promote a GNSS augmentation to the existing tsunami early warning systems.
- Initially to focus upon the Pacific region because the high frequency of tsunami events constitutes a large risk to the region's large populations and economies, by developing a prototype system, together with stakeholders, including scientific, operational, and emergency responders.

The GATEW CfP was distributed to the Earth science and disaster management agencies and institutions of more than 16 countries. The UN-GGIM-AP Secretariat distributed the GGOS GATEW CfP to the UN-GGIM membership. The GATEW working group currently comprises 17 agencies and institutions from 11 countries. The agencies and institutions of the GATEW working group are actively involved in the development of GNSS infrastructure, analysis, and disaster preparedness. The GATEW working group is a catalyst and motivating force for the definition of requirements, identification of resources, and for the encouragement of international cooperation in the establishment, advancement, and utilization of GNSS for Tsunami Early Warning. The GATEW CfP and registration to the GATEW working group remains open.

GGOS Working Group on GNSS Augmentation for Tsunami Warning

12 nations - 18 organizations

Country	Organization	Resources	Contact	Email
Australia	GeoScience Australia	Large National Real Time GNSS Network	John Dawson	John.Dawson@ga.gov.au
Chile	U.Chile, Department of Geophysics, CSN	Large National Real time Geodetic and Seismic Network	Sergio Barrientos, Sebastián Riquelme, Juan Baez	sbarrien@dgf.uchile.cl, sebastian@dgf.uchile.cl,jcbaez@csn.uchile.cl
China	GNSS Research Center, Wuhan University	First Real Time Asian Analysis Center	Jianghui Geng	jgeng@whu.edu.cn
China	Shanghai Observatory	Eminent geodetic research organization with strong experience in geodetic infrastructure, analysis and applications.	Shuanggen Jin	sgjin@shao.ac.cn
Colombia	Geological Survey Colombia	Large Real Time GNSS Network, Regional Data Sharing with Brazil, Peru, Panama, Venezuela, COCONet Data Center	Hector Mora	hmora@sgc.gov.co
France	Institut de Physique du Globe de Paris	Strong research in tsunami coupled ionospheric waves and tracking	Giovanni Occhipinti	ninto.a.paris@gmail.com
Germany	GeoForschung Zentrum, Department Geoservices	Strong research and development of GNSS Early Warning including Indonesia and Oman projects	Harald Shuh, Jörn Lauterjung	schuh@gfz-potsdam.de, lau@gfz-potsdam.de
India	Indian National Centre for Ocean Information Services (INCOIS)	INCOIS operates Tsunami Warning Center ESSO and a large array of seismic, tidal guages buoy, GNSS and strong motion accelerometers at sites including the Andaman and Nicobar Islands.	Mrs. Vijaya Sunanda Manneela	shenoi@incois.gov.in, sunanda@incois.gov.in
Italy	University of Rome Geodesy and Geomatics	Initiating research in GNSS Tsunami Warning	Mattia Crespi, Augusto Mazzoni	mattia.crespi@uniroma1.it , augusto.mazzoni@uniroma1.it
Mexico	Instituto de Geofisica, UNAM	Large National GNSS network and analysis system, COCONet Data Center	Enrique Cabral	ecabral@geofisica.unam.mx
New Zealand	GNS Science	Large National Network	Elisabetta D'Anastasion	E.DAnastasio@gns.cri.nz
New Zealand	Land Information New Zealand	Large National Network	Dion Hansen	DHansen@linz.govt.nz
Sri Lanka	Survey Department of Sri Lanka	Strong interest in developing Tsunami Early Warning	P. Sangakkara,Mr A. Dissanayeke	sangakkara@yahoo.com, addsgc@survey.gov.lk
USA	Georgia Tech	Significant focus on subduction zone activity and the generation of tsunamis	Andrew V. Newman	anewman@gatech.edu
USA	Jet Propulsion Laboratory	Real time expertise, Ionospheric mapping, global and operations, earthquake and tsunami warning	Attila Komjathy	attila.komjathy@jpl.nasa.gov
USA	UNAVCO	Global GNSS networks, real time data systems, Global GNSS support	Linda Rowan	rowan@unavco.org
USA	READI Working Group	NASA-NOAA working group developing GNSS Based Tsunami Warning	Yehuda Bock, Timothy Melbourne	ybock@ucsd.edu, tim@Geology.cwu.edu
USA	NASA	NASA Solid Earth Science. Provides funding from GNSS Tsunami Warning development. Cooperating with NOAA in this effort.	Gerald Bawden	gerald.w.bawden@nasa.gov

The GTEWS Initiative:

The GGOS Geohazards Focus Area Website provides links to the foundational documents for the **G**NSS augmentation of **T**sunami **E**arly **W**arning **S**ystems (GTEWS) Initiative. Additional links to presentations, newsletters, videos and other files of interest to the GTEWS community are available at the GATEW online library. https://www.dropbox.com/sh/fg20mtydg136vx6/AABNr2kSnMo429nCxEHhBDfoa?dl=0 .

The GTEWS Working Group held its first meeting in Sendai Japan as part of the GTEWS 2017 workshop July 25-27, 2017. The GGOS Geohazards Focus Area collaborated with NASA, the Association of Pacific Rim Universities (APRU) and the International Research Institute of Disaster Science (IRIDeS) of Tohoku University in support of the GTEWS 2017 workshop. 42 Participants reviewed the status and made recommendations on the development of a GNSS enhanced Tsunami Early Warning System as recommended by Resolution #4 of the IUGG 2015 General Assembly. Full recordings and presentations of the GTEWS 2017 workshop are available here.

The GTEWS 2017 Workshop Report:

Recommendations:

1. The GGOS/IUGG, APRU and the UN-GGIM are encouraged coordinate efforts to develop a GNSS Shield Consortium for the Indo-Pacific.
2. The GNSS Shield Consortium should work to encourage software, data exchange, and continued improvement of network design and performance.
3. Strengthen broadband communication to underserved regions of the GNSS Shield.
4. Work with national organizations including those mandated for natural hazards mitigation to develop agreements for inclusion of their GNSS receivers within the GNSS Shield.
5. Design an optimal GNSS Shield network for both crustal displacement and high-resolution TEC monitoring.
6. Understand the operational requirements of existing tsunami warning systems and determine the steps required to interface these tsunami warning systems.

Over 90% of the GTEWS organizations registered for GTEWS 2017 provided a majority of the presentations that are available on the GTEWS 2017 meeting recording.The GTEWS workshop report is available on numerous websites including the GGOS website, the APRU website and the UNDRR website for the 2019 Global Assessment Report (GAR19). These reports validate that GTEWS is effective and affordable providing tsunami risk reduction and broad economic benefits to both developing and developed nations. GTEWS 2017 workshop recommendations begin with the establishment of a GTEWS Consortium of Principals.

Unfortunately, the 2020 meeting GTEWS Principals Organizational Meeting planned to review and implement the GTEWS 2017 recommendations was postponed due to COVID-19 pandemic. The GTEWS Principals Meeting is postponed to Fall 2022 in Sendai, Japan. The following presents the current status of those plans and agreements for the 2022 GTEWS Principals Meeting.

Plans for the GTEWS Principals Meeting
Date and Venue: Fall 2022, Sendai, Japan
Forum: GEO Geodesy4Sendai Community Activity
Goal: Creation of the GTEWS Consortium per GTEWS 2017 recommendations

- The GTEWS initiative is supported by the 17 institutions of 12 nations that comprise the GTEWS working group of the GGOS Focus Area for Geohazards.
- APRU and Tohoku University IRIDeS pledged support
- The Group on Earth Observation has offered the Geodesy4Sendai community activity as a forum for the assembly of the GTEWS working group and other principal organizations for implementation of the GTEWS 2017 report.
- The GGOS and the IUGG have agreed to collaborate in support of the GTEWS initiative and the planned meeting of GTEWS Principals.
- The ITU Focus Group on AI for Natural Disaster Management (FG-AI4NDM-I-024) has initiated a topic group to advance the application of Artificial Intelligence to GTEWS. Leads: A. Craddock, A Komjathy, J. Rundle, B. Crowell
- Government agency participation is sought to advance sharing of real time data. The involvement of national emergency response agencies will help to solve funding issues and improve inter-agency and international collaborations
- Commercial and Non-government Organizations participation is sought to assist in the availability of international data networking, cloud computing resources, analysis and early warning software.

GGOS Focus Area 'Geodetic Space Weather Research'

Chair: Michael Schmidt (Germany)
Vice-Chair: Ehsan Forootan (Denmark)

Introduction

Space weather means a very up-to-date and interdisciplinary field of research. It describes physical processes in the near-Earth space mainly caused by the Sun's radiation of energy. The manifestations of space weather are multiple, e.g. variations of the Earth's magnetic field, variations of the upper atmosphere consisting of the compartments magnetosphere, ionosphere, plasmasphere, and thermosphere, also known as the MIPT system (due to coupling processes), as well as solar wind, i.e. the permanent emission of electrons and photons including the interplanetary magnetic field (IMF), i.e. the component of the solar magnetic field that is dragged out from the solar corona by the solar wind flow. The magnetosphere is the part of the near-Earth space in which the total magnetic field is dominated by the Earth's magnetic field and not by the IMF. It is well-known that the pressure of the solar wind compresses the magnetic field on the day side of the Earth and stretches it into a long tail on the night side.

Activities

The GGOS Focus Area on Geodetic Space Weather Research (FA-GSWR) has been installed in 2017. At the FA-GSWR splinter meeting during the IUGG 2019 General Assembly in Montreal, it was decided to extend the scientific content of the FA-GSWR by the magnetosphere and the plasmasphere such that it now deals with the complete MIPT system and the mutual couplings. As shown in Fig. 1 the scientific structure of the FA-GSWR can be visualized now as a double tetrahedron.

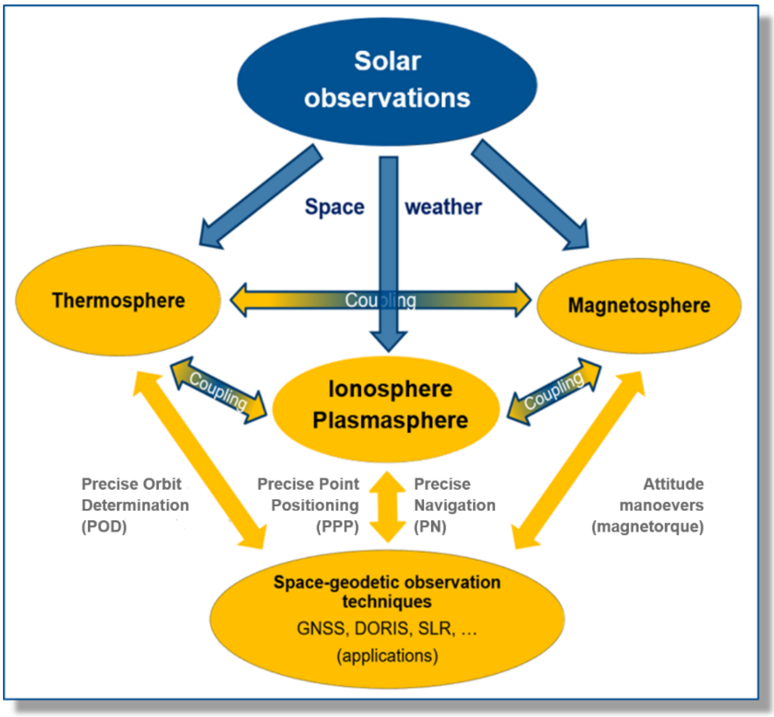


Fig. 1: Structure of the FA-GSWR including the plasmasphere and the magnetosphere: the yellow-colored parts are related to geodetic applications such as Precise Orbit Determination (POD) and Precise Point Positioning (PPP); the blue-colored parts are related to solar phenomena especially to space weather.

The most important task of the FA-GSWR is the development of a concept for the combined evaluation of measurements from solar and geodetic satellite missions as well as magnetic field information under the consideration of the physical coupling processes. Although rather challenging, this concept plays the most important role to reach the main objectives of the FA-GSWR, namely the development of an

(1) improved electron density model of the ionosphere including the plasmasphere and an

(2) improved model of the neutral density in the thermosphere.

In a study members of the FA-GSWR decided that both the electron density and the neutral density should be interpreted as so-called Essential Geodetic Variables (EGV); consequently, the developed improved models should finally be provided as GGOS products to potential users.

To approach these goals, an IAG GGOS Joint Study Group (JSG) and three IAG GGOS Joint Working Groups (JWG) have been established within the FA-GSWR. These IAG GGOS groups are titled as

JSG 1: Coupling processes between magnetosphere, thermosphere and ionosphere (implemented within the IAG ICCT and joint with GGOS)

JWG 1: Electron density modelling (joint with IAG Commission 4)

JWG 2: Improvement of thermosphere models (joint with IAG Commission 4)

JWG 3: Improved understanding of space weather events and their monitoring by satellite missions (joint with IAG Commission 4).

Their achievements in the last two years will be presented in more detail below.

The special issue ‘Observing and Modelling Ionosphere and Thermosphere using in situ and Remote Sensing Techniques’ of the journal ‘Remote Sensing’ was initiated by members of the FA-GSWR. The deadline for manuscript submission was December 31, 2020.

Website

We have significantly updated the GGOS web pages about the FA-GSWR by including more information about space weather in general, but also more detailed information about the work in the JSG and the 3 JWGs. Furthermore, we added on the GGOS web page ‘Geodetic Products’ information about ionosphere and thermosphere products.

Planned activities for the period 2021-2023

In the final two years of the IAG four-year period 2019 – 2023 the FA-GSWR will concentrate on the aspects:

- extensive simulation studies in order to assess the impact of space weather on technical systems and to define – as a consequence – necessary actions in case of severe space weather events
- development of ionosphere and thermosphere models as stated above as GGOS products for direct application
- establishment of recommendations for applications of the models, e.g. in satellite orbit determination, collision analysis and re-entry computations
- continuation of the work on the definition and selection of the EGVs in the framework of the FA-GSWR

- organization of an own conference part for the FA-GSWR at the 2nd International Symposium of the IAG Commission 4 'Positioning and Applications'. This conference was originally planned for September 2020 in Potsdam at GFZ, but due to the Corona pandemic postponed to September 2022.

Website

https://ggos.org/about/org/fa/geodetic-space-weather-research/

JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere

Chair: Andres Calabia (China)
Vice-Chair: Munawar Shah (Pakistan)
Research Coordinator: Binod Adhikari (Nepal)

(Led by ICCT; joint with GGOS, Focus Area on Geodetic Space Weather Research and Commission 4, Sub-Commission 4.3)

Members

Christine Amory-Mazaudier (France, Italy)
Astrid Maute (USA)
Yury Yasyukevich (Russia)
Gang Lu (USA)
Anoruo Chukwuma (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Munawar Shah (Pakistan)
Binod Adhikari (Nepal)
Andres Calabia(China)
Piyush M. Mehta (USA)
LiangLiang Yuan (Germany)
Naomi Maruyama (USA)
Toyese Tunde Ayorinde (Brazil)
Charles Owolabi (Nigeria)
Emmanuel Abiodun Ariyibi (Nigeria)
Olawale S. Bolaji (Australia)

Since this study group is part of the Inter-Commission Committee on Theory (ICCT), the mid-term report of JSG 1 (JSG T.27) can be found in the ICCT Section of this report and is not repeated here.

JWG 1: Electron density modelling

Chair: Fabricio dos Santos Prol (Germany)
Vice-Chair: Alberto Garcia-Rigo (Spain)
(Led by GGOS; joint with Commission 4, Sub-Commission 4.3)

Members

A. Goss (Germany)
A. Smirnov (Germany)
B. Nava (Italy)
D. Themens (United Kingdom)
F. Arikan (Turkey)
G. Jerez (Brazil)
G. Seemala (India)
H. Lyu (Spain)
J. Norberg (Finland)
K. Alazo (Italy)
M. Hoque (Germany)
M. Muella (Brazil)
Mir-Reza Razin (Iran)
O. Arikan (Turkey)
S. Jin (China)
S. Karatay (Turkey)
S. Yildiz (Turkey)
T. Gerzen (Germany)
T. Kodikara (Germany)
Y. Migoya-Orue' (Italy)

Activities during the period 2019-2021

The objective of JWG 1 Electron density modelling is to evaluate and improve established methods of 3D electron density estimation in terms of electron density, peak height, Total Electron Content (TEC), or other derived products that can be effectively used for GNSS positioning or studying perturbed conditions due to representative space weather events. This should be achieved through the realization of three main points:

- Development of a database, where the methods from the group members will be evaluated in terms of GNSS, radio-occultation, in-situ data, altimeters, among other electron density and TEC measurements.
- Pragmatic assessment of established methods for 3D electron density estimation in order to define their accuracy related to specific parameters of great importance for Space Weather and Geodesy.
- Generate products indicating the space weather conditions and expected errors of the methods.

The first two years of the project development were devoted to establish a group of experts and active members on the field in order to solve the project problems by means of a network of collaboration. So far, we have built a fair database for our evaluations, selecting proper instruments and pre-processing techniques to the dataset. A few campaigns were created to carry out a pragmatic model evaluation between the members. In future, the database is expected to be defined as a benchmark to other ionospheric modelling assessments.

Figure 2 shows an example of the global assessment that has been carried out by the group, where the Thermosphere-Ionosphere- Electrodynamics General Circulation Model (TIE-GCM) is evaluated in comparison to critical frequency values given by a global network of ionosondes. The same evaluation was already conducted by four models, including high-resolution global tomography techniques and empirical models. A direct comparison between the models is also being investigated (Prol et al. 2019a, Kodikara et al. 2021), in order to provide an overview of the quality of typical ionospheric models to the community interested in the GGOS focus area on Space Weather. Prol et al. (2018), for instance, have shown that high-resolution 3D ionospheric imaging can provide great improvements in the geodetic positioning when compared to the best VTEC models of the IGS products.

Besides ionosonde measurements, we have gathered in-situ data from C/NOFS, DMSP, GRACE and SWARM missions. Electron density profiles from Incoherent Scatter Radar and GNSS radio-occultation were also included in the analysis, as well as TEC measurements from altimeters and LEO-based satellites. In this regard, it is crucial to understand the quality of the ionospheric instruments used to collect the reference measurements. Therefore, we have conducted a few cross-validations between the electron density measurements provided by the instruments (Smirnov et al. 2021). We have also checked the feasibility of using ionosonde observations to evaluate established TEC models (Jerez et al. 2021).

It is relevant to notice that a main drawback of the 3D ionospheric models nowadays is to conduct a proper description of the topside ionosphere and plasmasphere. Empirical modelling of electron density needs to be essentially improved above the F2 layer peak (hmF2) for a better characterization of the topside TEC (Prol et al. 2019b), which can contribute from 10% to 60% to the ground-based TEC measurements. In this regard, a few studies of the group were devoted to better characterize the upper part of the ionized atmosphere. Recent advances from Prol et al. (2021) and Prol and Hoque (2020, 2021) have shown that great improvements on the topside ionosphere and plasmasphere can be obtained in comparison to typical models, in particular during disturbed conditions due to geomagnetic storm events.

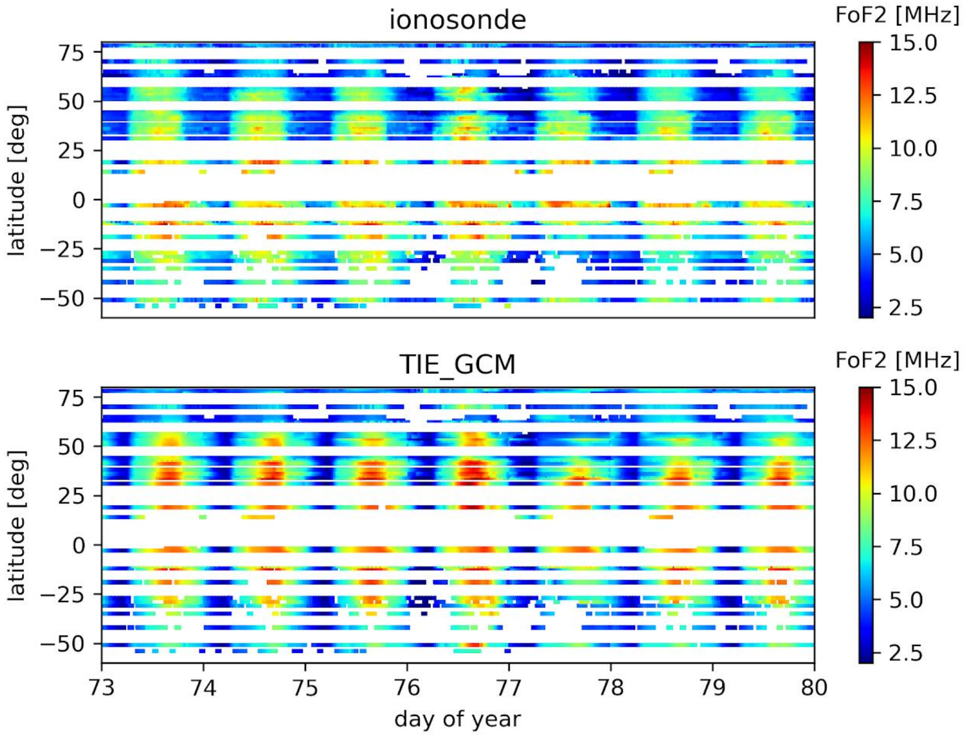


Fig. 2. Critical frequency (FoF2) evaluation during a campaign of 2013. The top panel shows the FoF2 values obtained by the ionosonde measurements. The bottom panel shows the corresponding FoF2 values computed using TIE-GCM model. y-axis is related to the geographical latitude. x-axis is related to the day of the year. The storm event main phase starts in the beginning of DOY 076.

In the next two years, it is expected to provide the final results of the current accuracy of ionospheric models using the best efforts to generate a fair evaluation between the models. Our investigation aims to provide a direct comparison of the accuracy of several models and techniques for ionospheric imaging, in which a simulated case scenario is also expected to be built. In principle, the simulations are planned to describe the electron density ionosphere during a quiet time. As we advance with the project goals, more complex dynamics are planned to be incorporated in the simulations.

Publications

Jerez G.O., Hernández-Pajares M., Prol F.S., Alves D.B.M., Monico J.F G. (2020) Assessment of Global Ionospheric Maps Performance by Means of Ionosonde Data. Remote Sens., 12, 3452. https://doi.org/10.3390/rs12203452

Kodikara T., Zhang K., Pedatella N.M., Borries C. (2021). The impact of solar activity on forecasting the upper atmosphere via assimilation of electron density data. Space Weather, 19, e2020SW002660. https://doi.org/10.1029/2020SW002660

Prol F.S., Camargo P.O., Hernández-Pajares M., Muella M.T.A.H. (2018). A new method for ionospheric tomography and its assessment by ionosonde electron density, GPS TEC, and single-frequency PPP. IEEE Transactions on Geoscience and Remote Sensing, 57, 2571-2582.

Prol F.S., Garcia-Rigo A., Hoque M.M., Schmidt M., Börger K. (2019a) Towards a global 3D ionospheric model for space weather monitoring and GNSS positioning. IUGG General Assembly, Montreal, Canada.

Prol F.S., Themens D.R., Hernández-Pajares M., Camargo P. O., Muella M. T. A. H. (2019b) Linear Vary-Chap Topside Electron Density Model with Topside Sounder and Radio-Occultation Data. Surv Geophys., 40, 277–293. https://doi.org/10.1007/s10712-019-09521-3

Prol F.S., Hoque M.M. (2020) Plasmaspheric electron density estimation based on COMISC/FORMOSAT-3 data, EGU General Assembly 2020, Online

Prol F.S., Hoque M.M. (2021) Topside Ionosphere and Plasmasphere Modelling Using GNSS Radio Occultation and POD Data. Remote Sens., 13, 1559. https://doi.org/10.3390/rs13081559

Prol F.S., Hoque, M.M., Ferreira A. A. (2021) Plasmasphere and topside ionosphere reconstruction using METOP satellite data during geomagnetic storms. J. Space Weather Space Clim., 11, 5. https://doi.org/10.1051/swsc/202007

Smirnov A., Shprits Y., Zhelavskaya I, Lühr H., Xiong C., Goss A., Prol F.S., Schmidt M., Hoque M.M., Pedatella N., Szabo-Roberts M. (2021) Intercalibration of the Plasma Density Measurements in Earth's Topside Ionosphere. Submitted to JGR Space Physics.

Data & Software Products

Andres Calabia, & Shuanggen Jin. (2019, May 29). Supporting Information for "Solar-cycle, seasonal, and asymmetric dependencies of thermospheric mass density disturbances due to magnetospheric forcing". Zenodo. http://doi.org/10.5281/zenodo.3234582

Calabia, Andres, & Jin, Shuanggen. (2019, December 5). Supporting Information for "New modes and mechanisms of long-term ionospheric TEC variations from Global Ionosphere Maps". Zenodo. http://doi.org/10.5281/zenodo.3563463

Calabia, Andres, & Jin, Shuanggen. (2020). Supporting Information for "Short-term ionospheric TEC variations from Global Ionosphere Maps" [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4280436

SIMuRG: System for Ionosphere Monitoring and Research from GNSS. https://simurg.iszf.irk.ru

Other Relevant Links

Community Coordinated Modeling Center:
https://ccmc.gsfc.nasa.gov/models/models_at_glance.php

JWG 2: Improvement of thermosphere models

Chair: Christian Siemes (The Netherlands)
Vice-Chair: Kristin Vielberg (Germany)

(Led by GGOS; joint with IAG Commission 4, Sub-Commission 4.3 and ICCC)

Members

Armin Corbin (Germany)
Ehsan Forootan (Denkmark)
Mona Kosary (Iran)
Lea Zeitler (Germany)
Christopher McCullough (USA)
Sandro Krauss (Austria)
Saniya Behzadpour (Austria)
Aleš Bezděk (Czech Republic)
Sean Bruinsma (France)
Michael Schmidt (Germany)
Barbara Süsser-Rechberger (Austria)
Peter Nagel (USA)

Activities during the period 2019-2021

This working group was founded in November 2019. Since accurate observations of the thermospheric neutral density are the basis for thermosphere models, we formulate the objective to improve thermosphere models through providing relevant space geodetic observations and increasing consistency between datasets by advancing processing methods. Thus, we assembled a group of scientists with a focus on the processing of thermospheric neutral densities from accelerometers, GNSS and satellite laser ranging observations. Additionally, we attracted group members with expertise in data assimilation of mass densities into models.

Our first ongoing activity is the review of space geodetic observations and state-of-the-art processing methods. We started with a comparison of accelerometer-derived mass densities, since our working group has a large expertise in this area. Figure 3 provides an overview of the processing from accelerometer measurements to thermospheric mass densities including the variety of models used in the intermediate steps. In a living document, we assessed the models used by five different institutes in the processing of the densities, which paves the way to decide on a standard processing algorithm in the future.

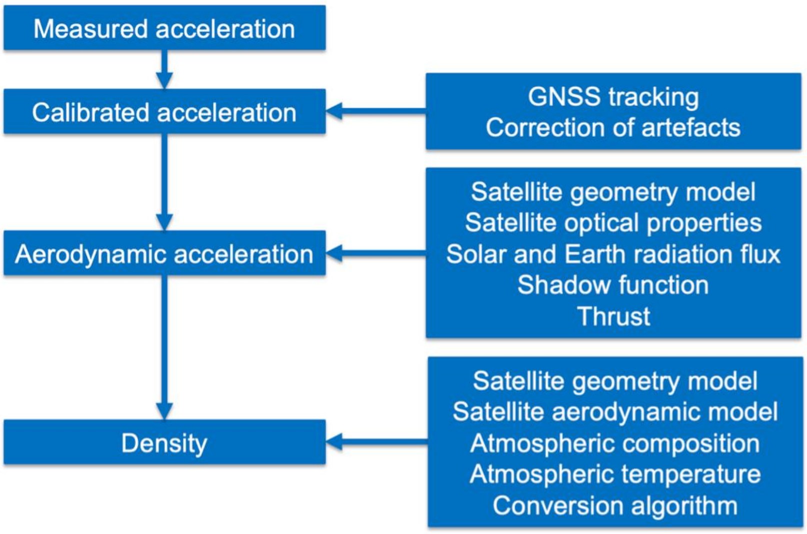


Fig. 3: Processing of measured accelerations to thermospheric mass density including required background models

Besides the theoretical model comparison, we initiated a data comparison. During our group meetings, we agreed on the comparison of GRACE data sets for selected periods with varying solar and geomagnetic activity and different eclipse conditions:

Table 1: Selected periods for the data and model comparison of accelerometer-derived mass densities from GRACE

Start date	Length of selected period	Characteristics
2002-11-20	10 days	high solar activity, includes some geomagnetic activity
2003-05-25	10 days	high solar activity, includes a geomagnetic storm
2008-03-01	5 days	low solar activity, geomagnetic quiet, no eclipses
2008-07-01	1 month	low solar activity, geomagnetic quiet, SRP large compared to aerodynamic acceleration
2015-03-15	5 days	high solar activity, St. Patrick's day storm

Already GRACE data sets from three processing centres are available for comparison. These include calibrated accelerometer data, orbits, modelled aerodynamic and radiation pressure accelerations and the final mass density. The ongoing comparison will provide insights into the major processing differences and will help to increase the consistency of accelerometer-derived densities in the future.

Beyond the joined activities of the working group, our group members published the following research papers relevant to improving thermospheric densities.

Publications

Bandikova, B., McCullough, C., Kruizinga, G. L., Save, H., and B. Christophe. "GRACE Accelerometer Data Transplant." Advances in Space Research. 2019, 64 (3), pages 623-644. doi: 10.1016/j.asr.2019.05.021

Behzadpour, S., Mayer-Gürr, T., and S. Krauss (2021). GRACE Follow-On accelerometer data recovery. Journal of Geophysical Research: Solid Earth, 126, e2020JB021297. https://doi.org/10.1029/2020JB021297

Farzaneh, S. and E. Forootan (2020), A least squares solution to regionalize VTEC estimates for positioning applications. MDPI Remote Sensing, 12 (21), pages 3545, doi.10.3390/rs12213545

Forootan, E., Farzaneh, S., Kosary, M., Schmidt, M., and M. Schumacher (2021), A simultaneous Calibration and Data Assimilation (C/DA) to improve NRLMSISE00 using Thermospheric Neutral Density (TND) from space-borne accelerometer measurements. Geophysical Journal International, 224 (2), pages 1096-1115, doi.10.1093/gji/ggaa507

Forootan, E., S. Farzaneh, C. Lück, and K. Vielberg (2019). Estimating and predicting corrections for empirical thermospheric models. Geophysical Journal International 218(1), 479-493. doi:10.1093/gji/ggz163

Krauss S., S. Behzadpour, M. Temmer and C. Lhotka (2020). Exploring Thermospheric Variations Triggered by Severe Geomagnetic Storm on 26 August 2018 Using GRACE Follow-On Data. Journal of Geophysical Research: Space Physics, 125, e2019JA027731. https://doi.org/10.1029/2019JA027731.

Palmroth, M., Grandin, M., Sarris, T., Doornbos, E., Tourgaidis, S., Aikio, A., Buchert, S., Clilverd, M. A., Dandouras, I., Heelis, R., Hoffmann, A., Ivchenko, N., Kervalishvili, G., Knudsen, D. J., Kotova, A., Liu, H.-L., Malaspina, D. M., March, G., Marchaudon, A., Marghitu, O., Matsuo, T., Miloch, W. J., Moretto-Jorgensen, T., Mpaloukidis, D., Olsen, N., Papadakis, K., Pfaff, R., Pirnaris, P., Siemes, C., Stolle, C., Suni, J., van den IJssel, J., Verronen, P. T., Visser, P. and M. Yamauch (2021). Lower-thermosphere–ionosphere (LTI) quantities: current status of measuring techniques and models. Annales Geophysicae, 39 (1), pages 189-237. Copernicus GmbH.

van den IJssel, J., Doornbos, E., Iorfida, E., March, G., Siemes, C., and O. Montenbruck (2020). Thermosphere densities derived from Swarm GPS observations. Advances in Space Research, 65 (7), pages 1758-1771.

Vielberg, K. and J. Kusche (2020). Extended forward and inverse modeling of radiation pressure accelerations for LEO satellites. Journal of Geodesy, 94 (43). https://doi.org/10.1007/s00190-020-01368-6

JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

Chair: Alberto Garcia-Rigo (Spain)
Vice-Chair: Benedikt Soja (Switzerland)

(Joint with IAG Commission 4, Sub-Commission 4.3)

Members

Anna Belehaki (Greece)
Anthony J. Mannucci (USA)
Jens Berdermann (Germany)
Xiaoqing Pi (USA)
Pietro Zucca (The Netherlands)
Denise Dettmering (Germany)
Consuelo Cid (Spain)
Rami Qahwaji (UK)
Jinsil Lee (Republic of Korea)

Activities during the period 2019-2021

JWG3 aims at gaining a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment. In particular, by analyzing the correlation between Space Weather data from different sources (including observations from spacecraft and radio telescopes) and perturbed ionospheric/plasmaspheric conditions derived from different space geodetic techniques (e.g. GNSS, DORIS, RO, VLBI, satellite altimetry) and identifying the main parameters that could be useful to improve their real time determination and their forecasts in extreme conditions.

For this purpose, a multidisciplinary team has been assembled. In fact, the members of the WG provide access to complementary models as well as operational products/services linked to: ionospheric Total Electron Content determination, ionospheric electron density, geomagnetic disturbances from the Sun to Earth, DORIS ionospheric products, TIDs and scintillations, solar flares detection/prediction, EUV flux-rate, CMEs and SEPs, solar corona electron density, dimmings and coronal holes, solar wind, polar depletions, among others. Combination of such measurements and estimates can pave the way for a better understanding of space weather events.

At first, an online survey form to gather feedback from JWG 3 members was carried out to have a better understanding of the complementarity within the team, which was helpful to identify the existing background in both geodetic and space weather domains.

In particular, we identified potential useful data sources to broaden our analysis, as well as the existing models and operational products/services being provided or accessible by the members. Furthermore, applications that could impact positively to end users were listed, complementing the initial considered ones. In addition, it was a way to interchange ideas on the objectives and expectations of what the JWG should be.

At first, a set of three historical representative space weather events were selected. Given these were coincident with the ones selected within JWG 1, we have finally extended the events to be analyzed adding a fourth case which was also considered by JWG 1. Thus, we will analyze storm-related periods in 2013, 2015, 2017 and 2018. Also note that the connection between both joint working groups was considered a key objective from the beginning.

Fig 4: Capture of the online survey form

We are currently working on the correlation between SW products and perturbed ionospheric electron density/Total Electron Content, jointly with JWG 1. In particular, we are compiling and/or generating data and plots from different sources (see few plots below) that could be linked to the selected events useful to understand perturbed conditions and features found within JWG 1 analysis. The possibility to provide insights of these correlations could be helpful for JWG 1 and may also be highlighted through their website and database, as part of the coordination process we are conducting with them. We also keep in mind that for the monitoring and prediction of space weather events' and their impact on geodetic measurements, low latency data availability would be of great importance, ideally in real time (RT) or near real time (NRT), also to enable triggering alerts.

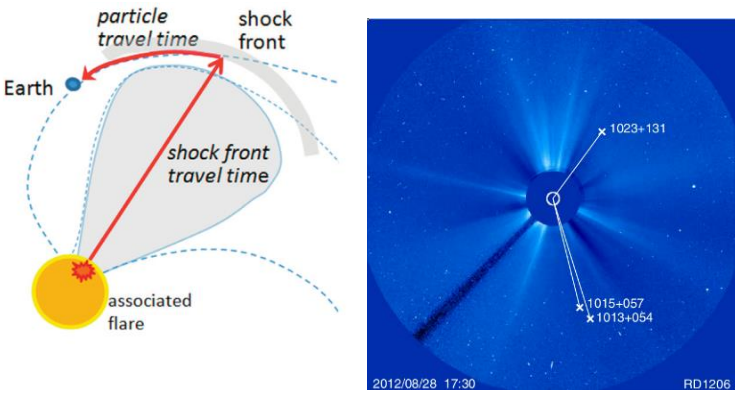


Fig. 5: Left: Shock interaction with the interplanetary magnetic field of SEP events associated to eastern events (Garcia-Rigo et al., 2016). Right: Radio source geometry and coronagraph images for VLBI experiment to assess the electron density of the solar corona (Soja et al., 2014)

The conducted analyses and the combination of measurements and estimates, derived from space geodetic techniques and from solar spacecraft missions, shall lead us to a better understanding of the main parameters that could be useful to improve real time determination as well as predictions derived from geodetic techniques, in case of extreme solar weather conditions. In fact, there is the interest within the team on how well models can reproduce changes during storms, understanding the interactions with the solar wind and magnetosphere, and how correlation of data from different available techniques could be key in this regard.

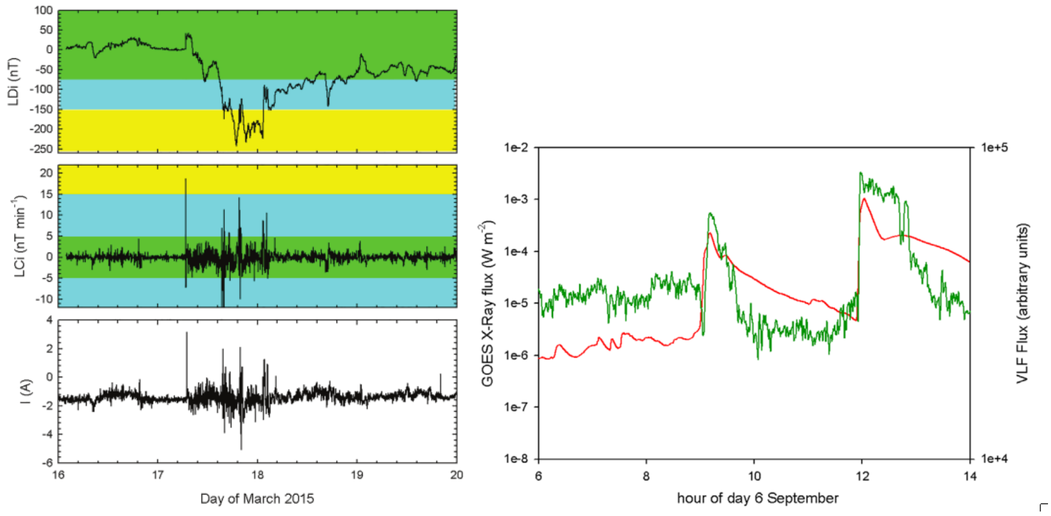


Fig. 6: Left: (from top to bottom) the LDi and LCi geomagnetic indices, and the geomagnetically induced current measured at a substation in the northwest of Spain by REE during the period from 16 to 20 March 2015. Colored areas in panels correspond to the five-level scale introduced to help decision makers in an operational environment (Cid et al., 2020). Right: Superposed plot of the GOES X-ray flux (red) and the amplitude of GQD recorded at UAH receiver (green) from 6 to 14 UT on 6 September 2017 (Guerrero, Cid et al., 2021).

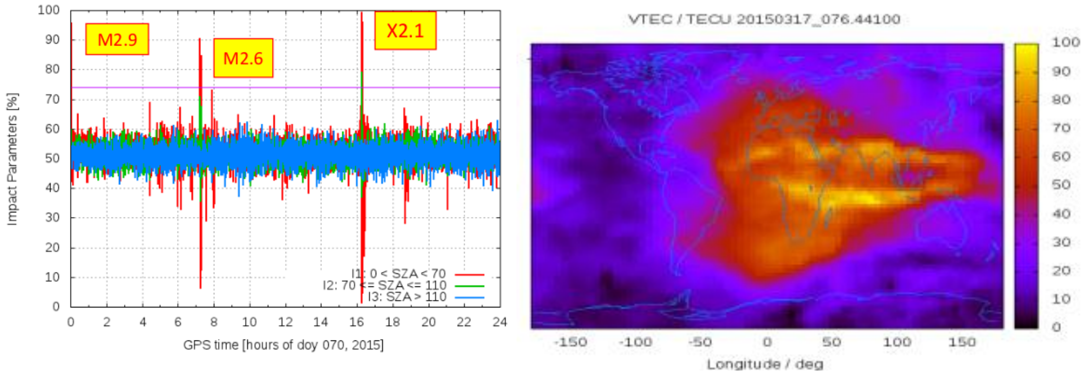


Fig. 7: Left: Detected solar flares prior to St. Patrick's day 2015 Geomagnetic Storm by means of SISTED detector, which relies on GNSS-based ionosphere monitoring (Garcia-Rigo et al., 2017; Borries et al. 2020). Right: UPC-IonSAT ionospheric TEC GIMs perturbed conditions during St. Patrick's day 2015.

Additional next steps include the possibility to conduct extensive simulations, combining different datasets and testing different algorithms, carry out comparisons and validation against external data, as well as deriving impact on end user' applications (such as in the case of HF communications, GNSS positioning and EGNOS performance degradation, influence on ground and space-based infrastructures, etc.).

Publications

Berdermann, J., Kriegel, M., Banys, D., Heymann, F., Hoque, M. M., Wilken, V., Borries, C., Heßelbarth, A. and Jakowski, N. (2018), Ionospheric response to the X9.3 Flare on 6 September 2017 and its implication for navigation services over Europe, Space Weather, Volume 16, Issue 10, Pages 1604-1615, https://doi.org/10.1029/2018SW001933.

Bloßfeld M., Zeitlhöfler J., Rudenko S., Dettmering D. (2020), Observation-Based Attitude Realization for Accurate Jason Satellite Orbits and Its Impact on Geodetic and Altimetry Results, Remote Sensing, 12(4), 682, https://doi.org/10.3390/rs12040682, 2020.

Borries, C., Wilken, V., Jacobsen, K. S., Garcia-Rigo, A., Dziak-Jankowska, B., ... & Hoque, M. M. (2020), Assessment of the capabilities and applicability of ionospheric perturbation indices provided in Europe, Advances in Space Research, 66(3), 546-562.

Guerrero, A., Cid, C., García, A., Domínguez, E., Montoya, F., & Saiz, E. (2021). The space weather station at the University of Alcala. J. Space Weather Space Clim., Volume 11, 2021, Topical Issue - Space Weather Instrumentation, 23, 13, https://doi.org/10.1051/swsc/2021007

Cid, C., Guerrero, A., Saiz, E., Halford, A. J., & Kellerman, A. C. (2020). Developing the LDi and LCi geomagnetic indices, an example of application of the AULs framework. Space Weather, 18, e2019SW002171. https://doi.org/10.1029/2019SW002171

Flores-Soriano, M., C. Cid, and R. Crapolicchio (2021), Validation of the SMOS Mission for Space Weather Operations: The Potential of Near Real-Time Solar Observation at 1.4 GHz, Space Weather 19, no. 3 (2021): e2020SW002649.

Garcia-Rigo, A., & Soja, B. (2020), New GGOS JWG3 on Improved understanding of space weather events and their monitoring, EGU General Assembly Conference Abstracts (p. 2049)

Garcia-Rigo, A., Soja, B. and the GGOS JWG3 team (2021), Overview on GGOS JWG3 - Improved understanding of space weather events and their monitoring, EGU General Assembly Conference Abstracts (p. 20492).

Garcia-Rigo, A., Soja, B. and the GGOS JWG3 team: Status of GGOS JWG3 on Improved understanding of space weather events and their monitoring, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14292, https://doi.org/10.5194/egusphere-egu21-14292, 2021.

Garcia-Rigo, A., Roma-Dollase, D., Hernández-Pajares, M., Li, Z., and Prol, F.D.S. (2017), St. Patrick’s day 2015 geomagnetic storm analysis based on real time ionosphere monitoring, Poster presentation in EGU General Assembly 2017, Vienna, Austria: 23-28 April 2017: Proceedings book. 2017.

Garcia-Rigo, A., M.Núñez, R.Qahwaji, O.Ashamari, P.Jiggens, G.Pérez, M.Hernández-Pajares, and A.Hilgers (2016), Prediction and warning system of SEP events and solar flares for risk estimation in space launch operations. J. Space Weather Space Clim., 6 (27), A28, 2016, DOI: 10.1051/swsc/2016021.

Mannucci, Anthony et al. (2020), Chapman Conference on Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes: Recommendations for the Community, Recommendations from the Chapman Conference on Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes, 11-15 February 2019, Pasadena, CA, USA. https://doi.org/10.5281/zenodo.3986940

Monte-Moreno, E., M. Hernandez-Pajares, H. Lyu, H. Yang and A. Aragon-Angel (2021), Estimation of Polar Depletion Regions by VTEC Contrast and Watershed Enhancing, IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3060107.

Sato, Hiroatsu, Jakowski, Norbert, Berdermann, Jens, Jiricka, Karel, Heßelbarth, Anja, Banyś (geb. Wenzel), Daniela, Wilken, Volker (2019), Solar Radio Burst events on September 6, 2017 and its impact on GNSS signal frequencies. Space Weather. Wiley. Volume17, Issue 6, 2019, Pages 816-826. DOI: 10.1029/2019SW002198 ISSN 1542-7390.

Schunk, Robert Walter, Ludger Scherliess, Vince Eccles, Larry C. Gardner, Jan Josef Sojka, Lie Zhu, Xiaoqing Pi et al. (2021), Challenges in Specifying and Predicting Space Weather, Space Weather 19, no. 2 (2021): e2019SW002404.

Soja, B., Heinkelmann, R. and Schuh, H. (2014). Probing the solar corona with very long baseline interferometry. Nature communications, 5(1), pp. 1-9.

Verkhoglyadova, O., X. Meng, A. J. Mannucci, J-S. Shim, and R. McGranaghan (2020), Evaluation of Total Electron Content Prediction Using Three Ionosphere-Thermosphere Models, Space Weather 18, no. 9 (2020): e2020SW002452.

Zucca, P., M. Núñez, K.L. Klein (2017), Exploring the potential of microwave diagnostics in SEP forecasting: The occurrence of SEP events, Journal of Space Weather and Space Climate 7, A13

Communication and Outreach Branch (COB)

http://www.iag-aig.org
President: Szabolcs Rózsa (Hungary)
Secretary: Gyula Tóth (Hungary)
IAG Newsletter Editor: Gyula Tóth (Hungary)

Activity Report

1. Introduction

The Communication and Outreach Branch (COB) is one of the components of the Association.
According to the new Statues (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members. The COB is hosted by the Department of Geodesy and Surveying of the Budapest University of Technology and Economics since 2003.
The Terms of Reference and program of activities of the COB, and a short report on the IAG website ("IAG on the Internet"), were published in The Geodesist's Handbook 2020 (Rózsa and Tóth, 2020; Rózsa, 2012), respectively.
In the reporting period of 2019-2021 COB was active in the establishment of a standardized web presence of IAG entities. In order to achieve this, a content management system was designed to incorporate the webpages of all the Commissions, Inter-commission Committees, Projects, etc.
Moreover, the IAG Newsletter has also been further developed and an e-mail marketing system has been introduced to distribute the newsletter, and automate the requests for the contribututions.

2. The IAG Website

The Communication and Outreach Branch maintains not only the IAG Website, but the website of most of the IAG entities. In order to standardize the URL of the Commission webpages, the following notation has been introduced: http://comX.iag-aig.org, where X stands for the number of the commission. Each entity has the opportunity to add contents to its own webpage using a WYSIWYG editor and drag&drop techniques. The webpage of the IAG Office has been transferred to the COB, too (https://office.iag-aig.org).

The website has been operational, no significant downtime has been experienced in the service.

3. The IAG Newsletters

The IAG Newsletters have been published monthly during the COVID pandemia, too. All of the issues have been published on the IAG website in HTML and PDF format and it is sent out to more than 600 e-mail addresses regularly. Since December 2020 the IAG Newsletter is distributed through Mailerlite.com, an online e-mail marketing application. The advantage of this solution is that it is fully GDPR compatible and provides reports of the activities of the recipients. In the past years we had very limited information on the success of the electronic newsletter. In the past 6 months, approximately 35% of the recipients (more than 200 people) opened the e-mail version of the newsletter.

We strive to publish only relevant information by keeping the Newsletter updated on a per-monthly basis. The call for contributions are automatically sent out to the IAG National Representatives as well as IAG Officers. COB would like to encourage everyone to send us inputs to the Newsletter.

Newsletters were compiled and have been sent regularly to Springer for publication for 32 issues of the Journal of Geodesy (Vol 85/1 – 87/8).

4. Outreach Activities

The COB president has been representing IAG in the Communication and Outreach Group of the UN GGIM Subcommittee on Geodesy.
Furthermore COB is active in collecting IAG related popular information to be published in the GIM International journal. Although the journal was not published in several months in 2020, we have successfully resumed the publication of IAG materials in GIM International.

References

Rózsa Sz., Tóth, Gy. 2020: Communication and Outreach Branch (COB). The Geodesist's Handbook 2020. *J. Geod.*, 94(109).
Rózsa Sz. 2020: IAG on the Internet. The Geodesist's Handbook 2020. *J. Geod.*, 94 (109).

Report 2015–2019 of the IAG Secretary General

https://www.iag-aig.org

Secretary General: Markku Poutanen (Finland)

Introduction

The IAG General Assembly, the Council, the Executive Committee, and the Office carry out the administration of IAG. The structure of IAG comprises a number of components: four Commissions, the Inter-Commission Committees on Theory (ICCT), Climate Research (ICCC), and Marine Geodesy (ICCM), Project Novel Sensors and Quantum Technology for Geodesy (QuGe), twelve International Scientific Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).

According to the IAG Bylaws, the Secretary General serves as secretary of the IUGG/IAG General Assembly, the IAG Scientific Assembly, the Council, the Executive Committee and the Bureau. He arranges for meetings of these bodies, distributes promptly the agenda, and prepares and distributes the minutes of all their meetings. He acts as the Director of the IAG Office and manages the affairs of the Association including the finances as per Bylaws §42(b). He continuously attends to the IAG correspondence, preserves the records and circulates all appropriate information related to the Association. He has to prepare the reports of the Association's activities and to perform other duties as may be assigned by the Bureau, the Council and the Executive Committee.

Administrative activities

IAG Council

The Council is composed by the delegates appointed by the national adhering bodies. Council meetings took place during the IUGG General Assembly 2019 in Montreal, Canada. Due to the COVID-19 pandemic, physical meetings were not arranged in 2020 and 2021. Next physical meeting is foreseen at the IUGG General Assembly in Berlin 2023. The Council has been informed by e-mail about activities of the Bureau and the Executive Committee, and if necessary, voting will be arranged as web-based. The list of national correspondents forming the IAG Council is regularly updated in contact with the IUGG Secretary General, who is responsible for the official accreditation.

IAG Executive Committee (EC)

The Executive Committee consists of the IAG Bureau, the immediate Past-President and the immediate Past Secretary General, the four Commission Presidents, four presidents of the Inter-Commission Committees and a Project, the Chair of the GGOS, the President of the COB, three representatives of the Services, and two Members-at-Large. Four EC meetings were held from July 2019 to May 2021: Montreal (July 2019), San Francisco (December 2019), and due to the Pandemic, two virtual meetings (October 2020, and March 2021). The fifth meeting will be in connection of the IAG Scientific Assembly in Beijing (also organized as a virtual meeting in June/July 2021). Minutes were prepared for the EC members, and the meeting summaries are available online at the IAG Website (http://www.iag-aig.org).

IAG Bureau

The IAG Bureau, i.e. the IAG President, Vice-President and Secretary General, has been communicated by e-mail, and the Bureau has monthly virtual meetings. The topics discussed in the monthly meetings concerned administrative and budget related running things, actual topics e.g. on UN Subcommittee on Geodesy relations, and EC meeting arrangements. Bureau also decided on travel awards for young scientists to participate and their present scientific results in IAG meetings. The President and Secretary General participated in the IUGG Executive Committee Meetings.

IAG Office

The IAG Office, currently consisting the Secretary General and the treasurer, took care of the administrative matters of all IAG business, meetings and events. This includes the budget management, the record keeping and fee accounting of the individual IAG membership, and the preparation and documentation of all Council and Executive Committee meetings with detailed minutes for the EC members and meeting summaries published in the IAG Newsletters and at the IAG Homepage. Important activity was the preparations for organization of the IAG Scientific Assembly 2021 in Beijing, China. Due to the COVID-19 pandemic, the meeting will be organized as virtual Zoom meeting, which created some extra complications in the planning.

The Geodesist's Handbook 2020, i.e. the organisation guide of IAG with the complete report on the past General Assembly, and the description of the upcoming IAG structure (terms of reference and officers of all IAG components and sub-components), the IAG Mid-Term Reports 2019–2021 (Travaux de l'AIG Vol. 42) were edited. The accounting of the Journal of Geodesy and the IAG Symposia series, both published by Springer-Verlag, were controlled. Applications for travel awards of young scientists for participation in IAG sponsored symposia were evaluated for decision of the IAG Bureau.

Communication and Outreach Branch (COB)

The COB is responsible for the IAG public relation in particular by maintaining the IAG Homepage and publishing the monthly Newsletter online and in the Journal of Geodesy. It also keeps track of all IAG related events by the meetings calendar. The IAG newsletter is regularly distributed to all IAG Officers, individual members, the Presidents and Secretaries General of the IUGG Associations, IAG liaison bodies, and other interested persons. The COB prepared, printed and distributed the IAG leaflet and IAG brochure and participated in the preparation of the Geodesist's Handbook 2020 and other presentations and publications.

Commissions and Inter-Commission Committee

There are four IAG Commissions (Reference Frames, Gravity Field, Earth Rotation and Geodynamics, Positioning and Applications) and the Inter-Commission Committees on Theory (ICCT), Climate Research (ICCC), and Marine Geodesy (ICCM), Project Novel Sensors and Quantum Technology for Geodesy (QuGe). They were coordinating their subcomponents (Sub-commissions, Study and Working Groups), reported regularly to the EC, and prepared their parts of the IAG Reports for publication in the IAG Reports 2019–2021 (Travaux de l'AIG Vols. 42). Each Commission maintained its individual Homepage and held several symposia, workshops and other meetings (see below). All of them were organising symposia at the IUGG/IAG General Assembly 2019 as well will do at the Scientific Assembly 2021.

Services

The presently twelve IAG Services split into three general fields: geometry (IERS, IDS, IGS, ILRS, and IVS), gravity (IGFS, ICGEM, IDEMS, IGeS, IGETS and BGI) and overlapping (PSMSL). All of them maintained their own Homepages and data servers and held their administrative meetings (Directing Board or Governing Board, respectively, and sub-components). They published their structure and programme 2019–2023 in the Geodesist's Handbook 2020, and the progress reports in the IAG Reports 2019–2021 (Travaux de l'AIG Vol. 42). Most of the Services held international meetings.

Global Geodetic Observing System (GGOS)

IAG's Global Geodetic Observing System (GGOS) is to monitor the geodetic and the global geodynamic properties of the Earth as a system. A new structure was implemented during the previous period 2015-2019. GGOS includes a Consortium composed by representatives of the Commissions and Services, the Coordinating Board as the decision-making body, the Executive Committee, the Science Panel, the Coordinating Office, two Bureaus with Standing Committees and Working Groups, and four Focus Areas. The GGOS Coordinating Office, responsible for all organizational affairs and the maintenance of the GGOS website (www.ggos.org), moved to the Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna, Austria. Annual GGOS days were held for the reporting of all the components but due to the pandemic 2020 meeting was cancelled and 2021 will be held as a virtual meeting. GGOS will organize symposia at the IAG Scientific Assembly 2021.

Coordination with other organisations

IAG maintains close cooperation with several organizations outside IUGG. These include

- Advisory Board on the Law of the Sea (ABLOS, together with IHO),
- Group on Earth Observation (GEO, with IAG as a participating organization),
- International Standards Organization (ISO, TC211 Geographic Information / Geomatics),
- United Nations Global Geospatial Information Management (UN-GGIM), where IAG became and an observer and a Subcommittee on Geodesy was established in 2017,
- UN-GGIM GS (former Joint Board of Geospatial Information Societies, JBGIS),
- United Nations Offices for Outer Space Affairs (UN-OOSA, with participation in Space-based Information for Disaster Management and Emergency Response, UN-SPIDER, and International Committee on Global Navigation Satellite Systems, ICG),

Individual IAG membership

At present (June 2021) IAG counts 245 individual members which include 35 students and 45 retired members, free of charge.

Meetings

IAG sponsored meetings from 2019 to 2021 were:

2019 03 14-20	24th Meeting of the European VLBI Group for Geodesy and Astronomy (EVGA) and 18th IVS Analysis Workshop	Las Palmas, Gran Canaria, Spain
2019 04 15-17	IGS 2019 Analysis Workshop	Potsdam, Germany
2019 05 05-09	10th IVS Technical Operations Workshop	Westford, MA, USA
2019 05 15-17	4th Joint International Symposium on Deformation Monitoring (JISDM)	Athens, Greece
2019 05 22-24	EUREF 2019 Symposium	Tallinn, Estonia
2019 07 08-19	27th IUGG General Assembly	Montreal, Canada
2019 07 29	Centennial International Cooperation in Earth and Space Sciences [IUGG/UNESCO meeting]	Paris, France
2019 08 07-09	Ninth Session of UN-GGIM	New York, USA
2019 09 16-20	Workshop for the Implementation of the GGRF in Latin America	Buenos Aires, Argentina
2019 09 18-20	Munich Remote Sensing Symposium 2019 (MRSS19)	Munich, Germany
2019 09 19-20	CODATA 2019: Towards next-generation data-driven science: Policies, practices and platforms	Beijing, China
2019 09 30-01	DORIS Analysis Working Group meeting	Paris, France
2019 10 01	ILRS Analysis Standing Committee (ASC) meeting	Paris, France
2019 10 01-04	5th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements (TG SMM 2019)	Saint Petersburg, Russia
2019 10 02-04	GGOS/IERS Unified Analysis Workshop	Paris, France
2019 10 07-09	Journées 2019: Astrometry, Earth Rotation and Reference Systems in the Gaia era	Paris, France
2019 10 10	BIPM Workshop on Advanced Time and Frequency Transfer	Sèvres, France
2019 10 21-25	2019 ILRS Technical Workshop	Stuttgart, Germany
2019 11 11	International Symposium on the occasion of 80th Anniversary of Prof. Erik Grafarend	Stuttgart, Germany
2019 11 11-14	GGOS Days 2019	Rio de Janeiro, Brazil
2019 11 11-14	SIRGAS Symposium 2019	Rio de Janeiro, Brazil

All physical meetings, symposia, schools and other planned activities were cancelled in 2020-2021 due to the COVID-19 pandemic. IAG components organized several on-line activities which can be found on their respective reports.

Publications

Based on the agreement with Springer Verlag, IAG Symposia Series will be open access, and free of charge to the Symposia participants. Volumes 148 (International Symposium on Gravity, Geoid and Height Systems 2016) and 149 (International Symposium on Advancing Geodesy in a Changing World) appeared in 2019. Volume 150 (Fiducial Reference Measurements for Altimetry) appeared in 2020, and next two are under preparation. The Geodesist's Handbook 2020 was published as the November issue of the Journal of Geodesy.
The IAG Reports (Travaux de l'AIG) Vol. 41, 2019 include reports of all IAG components about their activities in the past period. Vol 42 is compiled and will appear in connection of the 2021 Scientific Assembly.

Awards, anniversaries, obituaries

Levallois Medal was presented to Professor Christoph Reigber in Potsdam on the occasion of the 80th Anniversary and a Geoscientific Colloquium.

IAG Guy Bomford Prize was awarded to Michal Šprlák on the occasion of the IUGG General Assembly in Montreal, Canada.

On the occasion of the IUGG General Assembly in Montreal, Canada, two young authors' awards were granted. The IAG Young Authors Award 2017 is granted to Minghui Xu for the article "The impacts of source structure on geodetic parameters demonstrated by the radio source 3C371", and the 2018 award to Athina Peidou for the article "On the feasibility of using satellite gravity observations for detecting large-scale solid mass transfer events"

Travel awards with a total amount of 5500 EUR were granted to 9 young scientists for participating and presenting research results at 4 IAG sponsored Symposia.

An International Colloquium at GFZ, Potsdam, in honour of Professor Helmut Moritz on the occasion of his 85^{th} anniversary. Secretary General represented IAG in the occasion.

An international Symposium was held in Stuttgart in the occasion of 80^{th} Anniversary of Professor Erik Grafarend. Secretary General represented IAG in the occasion.

IAG Congratulated and published a short presentations in the IAG Newsletter for Anniversaries of Former IAG President, Professor Ivan I. Mueller on his 90^{th} Birthday and Academician, Professor Fakhraddin A. Kadirov on his 70^{th} Birthday

Obituaries published in IAG Newsletter

- Rodrigue Blais (1941-2019)
- Joseph David Zund (1939-2014)
- Günter Stangl (1952-2020)
- Richard Henry Rapp (1937-2020)
- Erik Wilhelm Grafarend (1939-2020)

International Earth Rotation and Reference Systems Service (IERS)

http://www.iers.org

Chair of the Directing Board: Tonie van Dam (Luxembourg/USA)
Director of the Central Bureau: Daniela Thaller (Germany)

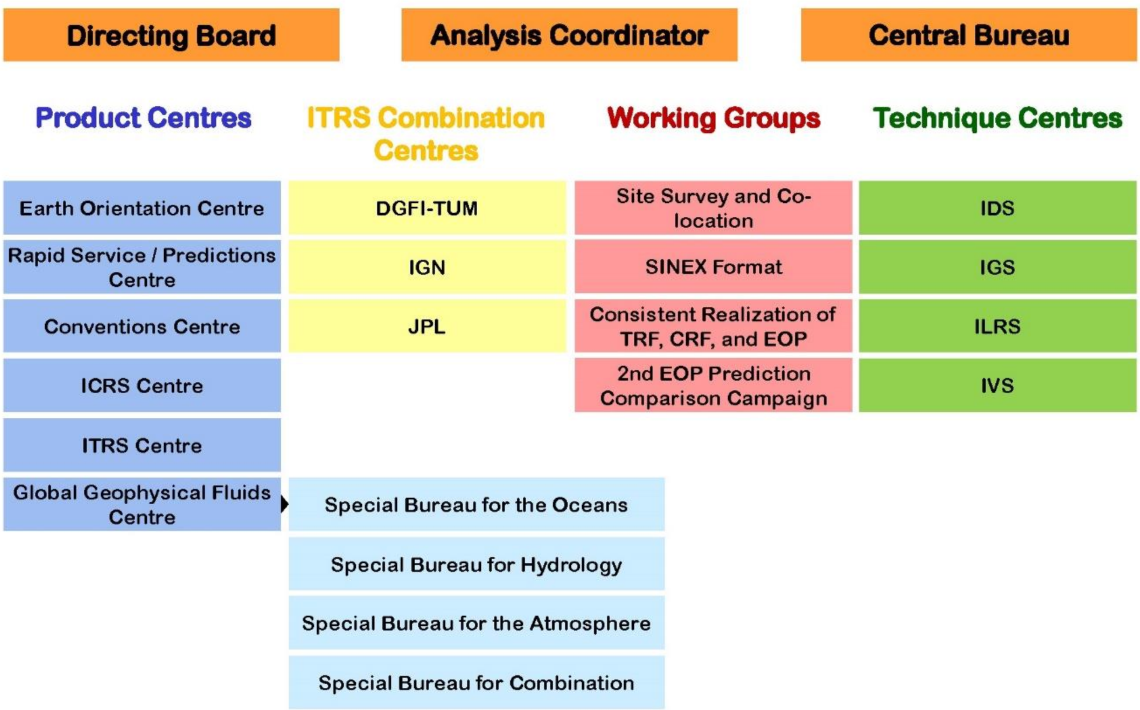
Structure

According to the Terms of Reference, the IERS consists of the following components:

- Directing Board
- Technique Centres
- Product Centres
- ITRS Combination Centre(s)
- Analysis Coordinator
- Central Bureau
- Working Groups

The Technique Centres are autonomous operations, structurally independent from the IERS, but which cooperate with the IERS.

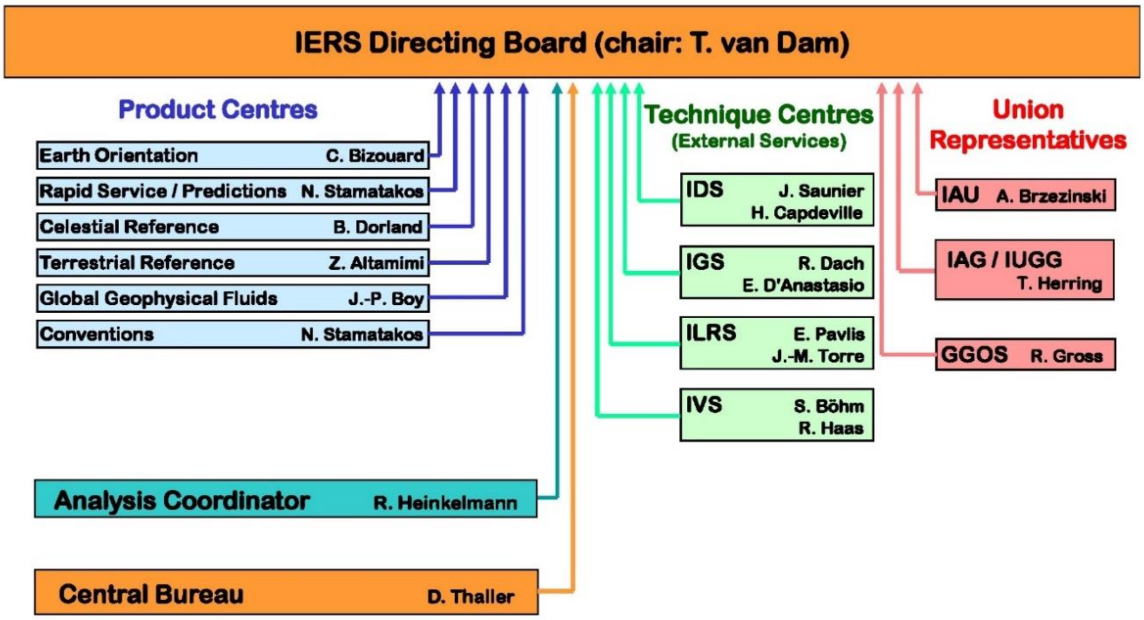
As of May 2021, the IERS consists of the following components:



Responsible persons are (as of May 2021):

- Product centres
    - Earth Orientation Centre: *Christian Bizouard (France)*
    - Rapid Service/Prediction Centre: *Nick Stamatakos (USA)*
    - Conventions Centre: *Christian Bizouard (France), Nick Stamatakos (USA)*
    - ICRS Centre: *Bryan Dorland (USA), Jean Souchay (France)*
    - ITRS Centre: *Zuheir Altamimi (France)*
    - Global Geophysical Fluids Centre: *Jean-Paul Boy (France), Tonie van Dam (Luxembourg)*
        - Special Bureau for the Oceans: *Henryk Dobslaw (Germany)*
        - Special Bureau for Hydrology: *Jianli Chen (USA)*
        - Special Bureau for the Atmosphere: *David Salstein (USA)*
        - Special Bureau for Combination: *Tonie van Dam (Luxembourg)*
- ITRS Combination Centres
    - Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM): *Manuela Seitz (Germany)*
    - Institut National de l'Information Géographique et Forestière (IGN): *Zuheir Altamimi (France)*
    - Jet Propulsion Laboratory (JPL): *Richard Gross (USA)*
- Analysis Coordinator: *Robert Heinkelmann (Germany)*
- Central Bureau: *Daniela Thaller (Germany)*
- Working groups
    - IAG/IERS Working Group on Site Survey and Co-location: *Sten Bergstrand (Sweden), John Dawson (Australia)*
    - Working Group on SINEX Format: *Daniela Thaller (Germany)*
    - IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP: *Robert Heinkelmann (Germany), Manuela Seitz (Germany)*
    - Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign: *Jolanta Nastula (Poland), Henryk Dobslaw (Germany)*

The current members of the Directing Board (representatives of scientific unions and of IERS' components) are:



Overview

The International Earth Rotation and Reference Systems Service continues to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other operationally oriented communities.

Earth orientation data have been issued on a sub-daily, daily, weekly, and monthly basis, and new global geophysical fluids data were added. The Earth Orientation Centre improved its software and applied several corrections to the 14 C04 EOP series. The Rapid Service / Prediction Centre transitioned their EOP solution to be consistent with the 14 C04 for polar motion, UT1-UTC, and celestial pole offsets.

The IERS continued to ensure that the user community has the most up-to-date terrestrial reference frame by beginning preparations for the International Terrestrial Reference Frame 2020 (ITRF2020). The three ITRS Combination Centres (DGFI, IGN, JPL) improved their combination software for ITRF2020 and made first test analyses with preliminary data. The final re-analysis data from IDS, IGS, ILRS, and IVS were submitted in April 2021. The ITRS Centre and the corresponding working group also participated in surveys of co-located sites.

A new realization of the International Celestial Reference System (ICRF3) was officially adopted by IAU on January 2019. Comparisons were made between the ICRF3 and preliminary versions of the Gaia optical reference frame.

Work on technical updates to the IERS Conventions (2010) was continued, with updates of existing content, expansion of models, and introducing new topics. Several chapters have been revised by the Conventions Centre. A new printed version of the Conventions will be printed in 2022. This version will incorporate a new style so that the main document will be greatly reduced in length, which will enhance the usability of the conventions for the general practitioner.

Members of the Working Group (WG) on Site Survey and Co-location participated in several local tie measurements. Automated monitoring with terrestrial instruments was further developed. Additional local tie surveys were collected following a call from the ITRS Centre, in preparation for ITRF2020. The WG on SINEX Format worked (with other IERS components) on modifications and revisions of the format, particularly for the provision of loading corrections and of SLR range biases in SINEX files. The WG on Site Coordinate Time Series Format, responsible for the definition of a common exchange format for coordinate time series for all geodetic techniques, was dissolved in May 2020. At the same time the IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP was also established as an IERS WG. It will compute multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. A new WG on the 2nd Earth Orientation Parameter Prediction Comparison Campaign was established in March 2021. It will re-assess the various EOP prediction capabilities by collecting and comparing operationally processed EOP predictions from different agencies and institutions over a representative period of time, with the aim to evaluate the accuracy of final estimates of EOP, to identify accurate (reliable) prediction methodologies, and to assess the inherent uncertainties in present-day EOP predictions.

The IERS continued to issue Technical Notes, Annual Reports, Bulletins, and electronic newsletters. It co-organized the GGOS/IERS Unified Analysis Workshop (UAW), October 2–4, 2019 in Paris. The final report provides a thorough summary of the workshop as well as conclusions and recommendations from the discussions (see GGOS website and IERS Annual Report 2019).

The IERS Data and Information System (DIS) at the web site www.iers.org, maintained by the Central Bureau, has been updated, improved and enlarged continually. It presents information related to the IERS and the topics of Earth rotation and reference systems. As the central access point to all IERS products it provides tools for searching within the products (data and publications), to work with the products and to download them. The DIS provides links to other servers, among these to about 10 web sites run by other IERS components.

Publications

The following IERS publications and newsletters appeared between mid-2019 and May 2021:

- IERS Technical Note No. 40 (2020): Z. Altamimi and W. R. Dick (eds.): Description and evaluation of DTRF2014, JTRF2014 and ITRF2014
- IERS Annual Report 2018
- IERS Bulletins A, B, C, and D (daily[1] to half-yearly)
- IERS Messages Nos. 378 to 434

IERS Directing Board

The *IERS Directing Board* (DB) met twice each year to decide on important matters of the Service such as structural changes, overall strategy, creating working groups, launching projects, changing Terms of Reference, etc.:

- Meeting No. 69 in San Francisco, December 8, 2019;
- No. 70, video conference, May 13, 2020;
- No. 71, video conference, November 18, 2020;
- No. 72, video conference, May 4 and 20, 2021.

Among the most important decisions made by the DB in 2019–2021 were the following:

- Elected Tonie van Dam as Chair of the Directing Board (2021–2024).
- Confirmed extended list of IERS Associate Members.
- Dissolved Working Group on Site Coordinate Time Series Format.
- Established IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP also as an IERS WG.
- Established Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign.

Technique Centres

The Technique Centres (TC) are autonomous independent services, which cooperate with the IERS:

- *International GNSS Service* (IGS)
- *International Laser Ranging Service* (ILRS)
- *International VLBI Service for Geodesy and Astrometry* (IVS)
- *International DORIS Service* (IDS)

For details about the work of the TCs, see their individual reports to IAG.

[1] Most users consider the "Bulletin A" IERS RS/PC product to contain EOP estimates updated at both daily and weekly intervals. The daily products are meant to be machine-readable; whereas, the weekly, original Bulletin A product is in a human-readable format and produced on Thursdays.

Product Centres

Earth Orientation Centre

Primary scientist: Christian Bizouard (France)

Overview

According to the IERS Terms of Reference, the IERS Earth Orientation Centre (EOC) is responsible for monitoring Earth Orientation Parameters including long-term consistency, publications for time dissemination (DUT1) and leap second announcements. Earth Rotation Parameters (ERPs: Polar motion, Universal Time (UT1), Length of Day (LOD) and Celestial pole offsets) are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. ERPs are initially collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) that starts in 1846 and extends until the end of the previous year and the Bulletin B / C04 given at one-day intervals, which is published monthly with a 30-day. The EOC is located at Paris Observatory.

Activities during the period 2019–2021

The EOC improved its software and applied several corrections to the 14 C04 EOP series. No leap seconds were issued through Bulletin C due to an acceleration of Earth’s rotation.

In October 2019, the EOC organized the *Journées Systèmes de Référence Spatio-temporels “Astrometry, Earth Rotation and Reference System in the Gaia era”* and edited the proceedings. A similar workshop planned for 2020 had to be postponed due to the Corona pandemic.

In addition, members of the EOC had a flourishing scientific activity, reflected by several scientific papers in peer-review journals and a book with de Gruyter.

Selected publications

Bizouard, C. (2020): Geophysical modelling of the polar motion, de Gruyter Studies in Mathematical Physics 31, 370 p., DOI 10.1515/9783110298093

Bizouard, C. (ed.) (2020): Proceedings of the Journées Systèmes de Référence Spatio-temporels 2019 “Astrometry, Earth Rotation and Reference System in the Gaia era”. Paris: Observatoire de Paris. *Includes several contributions by the EOC.*

Bizouard, C.; Nurul Huda, I.; Ziegler, Y.; Lambert, S. (2020): Frequency dependence of polar motion resonance, Geophysical Journal International 220(2):753–758, DOI 10.1093/gji/ggz463

Couhert, A.; Bizouard, C.; Mercier, F.; Chanard, K.; Greff, M.; Exertier, P. (2020): Consistent determination of the three first-degree Earth gravity coefficients, Journal of Geodesy 94(12), DOI 10.1007/s00190-020-01450-z

Lambert, S.; Nurul-Huda, I.; Ziegler, Y.; Richard, J. -Y.; Liu, N.; Gattano, C.; Rosat, S.; Bizouard, C. (2019): Measurement of Earth’s Nutation by VLBI: Direct Estimates from VLBI Delays and a Discussion on the Error. In: International VLBI Service for Geodesy and Astrometry 2018 General Meeting Proceedings: “Global Geodesy and the Role of VGOS – Fundamental to Sustainable Development”, Eds. K. L. Armstrong, K. D. Baver, D. Behrend, NASA/CP-2019-219039, p. 204–208

Nurul Huda, I.; Lambert; S., Bizouard; C.; Ziegler, Y. (2020), Nutation terms adjustment and implication for the Earth rotation resonance parameters, Geophysical Journal International 220(2), 759–767, DOI 10.1093/gji/ggz468

Nurul Huda, I. (2019): Etude des propriétés rhéologiques globales de la Terre à l'aune des observations VLBI, thèse de doctorat en Astronomie et Astrophysique (Observatoire de Paris)

Puente, V.; Richard, J. Y.; Folgueira, M.; Capitaine, N.; Bizouard, C. (2019): Comparison of VLBI-based Luni-solar Nutation Terms. In: Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, 17–19 March 2019, Las Palmas de Gran Canaria, Spain, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, ISBN 978-84-416-5634-5, pp. 257–226

Rapid Service/Prediction Centre

Primary scientist: Christine Hackman (USA), until Dec. 2020. Nick Stamatakos (acting Primary scientist, USA), since Dec. 2020
Production director and lead project scientist: Nick Stamatakos (USA)

Overview

The Rapid Service/Prediction Centre (RS/PC) provides high-quality Earth orientation estimates/predictions on a rapid turnaround basis, primarily for real-time-users. It issues the weekly IERS Bulletin A and corresponding data files, as well as daily and four-times-daily EOP estimate/prediction values. The centre also conducts research toward improving the accuracy and/or production robustness of its products. Lastly, the centre maintains a web-based Earth orientation matrix calculator that provides the full direction cosine matrix between celestial and terrestrial reference frames based on IERS conventions and given calendar date and time inputs.

Activities and publications during the period 2019–2021

In an effort to improve its EOP combination and short-term prediction results, the RS/PC contracted with Virginia Tech University to develop a better smoothing, weighted cubic spline (SWCP) implementation. The resulting new spline software was developed in MATLAB, and has the ability to combine state and derivate inputs (such as UT1–UTC and LOD). It was used to aid in improving the pre-processing of IGS Ultra Observation LOD and AAM forecasts before using those series as inputs to the newly-developed SWCP. Using the newly developed pre-processing and SWCP resulted in gains of 40% in 0-day prediction accuracy and 25% in 1-day prediction accuracy. Longer term prediction accuracies are still being reviewed (Stamatakos et al. 2021).

The RS/PC continued to study the effects of implementing atmospheric angular momentum (AAM) and oceanic angular momentum (OAM) values/predictions in its Polar Motion EOP estimation/prediction algorithms. Findings were published in posters presented at the AGU 2020 fall meeting and the EGU 2021 spring meeting.

As of 24 October 2019, the U. S. Naval Observatory's IERS RS/PC web/FTP sites (maia.usno.navy.mil and toshi.nofs.navy.mil) and the IERS Conventions web site (maia.usno.navy.mil/conventions), were taken offline as they undergo modernization. An Amazon gov-Cloud site that would host EOP results may be available sometime in late 2021; whereas, a USNO-sponsored site to host the web-based Earth orientation matrix calculator and IERS Conventions would take longer.

Stamatakos, N., McCarthy, D., and Salstein, D.: IERS Rapid Service Prediction Center Use of Atmospheric Angular Momentum for Earth Rotation Predictions, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1917, DOI 10.5194/egusphere-egu21-1917

Conventions Centre

Primary scientists: Christian Bizouard (France), Nick Stamatakos (USA)

Overview

The Conventions Centre is continuing work on technical updates to the IERS Conventions (2010), with updates of existing content, expansion of models, and introducing new topics as needed. The Conventions site is located at: http://iers-conventions.obspm.fr, Observatoire de Paris.

Activities and publications during the period 2019–2021

Until 24 October 2019, the conventions was co-hosted at maia.usno.navy.mil; however, due to a continued modernization effort of the maia site, a USNO-sponsored site to host the Conventions is delayed probably beyond calendar year 2021.

A versioning system has been implemented to handle intermediate updates of the conventions. The centre continued recruiting a group of talented experts in the field to work on updating the IERS Conventions. In 2018, it issued a Call for Participation in the next IERS Conventions. As of May 2021, over 15 experts have agreed to aid with this rewrite of the IERS Conventions.

ICRS Centre

Primary scientists: Bryan Dorland (USA), Jean Souchay (France)

Overview

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities have been run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU.

Activities during the period 2019–2021

Involvement by ICRS Centre personnel in the construction of the celestial reference frame from VLBI programs has continued, in particular from the participation in extensive observing programs. The ICRS Centre has fulfilled various tasks devoted to the monitoring of ICRF sources, the link with the dynamical system (in particular through LLR), the construction of new updates of the LQAC (Large Quasar Astrometric Catalogue) and of the LQRF (Large Quasar Reference Frame). A new realization of the International Celestial Reference System (ICRF3) was officially adopted by IAU on January 2019. Comparisons were made between the ICRF3 and preliminary versions of the Gaia optical reference frame.

Selected publications

Dorland, B.; Secrest, N.; Johnson, M.; Fischer, T.; Zacharias, N.; Souchay, J.; Lambert, S.; Barache, C.; Taris, F. (2020): The Fundamental Reference AGN Monitoring Experiment (FRAMEx). In: Proceedings of the Journées 2019 “Astrometry, Earth Rotation, and Reference Systems in the GAIA era”, Observatoire de Paris, Paris, France, 7–9 October 2019, Ed. C. Bizouard, pp. 165–171

Fischer, T.C.; Secrest, N.J.; Johnson, M.C.; Dorland, B.N.; Cigan, P.J.; Fernandez, L.C.; Hunt, L.R.; Koss, M.; Schmitt, H.R.; Zacharias, N.: Fundamental Reference AGN Monitoring Experiment (FRAMEx). I. Jumping Out of the Plane with the VLBA. The Astrophysical Journal 906(2), id. 88, 19 pp., DOI 10.3847/1538-4357/abca3c

ITRS Centre

Primary scientist: Zuheir Altamimi (France)

Overview

The main activities of the ITRS Centre during the period 2019–2021 include the maintenance of the ITRF network, database and website. The ITRS Centre, according to the IERS ToR, is responsible, among other duties, for the maintenance and update of the ITRF network database and its provision to the users through the ITRF website. The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments.

The ITRF web site, available at <http://itrf.ign.fr>, provides an interface to consult the IERS network database. Site and point information can be requested online; it contains approximate coordinates of the sites, the list of their points as well as their descriptions, their DOMES numbers and the list of ITRF versions in which they have been computed. Subsets of points can be selected and their ITRF coordinates can be requested at any epoch in any ITRF version if their coordinates are provided in the requested ITRF version.

Main activities and publications during the period 2019–2021

The main activities of the ITRS Centre during this period include:

- Preparation for ITRF2020. After the release of the ITRF2020 Call for Participation (CfP) which was published at the end of 2018 (see: http://itrf.ign.fr/doc_ITRF/CFP-ITRF2020.pdf), the ITRS Center continued the dialog with the 4 Technique Centers (TCs) for the preparation of their inputs to the ITRF2020. The ITRS Center emphasized the need for the TCs to implement the new recommended models which are annexed to the ITRF2020 CfP. The ITRS Center has in particular attended most meetings of the analysis working groups of the Technique Centres (in 2019: IDS, IGS, ILRS and IVS).
- The ITRS Center hosted the Unified Analysis Workshop 2019 at Institut de Physique de Globe de Paris, during 2–4 October, 2019. A number of the technique presentation addressed the preparation for the ITRF2020, including the implementation of updated models and analysis strategies.
- At the initiative of the ITRS Center, and with the help of the IERS Central Bureau, an IERS Technical Note (# 40) was published in order to, primarily; acknowledge the activities of the ITRS Combination Centers at DGFI and JPL, beside the ITRS Combination Center at IGN which is part of the ITRS Center (Altamimi and Dick, 2020). It includes the description of both DTRF2014 and JTRF2014, as well as their inter-comparisons with respect to the official IERS solution, the ITRF2014. The Technical Note was also intended to include evaluations of the three solutions by the IERS Technique Centers (IDS, IGS, ILRS and IVS) who constantly provide input solutions to the ITRF. In addition to DGFI, JPL and ITRS Center contributions, the Technical Note includes contributions from IDS, ILRS and IVS. A specific article by the ITRS Center evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (see IGN ITRS Combination Center Report below).
- Chapter 4 of the IERS Conventions has been re-written by the ITRS Center team which includes the following updates (IERS ITRS Center, 2019):
    - A description of ITRF2014, with its associated equations, to model the nonlinear station motions due to seasonal signals and post-seismic deformation of stations subject to major earthquakes.
    - A description of the mathematical model used in the ITRF combination.

  - A revision of Table 4.1, listing the transformation parameters relating ITRF2014 to previous ITRFs.
  - Improvements in wording and the removal of unnecessary paragraphs.
- Resolutions on ITRS/ITRF. The ITRS Center has prepared the text of an IUGG resolution on the ITRF which was adopted at the occasion of the IUGG General Assembly 2019 in Montreal, Canada, see:

  http:\\ www.iugg.org/resolutions/2019%20IUGG%20GA%20Resolutions.pdf.
- At its 9th Session, the UN-GGIM Committee of Experts supported the agreement of the Subcommittee on geodesy on the adoption of the International Terrestrial Reference System and the International Terrestrial Reference Frame as the standard for scientific, geospatial and operational geodetic applications. The ITRS Center has significantly contributed to the text of that agreement.
- Maintenance of the IERS network. The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments. The IERS network database, which contains the descriptions of the sites and points, is continuously updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web http://itrf.ign.fr, and should be sent to domes@ign.fr. An updated list of all available DOMES number is available at http://itrf.ign.fr/doc_ITRF/iers_sta_list.txt. The IERS site information is available to the users through the ITRF website interface. Several new stations, mainly GNSS permanent stations where added to the ITRF network and database.

Altamimi, Z. and W.R. Dick (Eds.), (2020), Description and evaluation of DTRF2014, JTRF2014 and ITRF2014, IERS Technical Note 40, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. 167 p., ISBN 978-3-86482-137-0.

IERS ITRS Center, (2019), Chapter 4 of the IERS Conventions (Terrestrial reference systems and frames), available at https://iers-conventions.obspm.fr/chapter4.php.

Global Geophysical Fluids Centre

Primary scientist: Jean-Paul Boy (France)
Co-chair: Tonie van Dam (Luxembourg/USA)

Overview

The Global Geophysical Fluid Centre (GGFC) of the International Earth Rotation and Reference Systems Service (IERS) provides the community with models of geodetic effects (Earth rotation, gravity and deformation) due to the temporal redistribution of the Earth geophysical fluids (http://loading.u-strasbg.fr/GGFC). These include fluid motions with the solid Earth (core and mantle) as well as motions at the Earth’s surface (ocean, atmosphere and continental hydrology).

The GGFC is composed of four operational entities: the Special Bureau for the Atmosphere (SBA, chair: D. Salstein), the Special Bureau for the Oceans (SBO, chair: R. Gross until Dec. 2020, H. Dobslaw from Jan. 2021), the Special Bureau for Hydrology (SBH, chair: J.-L. Chen) and the Special Bureau for the Combination Products (SBCP, chair: T. van Dam). The Atmosphere, Hydrology and Ocean SBs have been firmly established since the creation of the GGFC in 1998. The operational Combination Products SB was established in 2009 to host new datasets that model the mass movement of combined environmental fluids such as atmosphere + ocean. There is finally a non-operational component of the GGFC, the GGFC Science and

Support Products, serving as a repository for models and data used regularly in data processing, but that do not change often.

Activities and publications during the period 2019–2021

The Special Bureau for the Atmosphere (SBA) is concerned with the atmospheric information that is needed for a number of geodetic issues. During the period of this report, the SBA maintained series of the atmospheric angular momentum (AAM) vector, which can be used for analysis and predictions of Earth rotation parameters.

The Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analysing, archiving, and distributing data relating to non-tidal changes in oceanic processes affecting the Earth's rotation and related parameters. A new website for the SBO hosted at GFZ Potsdam has been established (https://isdc.gfz-potsdam.de/ggfc-oceans/). The SBO invites all interested colleagues working in the field to contribute new ocean model simulations and/or ocean reanalyses as well as geodetically relevant derived quantities to the GGFC.

The Special Bureau for Hydrology (SBH) provides access to data sets of terrestrial water storage (TWS) variations from major climate and land surface models and GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On satellite gravity measurements. The NASA GLDAS and GRACE/GRACE Follow-On data products are updated on a regular basis. SBH also provides gravity spherical harmonic representations of model-derived TWS changes.

At the beginning of 2017, GFZ Potsdam as one of the providers of combinational products introduced major changes to their data series (atmospheric, oceanic and hydrological loading). The products are consistent with the GRACE/GRACE-FO atmosphere and ocean dealiasing product AOD1B RL06, which is going to be replaced with RL07 by the end of the year 2021. It is expected that the combination product will be reprocessed back to the year 1975 shortly after the publication of AOD1B RL07.

In addition, GGFC produces loading time series (geocenter motion, time-variable gravity field and surface displacements) for the next reference frame ITRF2020. All products are available at http://loading.u-strasbg.fr/GGFC/itrf2020.php.

ITRS Combination Centres

Three ITRS Combination Centres (CCs) are responsible for providing ITRF products by combining ITRF inputs. Within the time frame covered by this report the CCs focused on the computation of the new ITRS realization 2014.

ITRS CC at DGFI-TUM

Primary scientist: Manuela Seitz (Germany)

Overview

DGFI-TUM has been acting as one of the ITRS Combination Centres within the IERS since 2001. The related activities are embedded into DGFI-TUM's research on the realization of Global Terrestrial Reference Frames within the research area Reference Systems.

Realizations of the ITRS are based on the combination of space geodetic observations of the four techniques VLBI, SLR, GNSS, and DORIS at globally distributed geodetic observatories. Respective input data are provided by the corresponding technique services (IVS, ILRS, IGS, IDS). The combination strategy developed at DGFI-TUM bases on the combination of normal equation systems, which allows for a pure physically realization of the origin and scale of the reference frames.

Activities and publications during the period 2019–2021

The CC at DGFI-TUM started to prepare the ITRS 2020 realization. In the framework of the development of the DOGS software and the compilation of a new DOGS version, the combination part DOGS-CS was improved with respect to the precision of the reference epochs of the parameters. This improves also all parameter transformations considering parameter epochs (e.g., the epoch transformation and the change of parameterization). Furthermore, now all meta-data given in the SINEX files can be stored in the DOGS internal format and transferred well through the combination process. In addition, a software (APROPOS) was developed, which allows for the approximation of post-seismic station motions by a combination of logarithmic and exponential functions. Thereby, also the relaxation time is considered as an unknown parameter. Thus, non-linear optimization algorithms are applied. Three different algorithms are implemented and compared, in order to obtain the best-fitting approximation. The software will be used within DTRF2020 computation to provide relaxation functions for the individual stations affected by earthquakes, which will be reduced from the station positions (on normal equation level) in a preparatory step. During 2020, preliminary input data for the ITRS 2020 realization were provided by all Technique Services. These data were analysed in order to test the new version of the DOGS-CS software and to give feedback to the Technique Centres.

ITRS CC at IGN

Primary scientist: Zuheir Altamimi (France)

Main activities and publications during the period 2019–2021

- *Research and development activities*. The members of the IGN CC, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Scientific results of specific data analysis and combination are published in peer-reviewed journals, as listed below, but also presented at international scientific meetings.

- *Investigation of the scale discrepancy between SLR and VLBI*. The scale of ITRF2014 was defined in such a way that it has zero scale and zero scale rate with respect to the arithmetic average of the implicit scales of SLR and VLBI solutions as obtained by the stacking of their respective time series. The resulting scale and scale rate differences between the two solutions (SLR and VLBI) are 1.37 ppb at epoch 2010.0 and 0.02 ppb/yr. The level of the scale agreement between SLR and VLBI confirms the ITRF2008 finding and is an indication of the persistent scale offset between the two technique solutions. These results suggest that there is still an urgent need for investigation on the causes of the scale discrepancy, e.g., range biases in case of SLR and possible effects due to VLBI antenna gravity deformations. The ILRS has initiated a pilot project on systematic errors including the range biases which will be estimated in the ILRS solution to ITRF2020. A preliminary SLR test solution was made available to the ITRS Center by Cinzia Luceri from the Italian Space Agency (ASI) where estimated range biases were taken into account. Analysing the time series of this SLR test solution showed a clear scale offset of about 1 ppb with respect to the ILRS solution which was used in the ITRF2014. We expect that this scale offset will greatly minimize the scale discrepancy between SLR and VLBI in the coming ITRF2020 solution.
- *Contribution to the IERS Technical Note 40*. As reported in the ITRS Center report, this issue, an IERS Technical Note (# 40) was published in order to, primarily, acknowledge the activities of the ITRS Combination Centers at DGFI and JPL, beside the ITRS Combination Center at IGN which is part of the ITRS Center (Altamimi and Dick, 2020). The Technical Note includes in particular a specific article by the ITRS Center which evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (Altamimi et al., 2020). The article concludes in particular that (1) SLR and VLBI intrinsic and discrepant scales coexist in the DTRF and JTRF 2014 solutions, and (2) with respect to ITRF2014 and assuming that its scale is homogeneous, the scale offsets and rates between SLR and VLBI solutions embedded in DTRF2014 and JTRF2014 are respectively 1.32 and 1.21 ppb at epoch 2010.0 and 0.04 and 0.01 ppb/yr. These results are in almost perfect agreement with the results of ITRF2014 analysis.

Altamimi, Z., P. Rebischung, X. Collilieux, and L. Métivier (2020), ITRS Center evaluation of DTRF2014 and JTRF2014 with respect to ITRF2014. In: Altamimi, Z. and W. Dick (Eds.), 2019, IERS Technical Note 40, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2020. 167 pp., ISBN 978-3-86482-137-0

Métivier, L., Altamimi, Z., and Rouby, H. (2020), Past and present ITRF solutions from geophysical perspectives, Advances in Space Research (65)12: 2711–2722, DOI 10.1016/j.asr.2020.03.031

Métivier, L., H. Rouby, P. Rebischung, and Z. Altamimi (2019), ITRF2014, Earth figure changes and geocenter velocity: implications for GIA and recent ice melting, Journal of Geophysical Research 125, e2019JB018333, DOI 10.1029/2019JB018333

See also the report of the ITRS Centre above.

ITRS CC at JPL

Primary scientist: Richard Gross (USA)

Overview

The ITRS Combination Centre at JPL focused on research regarding the representation of terrestrial reference frames by time series of smoothed positions of reference stations rather than by a parameterized model of the station positions. A Kalman filter and smoother for reference frames (KALREF) has been developed and used to determine time series representations of terrestrial reference frames. In addition, a square-root information filter for reference frames (SREF) is currently being developed that can be used to not only determine time series representations of terrestrial reference frames but that can also be used to jointly determine time series representations of terrestrial and celestial reference frames.

Activities and publications during the period 2019–2021

During 2019–2021, SREF continued to be developed. SREF allows a variable or fixed time step to be used to propagate the state vector and covariance matrix, includes a full process noise covariance matrix that will optionally allow regional correlations in station positions to be considered, includes linear, periodic, and postseismic displacement models for the evolution of the station positions, and can optionally process radio source coordinates and celestial pole offsets for joint TRF/CRF determinations. SREF will be used to determine JTRF2020, JPL's submission to the IERS for ITRF2020. It will also be used to produce updates to JTRF2020's predictions by using new observations as they become available. The updated predictions are expected to be generated on a monthly basis.

Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, and X. Wu (2020). A sequential estimation approach to terrestrial reference frame determination, Adv. Space Res., 65(4), 1235–1249, DOI 10.1016/j.asr.2019.11.016.

Analysis Coordinator

Analysis Coordinator: Robert Heinkelmann (Germany)

Overview

The Analysis Coordinator is responsible for the long-term and internal consistency of the IERS reference frames and other products. He is responsible for ensuring the appropriate combination of the Technique Centres products into the single set of official IERS products and the archiving of the products at the Central Bureau or elsewhere.

Activities and publications during the period 2019–2021

The work of the Analysis Coordinator focused on an analysis of the ITRF2014 and a comparison with the two other independent solutions: JTRF2014 and DTRF2014. The differences of these three frames are for the post-seismic deformation models, time-series vs. long-term parameters, least squares vs. Kalman filtering, datum definition and in the weighting and application of local ties and co-motion constraints. The analysis of the various differences of the TRFs needs more time and more dedicated investigations as many aspects cannot be clearly associated being caused by specific analysis or combination decisions. Besides the terrestrial reference frame, the new celestial frame, ICRF3, became effective in the beginning of 2019. ICRF3 fits much better to external high-precision star catalogues, such as DR2 and EDR3 of the ESA Gaia mission, than ICRF2 does, for which a small but systematic deformation was identified. ICRF3 also includes a correction for the aberration caused by the non-linear motion of the Milky Way galaxy w.r.t. other galaxies. The main EOP products of IERS, IERS

14 C04 and USNO finals were investigated and compared as well. During 2019 – 2021 several changes have been done to the IERS 14 C04 product, some of which cause significant differences for users. The effects and the necessity of the change are under investigation. Based on VLBI data analysis the consistency of the three products, TRF, CRF, and EOP, were in the focus of the activities. Besides GNSS, SLR, VLBI and DORIS, the LLR technique recently progressed towards more observations. LLR besides VLBI is the only technique capable of providing CPO and dUT1 estimates and hence, presents an important tool for verification of the celestial set of the EOP. The development of VLBI observations at higher frequencies, namely K- and X-/Ka-bands for ICRF3 and in general presents a novel data set for the verification of IERS products and their consistency. The IERS Analysis Coordinator is very much in favour of further fostering and broadening these observations. VLBI at other frequencies has the potential to provide an independent connection of terrestrial and celestial reference frames and EOP and thus qualifies for high accurate control of the IERS products. In the time frame 2019 – 2021, management efforts have been invested in the preparation of ITRF2020. For this product update, model updates had to be implemented, such as a new sub-daily EOP model, VLBI antenna gravitational deformation, and a new linear model of the mean Earth rotation pole applied for the modelling of pole tides. To oversee these model inclusions in the analysis, the IERS Analysis Coordinator took part in several Analysis Workshops of the four main space geodetic techniques. The Analysis Coordinator co-organized the 2019 Unified Analysis Workshop held in Paris, France together with IAG GGOS and developed recommendations from it. Currently, the 2021 Unified Analysis Workshop to be held in Munich, Germany, is in preparation again together with IAG GGOS.

Central Bureau

Director: Daniela Thaller (Germany)

Overview

The Central Bureau coordinates the work of the Directing Board and the IERS in general, organizes meetings and issues publications. It replies to questions of users regarding IERS products and general topics of Earth rotation and reference systems. It maintains an IERS Data and Information System (DIS) based on modern technologies for internet-based exchange of data and information like the application of the Extensible Markup Language (XML) and the generation and administration of ISO standardised metadata. The system provides general information on the structure and the components of the IERS, serves as a portal to websites of all IERS components and gives access to all products.

Activities and publications during the period 2019–2021

The IERS DIS is continuously being adapted and extended by new components in order to fulfil the requirements for a modern data management and for the access to the data by the users. Besides routine work like maintenance of the data bases of users, products and web pages, in 2019 further developments of the IERS DIS concentrated on the enhancement of the data management system and of the interactive tools to visualize and analyse IERS products. Especially security features were updated to meet current standards.

An improved monitoring system was established for the data management system to ensure a timely and error-free provision of the IERS products on the webpages and ftp server. A new feature has been implemented in the data management system, which allows the direct upload of USNO earth rotation data to the servers of the IERS Central Bureau. Further improvements of the IERS DIS included the development of a date converter tool and the availability of csv formatted files on the ftp server. The development of a new user management system was started. For the data exchange in the framework of ITRF 2020, the Central Bureau created internal areas at data server for https upload and download which replaces the former, less secure ftp exchange.

The Central Bureau edited, published and distributed IERS Technical Note No. 40 and IERS Annual Report 2018, as well as IERS Messages Nos. 378 to 434. It compiled reports by IERS to IAU Commission A2 and IAG.

Working Groups

Reports, meeting summaries, presentations and other documents of all working groups are available at the IERS web site.

IAG/IERS Working Group on Site Survey and Co-location

Chair: Sten Bergstrand (Sweden, until Dec. 2019), Ryan Hippenstiel (USA, since Jan. 2020)
Co-chair: John Dawson (Australia, until Dec. 2019), Sten Bergstrand (Sweden, since Jan. 2020)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation.

Activities and publications during the period 2019–2021

See the report of IAG Commission 1, SC 1.2 (Global Reference Frames), JWG 1.2.2: Methodology for surveying geodetic instrument reference points.

Working Group on SINEX Format

Chair: Daniela Thaller (Germany)

Overview

The SINEX (Solution INdependent EXchange) format is a well-established format used by the technique services of the IERS for several years. The aim of the working group is to maintain the SINEX format according to the needs of the IERS, the technique services (IDS, IGS, ILRS, IVS) and GGOS. The working group is the point of contact if any modifications or extensions are required. In order to have the best possible interaction with the groups working with the SINEX format (either as output or as input), the analysis and combination groups of all the technique services as well as the relevant components of the IERS and GGOS are represented within the working group.

Activities and publications during the period 2019–2021

In the framework of preparing ITRF2020, two aspects have been developed for the SINEX format:

1) A block for storing the corrections for non-tidal loading effects that were applied at the observation level was defined. This allows to un-do this correction when handling the normal equations provided in the SINEX file.
2) A block for providing the information about range and time biases applied during the SLR estimation process was defined.

IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP

Chair: Robert Heinkelmann (Germany)
Co-Chair: Manuela Seitz (Germany)

Overview

This IAG/IAU/IERS Working Group will compute multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. From 2016 to 2019 this was an IAG Working Group, since 2020 it has become joint with IAU and IERS.

Activities and publications during the period 2020–2121

See the report of IAG Commission 1, SC 1.4 (Interaction of Celestial and Terrestrial Reference Frames), JWG 1.4.3: Consistent realization of TRF, CRF, and EOP.

Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign

Chair: Jolanta Nastula (Poland)
Co-Chair: Henryk Dobslaw (Germany)

Overview

Earth orientation parameters (EOP) comprising of nutation offsets, pole coordinates, and dUT1 represent a critically needed link between the terrestrial and the celestial reference frame. Predictions of EOP are important for a number of operational activities including navigation of deep-space satellite missions, the pointing of astronomical instruments, or satellite-based positioning on Earth. Various agencies and institutions worldwide therefore maintain capacities to rapidly process space geodetic observations to obtain estimates for the Earth orientation parameters with short latencies as a basis for the subsequent prediction. Whereas many users require predictions for only a few days into the future, IERS routinely publishes predictions for up to 90 days within its Bulletin A.

Starting in 2021, a second international intercomparison campaign for predicted EOP is being performed under the auspices of the IERS. Valid predictions of all kind of EOP are collected once per week in an operational setting. The accuracy and reliability of different prediction methods will be only evaluated later when geodetic observations of those EOP are eventually available. The office of the campaign will be maintained by the Space Research Centre in Warszaw (Poland). The campaign is expected to run until 2023. New types of prediction methods might enter at any time during the course of the campaign.

First activities in 2021

The first online meeting of the WG took place on May 6th, 2021 to discuss details of the campaign with interested participants. A dedicated website serving as the interface between office and participants has been already established (http://eoppcc.cbk.waw.pl/). Rules and requirements for the campaign will be published as a technical report by the end of May 2021. After that, website and campaign server will be opened for a pre-operational phase. The campaign is expected to start officially in the second half of 2021.

International DORIS Service (IDS)

https://ids-doris.org/

Chairman of the Governing Board: Frank Lemoine (USA)
Director of the Central Bureau: Laurent Soudarin (France)

Overview

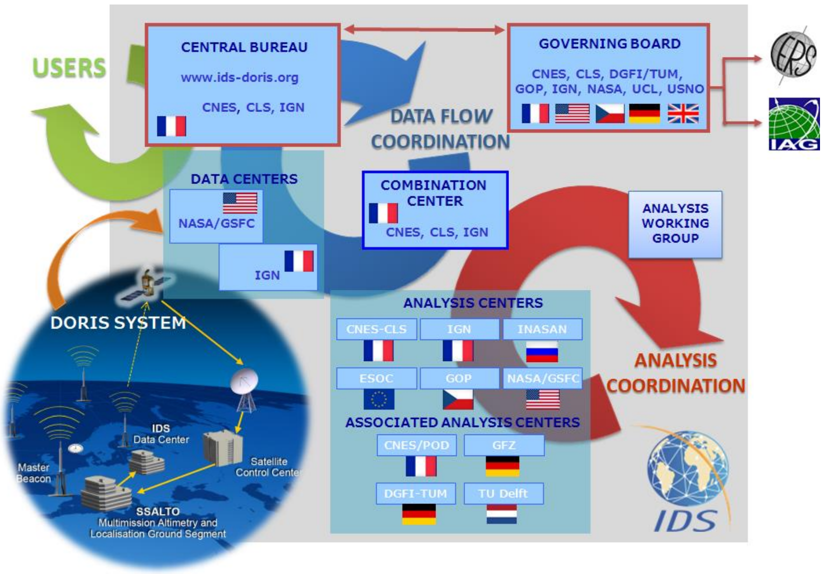
The current report presents the different activities held by all the components of the International DORIS Service (IDS) for the period from the middle of 2019 to the end of 2020.

The main achievements of the IDS over this period

(1) analysis, combination and stacking of the contributions from the four IDS Analysis Centers involved in the realization of the IDS contribution to the ITRF2020
(2) dissemination of the data of the brand-new missions HY-2C and Sentinel-6A
(3) renewal of several positions within the Governing Board

The IDS has been impacted by the Covid-19 pandemic. The events planned for 2020 could not take place. The IDS workshop planned in Venice in October 2020 was cancelled and was first postponed to 2021. In the Spring of 2021, the IDS Workshop was again postponed to March 2022. The service had also launched the organization of a "DORIS Day" on Saturday 2 May 2020 at the Technical University of Vienna, Austria, prior to the EGU 2020, with the aim of introducing the DORIS technique and fostering the use of the IDS routine products (coordinate time series, DORIS RINEX data, ephemerides of DORIS satellites...) to people who are not familiar with this satellite positioning technique. Because of the covid crisis, it also had to be cancelled. It will be organized in person as soon as the conditions allow it.

During the period of this report, the DORIS system had its 30th anniversary. The first DORIS measurement was recorded on February 3, 1990, on board SPOT-2.



Structure

The IDS organization is very similar to the other IAG Services. The service accomplishes its mission through the following components:

- Satellites carrying a DORIS receiver
- Network of tracking stations
- Data Centers
- Analysis centers and Analysis Coordinator
- Combination Center
- Working Groups
- Central Bureau
- Governing Board

Activities

1. DORIS system

1.1 DORIS satellites

As described in **Table 1**, two new satellites were launched over the report period: HY-2C and Sentinel-6A Michael Freilich in 2020. Both use the new 7-channel DGXX-S DORIS on-board receiver. During the same period, two missions were decommissioned: Jason-2 and HY-2A. The number of satellites in the DORIS constellation remains stable with 7 spacecraft in operation, at altitudes between 720 and 1336 km, with near-polar or TOPEX-like inclination (66°).

Table 1: DORIS data available at IDS data centers, as of December 2020.

Satellite	Start	End	Space Agency	Type
SPOT-2	31-MAR-1990 04-NOV-1992	04-JUL-1990 15-JUL-2009	CNES	Remote sensing
TOPEX/Poseidon	25-SEP-1992	01-NOV-2004	NASA/CNES	Altimetry
SPOT-3	01-FEB-1994	09-NOV-1996	CNES	Remote sensing
SPOT-4	01-MAY-1998	24-JUN-2013	CNES	Remote sensing
JASON -1	15-JAN-2002	21-JUN-2013	NASA/CNES	Altimetry
SPOT-5	11-JUN-2002	1-DEC-2015	CNES	Remote sensing
ENVISAT	13-JUN-2002	08-APR-2012	ESA	Altimetry, Environment
JASON -2	12-JUL-2008	10-OCT-2019	NASA/CNES	Altimetry
CRYOSAT-2	30-MAY-2010	PRESENT	ESA	Altimetry, ice caps
HY-2A	1-OCT-2011	14-SEP-2020	CNSA, NSOAS	Altimetry
SARAL/ALTIKA	14-MAR-2013	PRESENT	CNES/ISRO	Altimetry
JASON-3	19-JAN-2016	PRESENT	NASA/CNES/NOAA/ Eumetsat	Altimetry
SENTINEL-3A	23-FEB-2016	PRESENT	GMES/ESA	Altimetry
SENTINEL-3B	25-APR-2018	PRESENT	GMES/ESA	Altimetry
HY-2C	21-SEP-2020	PRESENT	CNSA, NSOAS	Altimetry
SENTINEL-6A	21-NOV-2020	PRESENT	NASA/CNES/NOAA/ Eumetsat/ESA	Altimetry

Note that an eighth satellite joined the DORIS constellation in May 2021. It is the HY-2D mission of China's National Satellite Ocean Application Service (NSOAS), which also carries a DGXX-S DORIS receiver.
In the next few years, more DORIS satellites are planned: Sentinel-3C and 3D, HY-2E, Sentinel-6B, SWOT (Surface Water Ocean Topography). In addition, other missions are under consideration.

Figure 1 summarizes the evolution of the DORIS constellation since the launch of the SPOT-2 satellite in 1990 and includes satellites that are currently planned. It must be noted that since 2002, five or more DORIS satellites have been available to IDS users, which is a key requirement for the precision of the geodetic products.

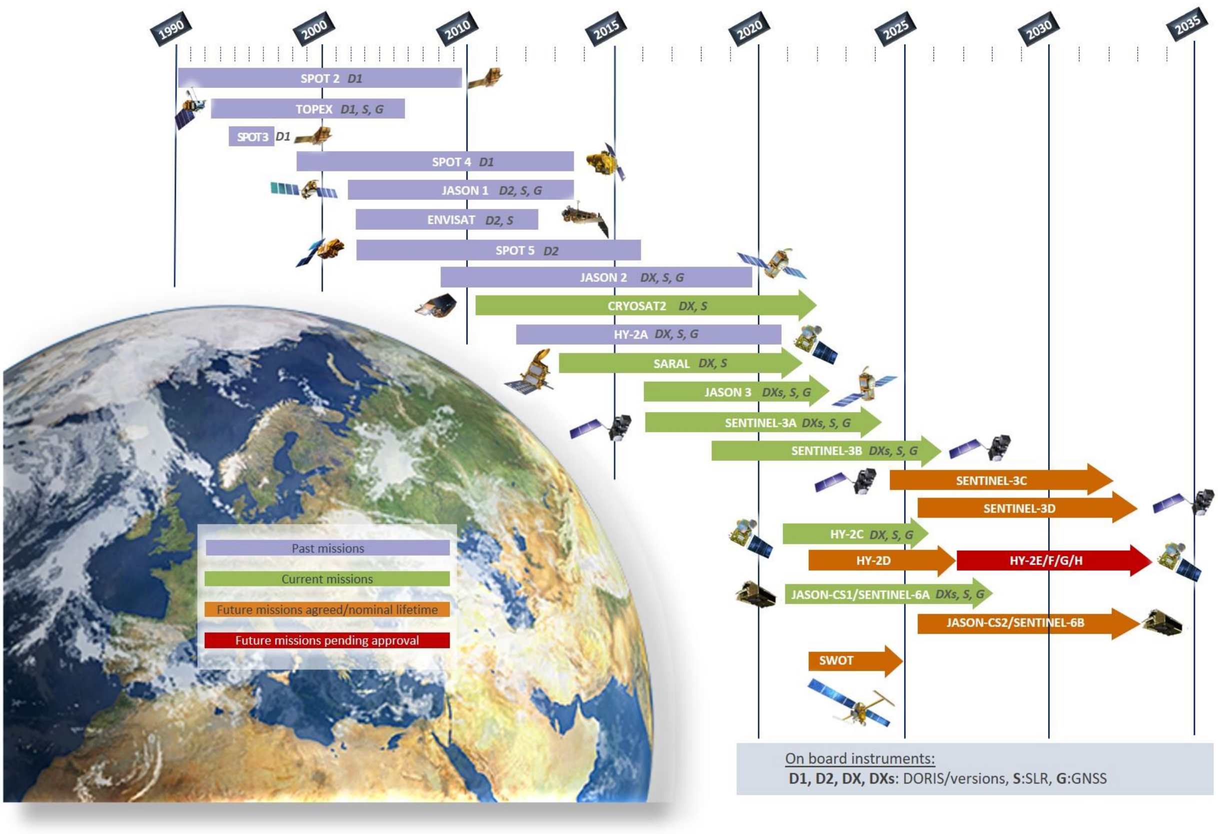


Figure 1: DORIS satellite constellation. As of December 2020.

1.2 DORIS network

DORIS has a globally distributed network of 59 permanent stations dedicated for precise orbit determination and altimetry with four master beacons (Papeete, Hartebeesthoek, Kourou, Toulouse), one time beacon (Terre-Adélie), and one experimental beacon dedicated to IDS for scientific purposes (Wettzell). Mangilao (Guam Island, USA), initially dedicated to IDS, joined the permanent DORIS network in September 2019. See **Figure 2**.

As regards maintenance, the good news is that after a very long outage the DORIS station at Santa-Cruz, Galapagos Islands, Ecuador, has been back in operation since December 2019. The station was completely reinstalled, and a new relationship was initiated with the new local staff. In 2020, two stations were fully renovated to enhance performance by changing the antenna environment and upgrading the equipment: antenna relocation at La Réunion Island (France, Indian Ocean) and new DORIS site in Höfn (Iceland) in place of Reykjavik. On the other hand, the extensive power outage at Betio has not yet been solved and the two Russian stations (Badary and Krasnoyarsk) are still awaiting authorization from the government authorities for transmitting the DORIS signal.

Notwithstanding those local difficulties and the global health crisis complicating maintenance operations in 2020, DORIS network provided a reliable service with a mean of 84% of active sites over the two-year period 2019-2020 thanks to the responsiveness of the agencies hosting the stations and an efficient and effective overall management and coordination steered by the CNES and the IGN: 13 failed beacons and 5 failed antennas were replaced.

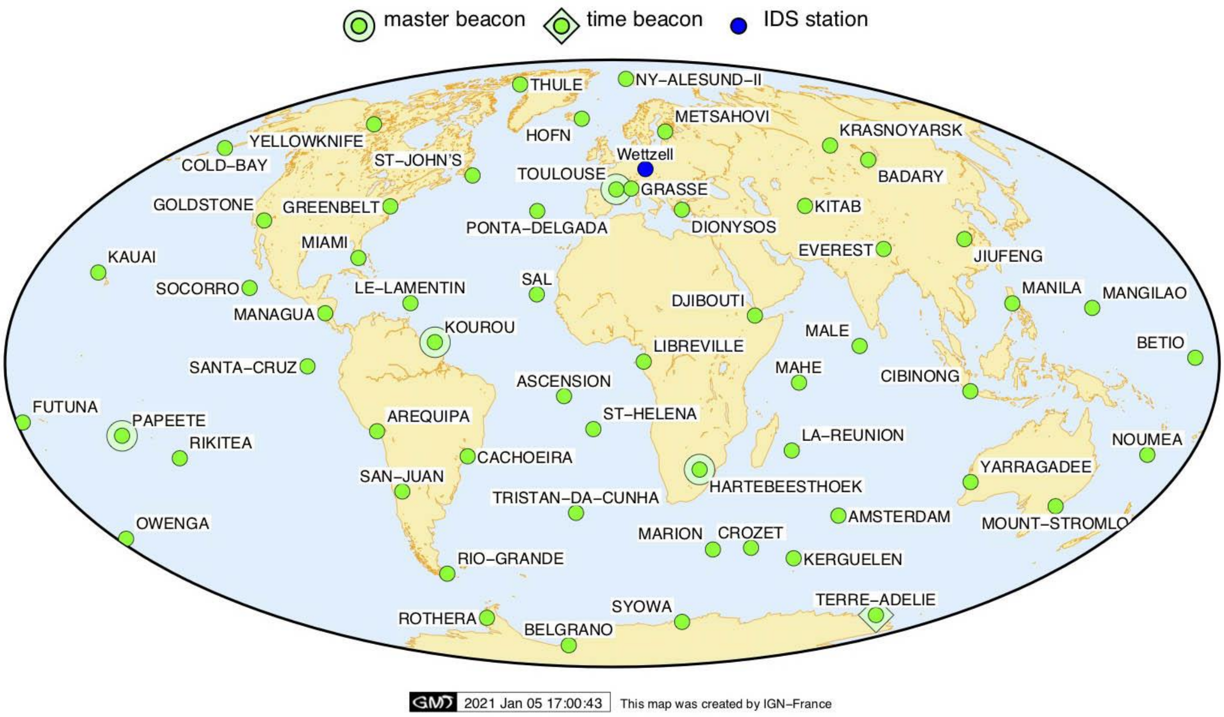


Figure 2: DORIS tracking network. Co-location with other IERS techniques as of January 2021.

Evolution and development

2019 was a year marked by the start of the deployment of 4th generation DORIS beacon (B4G), a much-awaited development. Indeed, a new architecture built with up-to-date electronic technology and advanced components will allow reliable operation through 2030+ and the addition of a signal amplifier at the foot of the antenna will allow a larger distance between beacon and antenna (50m instead of only 15 m) providing better options to satisfy the sky-clearance criterion for new or renovated DORIS sites. Although the installation of a site requires balancing different requirements as well as the specific site and host agency constraints, the goal is to maintain a clear sky visibility down to 10 degrees elevation.

The B4G deployment started from mid-2019 at St-John's (Newfoundland), Canada. The deployment strategy consists of replacing gradually the aging equipment, and renovating sites for which the relocation of the antenna will enhance the station performance. 12 sites have been equipped with B4G over the past two years: Grasse, St-John's, Ponta-Delgada, and Saint Helena in 2019, then Crozet, La Réunion, Mount-Stromlo, Toulouse, Höfn, Amsterdam and Yarragadee in 2020.

Furthermore, we have continued to deploy the new generation of ground antennae (Starec C type) for which standard uncertainty in the location of the 2GHz phase center in the vertical direction was significantly reduced to improve the DORIS measurement accuracy. We achieved the antenna replacement of 35% of the network (21 sites) by the end of 2020.

Throughout the network development there has been a continuing effort to co-locate DORIS with other space geodetic techniques and with tide gauges. 49 DORIS stations out of 59 are co-located with at least one other IERS technique: GNSS, SLR, and/or VLBI and 27 with tide gauges. All tie vectors at co-located sites with DORIS are available in a maintained file "DORIS_ext_ties.txt" available on the IDS data centers and IDS Central Bureau ftp:
ftp://ftp.ids-doris.org/pub/ids/stations/DORIS_ext_ties.txt

2. IDS organization

Like the other IAG Services, an IDS Governing Board (GB), helped by a Central Bureau (CB), organizes the activities done by the Analysis Centers (AC), the Data Centers (DC), and the Combination Center (CC).

2.1 Governing Board

The GB consists of eleven voting members and several nonvoting members. The voting membership of the GB is composed of 5 members elected by the IDS Associates, and 6 appointed members. The elected members have staggered four-year terms, with elections every two years. The Analysis Centers' representative, the Data Centers' representative, and one Member-at-Large are elected during the first two-year election. The Analysis Coordinator and the other Member-at-Large are elected in the second two-year election. In accordance with the Terms of Reference of the IDS, the GB was then partially renewed in January 2017 and January 2019 (see **Table2**).

Normally scheduled for late 2020, the last elections were held in early January 2021. The purpose of the elections was to renew the position of the Analysis Centers' representative, the Data Centers' representative, and one Member-at-Large. In addition, IDS proceeded to the renewal of three representatives appointed respectively by CNES (DORIS system), IGN (network), and IERS. First, the CB contacted the relevant organizations to appoint their representatives; second, the CB organized the elections for the three vacant positions. In a final step the GB elected its new chairman.

The members who were elected or appointed for the term 2021-2024 are:

- Frank Lemoine (NASA/ GSFC, USA) as Analysis Center Representative,
- Patrick Michael (NASA/GSFC, USA) as Data Center Representative,
- Karine Le Bail (Chalmers University of Technology, Sweden) as Member-at-Large,
- Pascale Ferrage (CNES, France), reappointed by CNES as the DORIS system representative,
- Jérôme Saunier (IGN, France), reappointed by IGN as the Network representative.
- Tonie van Dam (University of Luxembourg, Luxembourg), appointed by IERS as the IERS representative.

Note that Ernst Schrama (TU Delft, The Netherlands) was designated by IAG as its representative within the Governing Board for 2019-2022, to replace Petr Štěpánek (Geodetic Observatory Pecny, Czech Republic), who resigned from this position after he was elected with Hugues Capdeville (CLS, France) to form the Analysis Coordination team for the term 2019-2022.

The new Governing Board has re-elected Frank Lemoine as the Chairperson of the IDS Governing Board for 2021-2024.

Denise Dettmering remains an ex officio member of the IDS GB, in the role of Chair of the IDS Working Group on Near Real Time Data

2.2 IDS strategic plan

After the IDS Retreat held in June 2018, the IDS GB worked on the development of a strategic plan for the IDS. In the coming years, IDS will focus on growing the community, extending the DORIS applications, and improving the technology, the infrastructure, and the processing.

2.3 IDS life

The period 2019-2020 started sadly because on February 4, 2019 we lost our colleague and friend Richard Biancale recently retired from the CNES in September 2018, and newly installed at the GFZ (Oberpfaffenhofen) to work with Dr. Frank Flechtner on GRACE Follow-On. A tribute was paid to him in the IDS Newsletter #6:

https://ids-doris.org/images/documents/newsletters/IDS-Newsletter6.pdf#page=5.

IDS also experienced a more joyful departure as in April 2020 Pascal Willis retired from the Institut Géographique National (IGN) after a long and active career promoting analysis and use of DORIS data in geodesy, an article was dedicated to him in the IDS Newsletter #8:

https://ids-doris.org/images/documents/newsletters/IDS-Newsletter8.pdf#page=8.

Arnaud Pollet and Samuel Nahmani will lead the IGN/DORIS Analysis Center activities following the retirement of Pascal Willis.

The application of the DGFI-TUM (Munich, Germany) to become an Associate Analysis Center was approved by the IDS Governing Board at its meeting on October 1st, 2019. In addition to the six regular Analysis Centers, four Associate Analysis Centers now contribute to the IDS analysis activities.

Frank Lemoine and Laurent Soudarin attended the International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America held in Buenos Aires, Argentina, from September 16 to 20, 2019. It was the opportunity to meet the friendly colleagues from the agencies hosting DORIS stations in this part of the world.

Table 2: IDS GB members since 2003, with members in office on January 1st, 2021, indicated in bold.

Position	Term	Status	Name	Affiliation	Country
Analysis coordinator	**2019-2022**	Elected	**Hugues Capdeville**	CLS	France
			Petr Štěpánek	Geodetic Observatory Pecný	Czech Republic
	2015-2018	*Elected*	*Hugues Capdeville*	CLS	*France*
			Jean-Michel Lemoine	*CNES/GRGS*	
	2013-2014	*Ext'd*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2009-2012	*E.b.GB*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2005-2008		*Frank Lemoine (substitute)*	*NASA/GSFC*	*USA*
	2003-2005		*Martine Feissel-Vernier*	*IGN/Paris Observatory*	*France*
Data Centers' representative	**2021-2024**	Elected	**Patrick Michael**	NASA/GSFC	USA
	2017-2020	*Elected*	*Patrick Michael*	*NASA/GSFC*	*USA*
	2013-2016	*Elected*	*Carey Noll*	*NASA/GSFC*	*USA*
	2009-2012	*Elected*	*Carey Noll*	*NASA/GSFC*	*USA*
	2003-2008		*Carey Noll*	*NASA/GSFC*	*USA*
Analysis Centers' representative	**2021-2024**	Elected	**Frank Lemoine (chair)**	NASA/GSFC	USA
	2017-2020	*Elected*	*Frank Lemoine (chair)*	*NASA/GSFC*	*USA*
	2013-2016	*Elected*	*Pascal Willis (chair)*	*IGN+IPGP*	*France*
	2009-2012	*Elected*	*Pascal Willis (chair)*	*IGN+IPGP*	*France*
	2003-2008		*Pascal Willis*	*IGN+IPGP*	*France*
Member at large	**2019-2022**	Elected	**Claudio Abbondanza**	NASA/JPL	USA
	2015-2018	*Elected*	*Marek Ziebart*	*UCL*	*UK*
	2013-2014	*Ext'd*	*John Ries*	*University of Texas/CSR*	*USA*
	2009-2012	*E.b.GB*	*John Ries*	*University of Texas/CSR*	*USA*
	2003-2008		*John Ries*	*University of Texas/CSR*	*USA*
Member at large	**2021-2024**	Elected	**Karine Le Bail**	Chalmers University of Technology	Sweden
	2017-2020	*Elected*	*Denise Dettmering*	*DGFI/TUM*	*Germany*
	2013-2016	*Elected*	*Richard Biancale*	*CNES/GRGS*	*France*

	2009-2012	*E.b.GB*	*Pascale Ferrage*	*CNES*	*France*
	2003-2008		*Gilles Tavernier (chair)*	*CNES*	*France*
Director of the Central Bureau	Since 2003	Appointed	**Laurent Soudarin**	CLS	France
Combination Center representative	Since 2013	Appointed	**Guilhem Moreaux**	CLS	France
Network representative	**2021-2024**	Appointed	**Jérôme Saunier**	IGN	France
	2017-2020	*Appointed*	*Jérôme Saunier*	*IGN*	*France*
	2013-2016	*Appointed*	*Jérôme Saunier*	*IGN*	*France*
	2010-2012		*Bruno Garayt (substitute)*	*IGN*	*France*
	2009	*E.b.GB*	*Hervé Fagard*	*IGN*	*France*
	2003-2008		*Hervé Fagard*	*IGN*	*France*
DORIS system representative	**2021-2024**	Appointed	**Pascale Ferrage**	CNES	France
	2017-2020	*Appointed*	*Pascale Ferrage*	*CNES*	*France*
	2013-2016	*Appointed*	*Pascale Ferrage*	*CNES*	*France*
IAG representative	**2019-2022**	Appointed	**Ernst Schrama**	TU Delft	The Netherlands
	2017-2018	*Appointed*	*Petr Štěpánek*	*Geodetic Observatory Pecný*	*Czech Republic*
	2013-2016	*Appointed*	*Michiel Otten*	*ESOC*	*Germany*
	2009-2012	*Appointed*	*Michiel Otten*	*ESOC*	*Germany*
	2003-2008		*Not appointed*		
IERS representative	**2021-2024**	Appointed	**Tonie van Dam**	University of Luxembourg	Luxembourg
	2017-2020	*Appointed*	*Brian Luzum*	*USNO*	*USA*
	2013-2016	*Appointed*	*Brian Luzum*	*USNO*	*USA*
	2009-2012	*Appointed*	*Chopo Ma*	*NASA/GSFC*	*USA*
	2003-2008		*Ron Noomen*	*TU Delft*	*The Netherlands*
Chair of WG "NRT DORIS data"	**Nov. 2016-**	Ex-officio	**Denise Dettmering**	DGFI/TUM	Germany

Elected = Elected by IDS Associates
E.b.GB = Elected by the previous Governing Board
Ext'd = Extended term for two years linked to the set-up of the partial renewal process

2.4 Central Bureau

The Central Bureau, funded by CNES and hosted at CLS, is the executive arm of the Governing Board and as such is responsible for the general management of the IDS consistent with the directives, policies and priorities set by the Governing Board. It brings its support to the IDS components and operates the information system.

The Central Bureau participated in the organization of the AWG meetings held in 2019 (see **Table 4**). It documented the Governing Board meetings held on these occasions. The Minutes of the GB meetings are available on the website at https://ids-doris.org/ids/reports-mails/governing-board.html#minutes.

Website

The Central Bureau maintains the web resources of the IDS. Besides the regular updates of pages and additions of documents, the website has been upgraded and was enriched with new information. New features were added to the network viewer (https://apps.ids-doris.org/apps/map.html). IVS and ILRS co-located stations with DORIS sites can now be displayed in addition to the IGS stations. The list of the colocations is based on the file of ties between DORIS and GNSS, VLBI and SLR stations managed (see **Figure 3**). This item completes the list already in place: boundaries of the tectonic plates (Bird, 2003), large Earthquakes (magnitude greater or equal to 6) within a 500 km radius of the DORIS stations (source USGS), horizontal and vertical velocity vectors of the DPOD2014 solution, as well as rates (North, East and Up; in mm/yr) and local events, i.e., the events of the station (dates of installation, change of beacon equipment, Earthquakes in the vicinity).

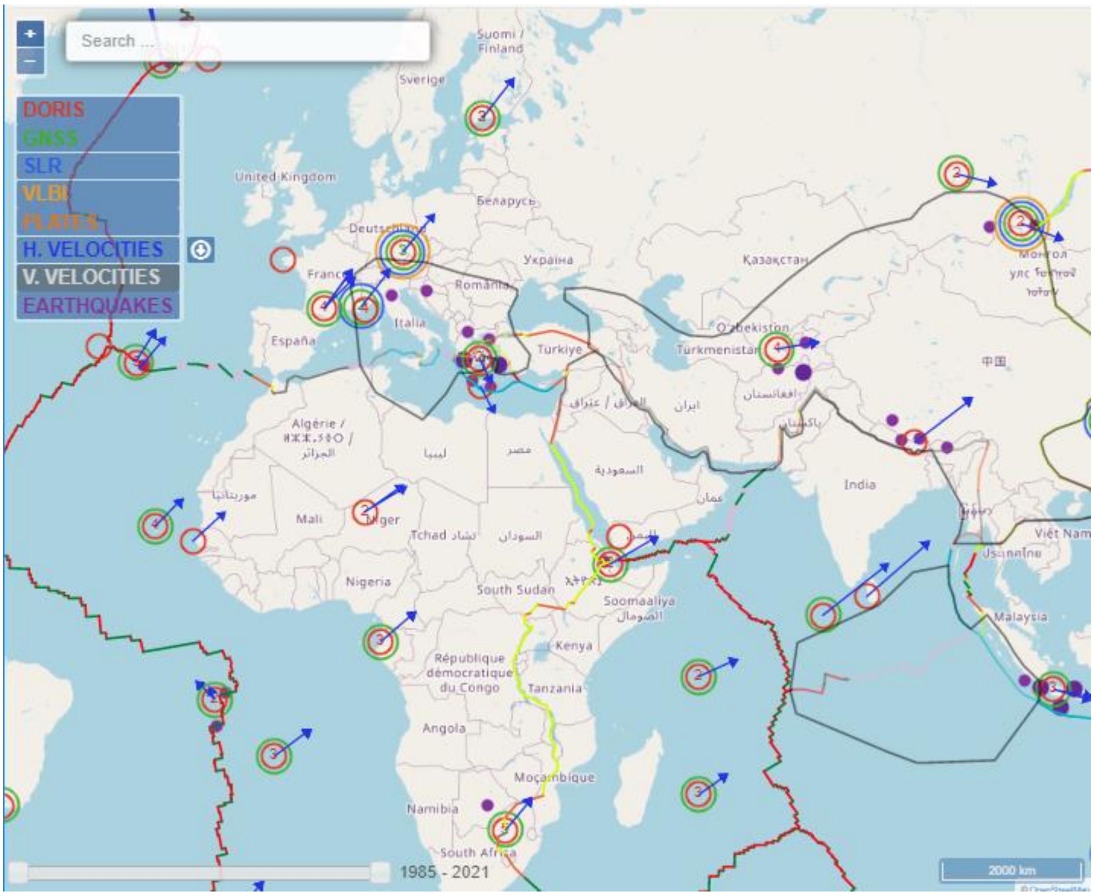


Figure 3: screenshot of the network viewer on the IDS web (https://apps.ids-doris.org/apps/map.html).

Newsletter

Launched in April 2016, the IDS Newsletter aims to provide regular information on the DORIS system and the life of IDS to a wide audience, from the host agencies to the other sister services.

The issues are distributed via email to the subscribers to the DORISmail and several identified managers and decision-makers. They are also available from the IDS website (https://ids-doris.org/ids/reports-mails/newsletter.html).

Three issues were published in 2019 (#6 in February) and 2020 (#7 in January, #8 in December). A new more dynamic presentation has been adopted since issue #7.

Data dissemination

The Central Bureau works with the SSALTO multi-mission ground segment and the Data centers to coordinate the data and products archiving and the dissemination of the related information. Data, metadata, and documentation of the two missions HY-2C and Sentinel-6A, were put online the IDS data and information sites as they become available.

2.5 Data Centers

Two data centers currently support the archiving and distribution of data for the IDS:

- Crustal Dynamics Data Information System (CDDIS), funded by NASA and located in Greenbelt, Maryland USA,
- l'Institut National de l'Information Géographique et Forestière (IGN) in Marne la Vallée France.

Both institutions have archived DORIS data since the launch of TOPEX/Poseidon in 1992. The CDDIS (ftp://cddis.nasa.gov) runs fully redundant systems with both primary and secondary systems at different physical locations with access transparent to the end user. IGN in France uses two sites (ftp://doris.ign.fr) and (ftp://doris.ensg.ign.fr) which are exact mirrors of each other offering continued operations even if one of them is inaccessible due to a temporary failure. The data holdings between CDDIS and IGN are not mirrored between the sites but rely on data providers to upload data and products to both to ensure full coverage at each center.

From mid-2019, CNES developed a new tool to control the SSALTO deliveries of DORIS data and products at both IDS Data Centers (CDDIS and IGN). Missing files and anomalies were identified and fixed for the whole sub-tree of both data centers through detailed joint work between the IDS Central Bureau, SSALTO team and the Data Centers teams. This routine maintenance is now regularly carried out to ensure the integrity of SSALTO data and products (orbits, RINEX, quaternions…).

Following the IDS Retreat in 2019, the provision of Near-Real-Time DORIS data and products was decided. A first experience is planned at the beginning of 2021 with the IGN Data Center: Jason-3 RINEX data and Diode orbits will be distributed with a latency of about 3 hours.

CDDIS Data Center

The NASA CDDIS Data Center stopped providing anonymous ftp services as of 1 November 2020. All users are now requested to use https, and a NASA Earthdata login as a method of access to the CDDIS archive. Instructions and example links are available here: https://cddis.nasa.gov/Data_and_Derived_Products/CDDIS_Archive_Access.html

Unencrypted anonymous ftp services are still available at IGN Data Center for the time being.

<u>IGN Data Center</u>
To ensure a more reliable data flow and a better availability of the IGN Data Center, two identical infrastructures and configurations have been set up in two different locations at IGN: (1) Saint-Mandé and (2) Marne-la-Vallée.
Each site offers:

- FTP deposit server for data and analysis centers uploads, requiring special authentication
- Free FTP anonymous access to observations data and products
- Independent Internet links

All the DORIS data and products archived and available at IGN DC may be access through:

1. ftp://doris.ign.fr (Saint-Mandé)
2. ftp://doris.ensg.eu (Marne-la-Vallée)

The mirroring applied between both IGN DORIS Data Centers will be consolidated to have exact identical contents.
Finally, IGN Data Center is thinking about possible evolution regarding file access and transfer by implementing the Secure File Transfer Protocol (SFTP).

After more than 12 years of service for the IGN DORIS Data Center, Bruno Garayt handed over to Jérôme Saunier from January 2019. Thank you Bruno!

2.6 Analysis Centers and Analysis Coordination

The activities of all the DORIS analysts of the past years 2019-2020 have been dominated by the preparation (2019) and the realization (2020) of ITRF2020 DORIS data re-processing. The two Analysis Working Group meetings were realized in 2019, in April (Munich, Germany) and in September/October (Paris, France). As the major topics we can highlight ITRF reprocessing schedule and standards, South Atlantic Anomaly mitigation, satellite attitude/orbit modeling and stability of the scale. Also, the Geocenter working group was established.

<u>Analysis Working Group (AWG) meetings</u>
The first AWG meeting in 2019 was hosted in Munich on April 4, thanks to our hosts Denise Dettmering and Mathis Bloßfeld of DGFI-TUM. As usual, the Analysis Centers and the Combination Center gave their processing status. The new DORIS groups as DGFI-TUM and Copernicus POD service presented results of their DORIS satellite data processing. The CNES POD team presented studies on the update of the HY-2A SRP model, on the progress on CNES mascon solutions and on the preprocessing of DORIS phase data for Doppler solutions. The main objective of this meeting was the IDS contribution to the ITRF2020.
The second AWG meeting in 2019 took place at CNES Headquarters, in Paris on September 30 and October 1, thanks to our host Pascale Ferrage. The first part of the meeting was devoted to the general IDS presentations, while the second part focused on the most important topics relevant for ITRF 2020 reprocessing.

In 2020, all AWG meetings as well as IDS workshop were cancelled due to COVID pandemic. Meetings resumed in 2021, with an online meeting in April. The analysis centers involved in the ITRF2020 reanalysis also held periodic virtual meetings with the IDS Combination Center to discuss issues with regard to their contributions, and the preparation of the IDS Combination for ITRF2020.

<u>Analysis Centers and Combination Center</u>
The IDS includes six Analysis Centers (AC) and four Associate Analysis Centers (AAC) who

use eight different software packages, as summarized in **Table 3**. Some analysis centers perform POD analyses of DORIS satellites on a routine basis using other geodetic techniques (SLR and GNSS). For ITRF 2020 reprocessing, the analysis centers ESA, GOP, GRG and GSC promised full participation, while INA plans a limited contribution processing pure DORIS RINEX data. A Geocenter Working Group was established including CNES, GOP, GRG, and DGFI-TUM.

Name	Center	Location	Contact	Software	Multi-technique
ESA	**AC**	Germany	Michiel Otten	NAPEOS	SLR, GNSS
GOP (Geodetic Observatory Pecny)	**AC**	Czech Republic	Petr Stepanek	Bernese	
GRG (GRGS)	**AC**	France	Hugues Capdeville	GINS	SLR, GNSS
GSC (NASA/GSFC)	**AC**	USA	Frank Lemoine	GEODYN	SLR
IGN	**AC**	France	Pascal Willis	GIPSY	
INA (Inasan)	**AC**	Russia	Sergei Kuzin	GIPSY	
CNES/POD	**AAC**	France	Alexandre Couhert	Zoom	SLR, GNSS
GFZ	**AAC**	Germany	Rolf Koenig	EPOS-OC	SLR, GNSS
TU Delft	**AAC**	The Netherlands	Ernst Schrama	GEODYN	SLR
DGFI-TUM	**AAC**	Germany	Mathis Bloßfeld, Sergei Rudenko	DOGS	SLR

Table 3: Summary of IDS Analysis Centers (AC) and Associate Analysis Centers (AAC)

Status of ITRF2020 reprocessing

Four analysis centers participated in ITRF 2020 reprocessing: GSC, GRG, GOP, and ESA. GSC, GRG and GOP processed data 1993.0-2020.0. GSC did not include Sentinel-3A and Sentinel-3B data but plans its inclusion in final solution. GOP completely excluded Jason-1 data. ESA data processing is delayed but with anticipation of full contribution. IGN and INA were not able fully contribute.
The schedule followed by IDS for this reprocessing was as follows:

- 2020, March 30: delivery by ACs of 1993.0 2002.3 (until start of Envisat First DORIS 2G receiver)
- 2020, June 30: delivery by ACs of 2002.3 2011.8 (until start of HY-2A).
- 2020, Sept. 30: delivery by ACs of 2011.8 2020.0.
- 2021, Feb. 10: First delivery of the IDS combined solution to the IERS (1993.0 2020.0).
- 2021, Feb. 14: delivery by ACs of 2020
- 2021, Mar. 15: Complete delivery to the IERS of the IDS combined solution (1993.0-2021.0).

2.7 Combination Center

In addition to the routine evaluation and combination of the solutions of the IDS Analysis Centers, in 2019 and 2020, the IDS Combination Center (CC) released the two versions of the IDS cumulative position and velocity and DPOD2014 solutions. The CC also performed some analysis mostly related to the forthcoming realization of the IDS contribution to the ITRF2020 and initialized the analysis and construction of the IDS series for the ITRF2020.

IDS Routine Evaluation and Combination
At the end of 2020, the time span of the SINEX files of the IDS combined solution was 1993.0-2020.5. These files correspond to the new IDS series 14 which differs from the previous series 13 by a new preprocessing of the inputs, i.e., the weekly SINEX files provided by the Analysis Centers (ACs).

Late 2019, the Combination Center released a new version of the coordinate time series plots which are routinely delivered to the Data Centers. That new version (see **Figure 4**) displays as vertical lines dates of events which may have an impact of the positions and/or velocities. Depending on their origin, three types of events are displayed: seismic, technical (beacon or USO change, antenna displacement…) and unknown.

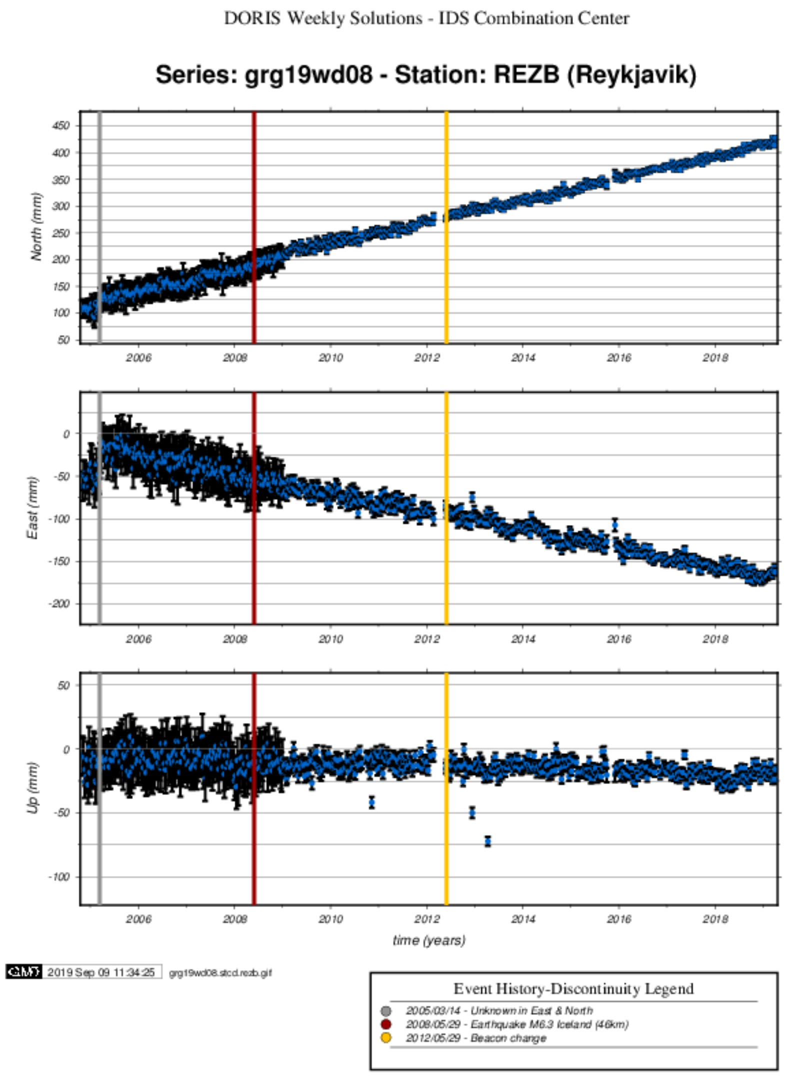


Figure 4: Example of the new version of the coordinate time series plots delivered to the IDS Data Centers

<u>IDS Cumulative Solution</u>

In 2019, the Combination Center realized and made available (through the IDS Data Centers) the fourth version of the DORIS cumulative solution (ids19d04) which provides with the mean positions and velocities of the DORIS stations. That solution is obtained by the stacking of the ids 13 weekly combined solution from 1993.0 to 2019.0. All the cumulative solutions are available in SINEX format at the IDS Data Centers. Internal validation reports as well as plots of the station position residuals (differences between the weekly positions as input and the positions deduced from the mean positions and velocities) are available on the IDS website.

Mid-2020, due to both the evolution of the beacon ground network and of new geophysical

events, a new cumulative solution over 1993.0-2020.0 was produced based on the ids13 and ids14 weekly combined solutions.
To better understand the differences between the solutions of the Analysis Centers and their impact on the estimation of the mean positions and velocities, the Combination Center adapted the cumulative processing chain to get position and velocity cumulative solutions for each operational AC. As the IDS cumulative solution, these solutions are also aligned to the ITRF2014 and make use of the same discontinuities.

DPOD2014

In line with the realization of the fourth version of the DORIS cumulative solution, the Combination Center delivered to the IDS community the fourth and fifth versions of the DORIS extension of the ITRF2014, called DPOD2014 (see **Figure 5**). Compared to the cumulative solution, the DPOD2014 contains the stations observed before 1993 as well as the stations turned on after the ending date of the stacking. The DPOD2014 solution is available for download from the IDS Data Centers in both SINEX and text formats.
From the DPOD2014, the Combination Center generates a so-called IDS SINEX Master file containing the names and locations of all the DORIS stations since the start of DORIS. The SINEX Master file is freely available for download from the IDS Central Bureau ftp site.

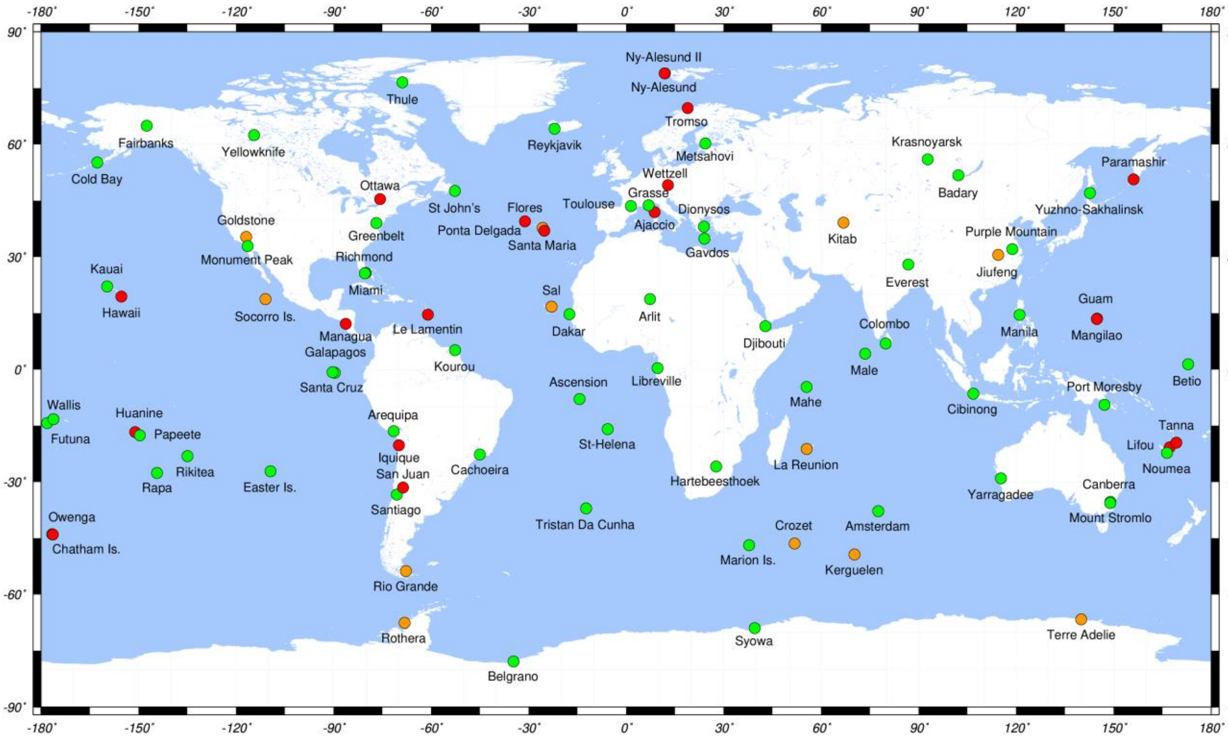


Figure 5 - DORIS sites included in the version 5 of the DPOD2014 (i.e., DORIS extension of the ITRF2014). Green: ITRF2014 sites. Orange: ITRF2014 sites with new station(s) since ITRF2014. Red: sites not included in the ITRF2014.

ITRF2020

So far, nearly fifteen series were delivered by the four IDS ACs (ESA, GOP, GRG and GSC) which agreed to participate to the realization of the DORIS contribution to the ITRF2020. All these series are fully compliant with the latest IERS standards and recommendation to the ITRF2020 call of participation. The delivery of the ACs were scheduled over time-periods

linked with the time evolution of the DORIS satellite constellation: 1993.0-2002.5, 2002.5-2011.7 and 2011.7-2020.0. Due the DORIS data and model latencies, the final year will be delivered around February 2021.
The year 2020 was devoted to evaluating the performance of the received series, analyzing the anomalies, iterating with the Analysis Centers to correct them, improving the combination chain, and defining the combination strategy.
Prior to AGU 2020 Fall meeting, the IDS CC made available for evaluation to the IERS combination centers (DGFI, IGN and JPL) a preliminary IDS solution from 1993.0 to 2020.0.

2.8 Working Group "NRT DORIS DATA"
Chair: Denise Dettmering (DGFI-TUM, Germany)

Following user requests for rapid dissemination of DORIS data for assimilation in ionospheric models, the IDS Governing Board created a Working Group (WG) dealing with near real-time (NRT) DORIS data, on November 1st, 2017, and appointed Denise Dettmering (DGFI-TUM) as chair.
The general objective of this working group is a thorough assessment on benefits, requirements, and prospects of DORIS data with improved data latency with a focus on applications in ionospheric research.

The main topics addressed by the WG are:

- Development of a DORIS ionospheric product (STEC/VTEC or dSTEC/dVTEC),
- Using DORIS data for global real-time ionospheric modeling,
- Using DORIS data to validate the performance of global ionospheric TEC models,
- Improving ionospheric modelling with focus on the combination of different space-based observation datasets,
- Networking with other IAG working groups: GGOS JWG 3 “Improved understanding of space weather events and their monitoring by satellite missions” and IAG JWG 4.3.1 “Real-time ionosphere monitoring and modelling”.

At the end of 2020, the ongoing activities are:

- Simulated DORIS NRT test data set (RINEX and sp3) currently under investigation,
- Software preparation to use the data.

The WG did not meet in 2020.

3. IDS meetings and publications

3.1 Meetings

IDS organizes two types of meetings:

- IDS Workshops (every two years), opened to a large public and related to scientific aspects or applications of the DORIS systems.
- Analysis Working Group Meetings (AWG) (when needed), more focused on technical issues, and usually attended by representatives of Analysis Centers.

Table 4: IDS Meetings (2019-2020)

Meeting	Location	Country	Dates
DORIS AWG Meeting	Munich	Germany	4 April 2019
DORIS AWG Meeting	Paris	France	30 September – October 2019

Due to the global Covid-19 pandemic, no event was organized in 2020.

3.2 Publications

During the last two years, IDS published the following activity reports:

International DORIS Service (IDS), Report of the International Association of Geodesy 2015-2019, Travaux de l'Association Internationale de Géodésie, Frank Lemoine (chairman of the Governing Board), 2019. https://ids-doris.org/documents/report/IDS_Report_mid2015_mid2019_for_IAG.pdf

International DORIS Service Activity report 2018, Laurent Soudarin and Pascale Ferrage (Eds), 108 pages, 2019. https://ids-doris.org/documents/report/IDS_Report_2018.pdf

3.3 Peer-reviewed publications related to DORIS

IDS maintains on its Web site a complete list of DORIS-related peer-reviewed articles published in international Journals (https://ids-doris.org/report/publications/peer-reviewed-journals.html). In the last two years, the following articles were published (by year):

2020

Abbondanza, C.; Chin, T.M.; Gross, R.S.; Heflin, M.B.; Parker, J.W.; Soja, B.; Wu, X., 2020. A sequential estimation approach to terrestrial reference frame determination, ADVANCES IN SPACE RESEARCH, 65(4):1235-1249, DOI: 10.1016/j.asr.2019.11.016

Bertiger, W.; Bar-Sever, Y.; Dorsey, A.; Haines, B.; Harvey, N.; Hemberger, D.; Heflin, M.; Lu, W.; Miller, M.; Moore, A.W.; Murphy, D.; Ries, P.; Romans, L.; Sibois, A.; Sibthorpe, A.; Szilagyi, B.; Vallisneri, M.; Willis, P., 2020. GipsyX/RTGx, A New Tool Set for Space Geodetic Operations and Research, ADVANCES IN SPACE RESEARCH, 66(3):469-489, DOI: 10.1016/j.asr.2020.04.015

Beutler, G.; Villiger, A.; Dach, R.; Verdun, A.; Jäggi, A., 2020. Long polar motion series: Facts and insights, ADVANCES IN SPACE RESEARCH, 66(11):2487–2515, DOI: 10.1016/j.asr.2020.08.033 OPEN ACCESS

Bloßfeld, M.; Zeitlhöfler, J.; Rudenko, S.; Dettmering, D., 2020. Observation-Based Attitude Realization for Accurate Jason Satellite Orbits and Its Impact on Geodetic and Altimetry Results, REMOTE SENSING, 12(4):682, DOI: 10.3390/rs12040682 OPEN ACCESS

Hernández-Pajares, M.; Lyu, H.; Garcia-Fernandez, M.; Orus-Perez, R., 2020. A new way of improving global ionospheric maps by ionospheric tomography: consistent combination of multi-GNSS and multi-space geodetic dual-frequency measurements gathered from vessel-, LEO- and ground-based receivers, JOURNAL OF GEODESY, 94(8):, DOI: 10.1007/s00190-020-01397-1

Jagoda, M.; Rutkowska, M.; Suchocki, C.; Katzer, J., 2020. Determination of the tectonic plates motion parameters based on SLR, DORIS and VLBI stations positions, JOURNAL OF APPLIED GEODESY, 14(2):121-131, DOI: 10.1515/jag-2019-0053

Kong, Q.; Zhang, L.; Han, L.; Guo, J.; Zhang, D.; Fang, W., 2020. Analysis of 25 Years of Polar Motion Derived from the DORIS Space Geodetic Technique Using FFT and SSA

Methods, SENSORS, 20(10), DOI: 10.3390/s20102823 OPEN ACCESS
Kosek, W.; Popiński, W.; Wnęk, A.; Sośnica, K.; Zbylut-Górska, M., 2020. Analysis of Systematic Errors in Geocenter Coordinates Determined From GNSS, SLR, DORIS, and GRACE, PURE AND APPLIED GEOPHYSICS, 177(2):867-888, DOI: 10.1007/s00024-019-02355-5 OPEN ACCESS
Štěpánek, P.; Bingbing, D.; Filler, V.; Hugentobler, U., 2020. Inclusion of GPS clock estimates for satellites Sentinel-3A/3B in DORIS geodetic solutions, JOURNAL OF GEODESY, 94(116):, DOI:10.1007/s00190-020-01428-x
Zhou, C.; Zhong, S.; Peng, B.; Ou, J.; Zhang, J.; Chen, R., 2020. Real-time orbit determination of Low Earth orbit satellite based on RINEX/DORIS 3.0 phase data and spaceborne GPS data, ADVANCES IN SPACE RESEARCH, 66(7):1700 - 1712, DOI: 10.1016/j.asr.2020.06.027

2019

Kong, Q.; Gao, F.; Guo, J.; Han, L.; Zhang, L.; Shen, Y., 2019. Analysis of precise orbit predictions for a HY-2A satellite with three atmospheric density models based on dynamic method, REMOTE SENSING, 11(1), 40, DOI: 10.3390/rs11010040
Kong, Q.; Guo, J.; Han, L.; Shen, Y., 2019. Performance of three atmospheric density models on precise orbit determination for Haiyang-2A satellite using DORIS data, in Enhancements in Applied Geomechanics, Mining, and Excavation Simulation and Analysis. GeoChina 2018, Sevi A., Neves J., Zhao H. (Eds.), SUSTAINABLE CIVIL INFRASTRUCTURES, 126-135, DOI: 10.1007/978-3-319-95645-9_12
Lian, L.; Wang, J.; Huang, C., 2019. Analysis and combination of four technique-individual EOP time series, GEODESY AND GEODYNAMICS, 10(2): 130 - 139, DOI: 10.1016/j.geog.2018.04.005 OPEN ACCESS
Merkowitz, S. M.; Bolotin, S.; Elosegui, P.; Esper, J.; Gipson, J.; Hilliard, L.; Himwich, E.; Hoffman, E.D.; Lakins, D.D.; Lamb, R.C.; Lemoine, F.G.; Long, J.L.; McGarry, J.F.; McMillan, D.S.; Michael, B.P.; Noll, C.E.; Pavlis, E.C.; Pearlman, M.R.; Ruszczyk, C.; Shappirio, M.D.; Stowers, D.A., 2019. Modernizing and expanding the NASA Space Geodesy Network to meet future geodetic requirements, JOURNAL OF GEODESY, 93(11):2263–2273, DOI: 10.1007/s00190-018-1204-5
Moreaux, G.; Willis, P.; Lemoine, F.G.; Zelensky, N.P.; Couhert, A.; Ait Lakbir, H.; Ferrage, P., 2019. DPOD2014: a new DORIS extension of ITRF2014 for Precise Orbit Determination, ADVANCES IN SPACE RESEARCH, 63(1):118-138, DOI: 10.1016/j.asr.2018.08.043
Rudenko, S.; Esselborn, S.; Schöne, T.; Dettmering, D., 2019. Impact of terrestrial reference frame realizations on altimetry satellite orbit quality and global and regional sea level trends: a switch from ITRF2008 to ITRF2014, SOLID EARTH, 10(1):293-305, DOI: 10.5194/se-10-293-2019 OPEN ACCESS

International GNSS Service

Felix Perosanz, IGS Governing Board Chair
Centre National d'Etudes Spatiales (CNES)

Allison Craddock, IGS Central Bureau Director, &
Mayra I. Oyola-Merced, IGS Central Bureau Deputy Director
National Aeronautics and Space Administration (NASA)
Jet Propulsion Laboratory, California Institute of Technology (JPL-Caltech)

http://www.igs.org

Figure 1 IGS at Glance

Overview

For over twenty-five years, the International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite Systems) has carried out its mission to advocate for and provide freely and openly available high-precision GNSS data and products. Despite a global pandemic and interruptions on our life and work schedules, the IGS has continued to meet our users and community needs. While delivery of the IGS core reference frame, orbit, clock and atmospheric products continues to drive the core activities, the IGS transformation to a multi-GNSS service continues as more stations are added into the core IGS network and as we re-evaluate the IGS role in achieving multi-GNSS excellence.

The IGS operates as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS), where it facilitates cost-effective geometrical linkages with and among other precise geodetic observing techniques, including: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). These linkages are fundamental to generating and accessing the International Terrestrial Reference Frame (ITRF). Accordingly, a number of the Governing Board (GB) members participate in IAG and GGOS governance, bureaus, commissions and working groups, ensuring the IGS retains its strong level of international significance and sustainability. Similarly, we continue to engage with our collaborators through the United Nations (UN) International Committee on Global Navigation Satellite Systems (ICG) as well as the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) and its Subcommittee on Geodesy, while aiming to enhance the sustainability of the global geodetic reference frame through intergovernmental advocacy for geodesy.

The 2020 IGS Workshop was postponed due to the travel restrictions that resulted as a consequence of the novel COVID-19, however, we continued to interact with the community members discussing the extensive contribution and views of the organization as it pertains to the next decade. With this in mind, during 2020
we unveiled three new formats in line with community requirements: The Radio Technical Commission for Maritime Services (RTCM) State Space Representation (SSR) Messages, the RINEX 3.05 and GZIP RINEX; and completed the third reprocessing campaign (repro3) in support of the ITRF2020. Additionally, we completed the process for our Vision 2020+**,** a forward-looking IGS Strategic Plan addressing the role of IGS as facilitator, incubator, coordinator, and advocate on behalf of the community started in 2020. The results of this plan will be published early 2021.

IGS Membership and Governance

Membership Growth and Internal Engagement

As of May 2021, the IGS membership consists of 335 Associate Members, and is expected to continue to grow in the coming years. Our membership is representative of over 45 countries. The 36-member IGS Governing Board guides the coordination of over 200 contributing organizations participating within IGS, including 108 operators of GNSS network tracking stations, 6 global Data Centers, 13 Analysis Centers, and 4 product coordinators, 21 associate Analysis Centers, 23 regional/project Data Centers, 14 technical Working Groups, an ongoing Multi-GNSS Pilot Project, and the Central Bureau. The IGS structure is depicted on Figure 2.

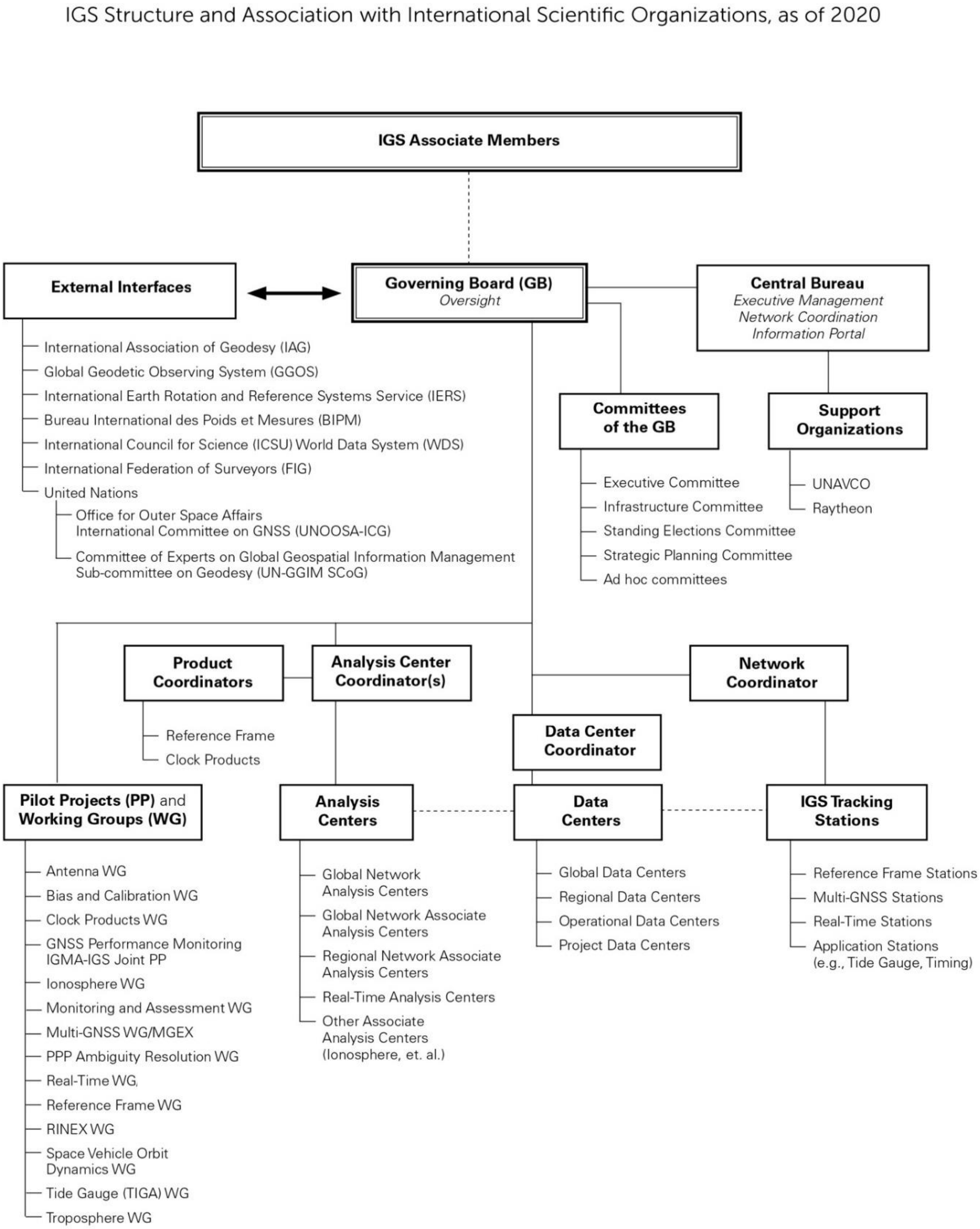


Figure 2 IGS Structure

Governing Board Appointments

The IGS is led by an International Governing Board that is elected by the Associate Members who represent the principal IGS participants. The Governing Board discusses the activities of the various IGS components, sets policies and monitors the progress with respect to the agreed strategic plan and annual implementation plan.

During the past two years, the Governing Board experienced several personnel changes. The Governing Board Chair position transitioned from Mr. Gary Johnston from Geoscience Australia to Dr. Felix Perosanz from the Centre National d'Etudes Spatiales (CNES, France) in May 2020, following Johnston's retirement. Additionally, Dr. Ignacio Romero from the he European Space Agency European Space Operations Centre in Germany transitioned from his former position as the Infrastructure Committee Chair to lead the RINEX Working Group. This position had remained vacant after the retirement of Mr. Ken McLeod from National Resources Canada in 2019. Another major introduction was the election and approval of Markus Bradke as the new Infrastructure CommitteeChair in August 2020, a role that was later reclassified as Infrastructure Committee Coordinator. Finally, several ex-officio appointments were confirmed and renewed. These appointments are described on Table 1.

Besides Johnston, other notable long-serving retirees from the GB in 2020 included Data Center Coordinator, Ms. Carey Noll from NASA Goddard Space Flight Center (USA) and Dr. Charles Meertens from UNAVCO who served as an Executive Committee (EC) Member and IERS representative. They are succeeded by Dr. Pat Michaels (NASA Goddard/CDDIS, USA) and Appointed Member Dr. Elisabetta D'Anastasio (GNS, New Zealand)

Table 1 summarizes the Governing Board Membership at the end of 2020. Blue represents members of the GB who have transitioned into a new position. New members are highlighted with an asterisk (*).

Name	Surname	Agency/Institute	Country	Position
Felix	Perosanz	CNES	France	Board Chair
Gary	Johnston	Geoscience Australia	Australia	Past Board Chair
Ryan	Ruddick	Geoscience Australia (GA)	Australia	Network Representative
*Salim	Masoumi	GA	Australia	Analysis Center Co-Coordinator
Suelynn	Choy	RMTI	Australia	International Federation of Surveyors (FIG) Representative
Simon	Banville	NRCan	Canada	PPP-AR Working Group Chair
*José Antonio	Tarrio-Mosquero	Universidad de Santiago de Chile	Chile	Appointed (IGS)
Qile	Zhao	Wuhan University	China	Appointed (IGS)
Zuheir	Altamimi	IGN	France	IAG Representative
Paul	Rebischung	IGN	France	IGS Reference Frame Coordinator
Gérard	Petit	BIPM	France	BIPM/CCTF Representative
Benjamin	Männel	GFZ	Germany	Analysis Center Representative

Werner	Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)
Laura	Sánchez	DGFI-TUM	Germany	Network Representative
Wolfgang	Söhne	BKG	Germany	Network Representative
Loukis	Agrotis	ESA	Germany	Real-time Analysis Coordinator
Tim	Springer	ESA	Germany	IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair
Ignacio	Romero	ESA	Germany	RINEX-RTCM Working Group Chair
Oliver	Montenbruck	DLR	Germany	Multi-GNSS Working Group Chair
Andre	Hauschild	DLR	Germany	Real-time Working Group Chair
Tim	Springer	ESA	Germany	Satellite Vehicle Orbit Dynamics Working Group Chair
Tilo	Schöne	GFZ	Germany	TIGA Working Group Chair
*Markus	Bradke	GFZ	Germany	Infrastructure Committee Chair (Interim, later confirmed)
Satoshi	Kogure	NSPS	Japan	Appointed (IGS)
Basara	Miyahara	GSI	Japan	IAG Representative
*Elisabetta	D'Anastasio	GNS Science	New Zealand	Appointed (IGS)
Andrzej	Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere Working Group Chair
Rolf	Dach	AIUB	Switzerland	Analysis Center Representative
Arturo	Villiger	AIUB	Switzerland	Antenna Working Group Chair
Stefan	Schaer	swisstopo	Switzerland	Calibration & Bias Working Group Chair
Thomas	Herring	MIT	USA	Analysis Center Coordinator
Charles	Meertens	UNAVCO	USA	Appointed (IGS)
Allison	Craddock	NASA JPL	USA	Central Bureau Director
David	Stowers	NASA JPL	USA	Data Center Representative
Richard	Gross	NASA JPL	USA	IERS Representative
Michael	Coleman	NRL	USA	IGS Clock Products Coordinator
*Patrick	Michael	NASA GSFC	USA	Data Center Coordinator
David	Maggert	UNAVCO	USA	Network Coordinator
Mayra	Oyola	NASA JPL	USA	Central Bureau Deputy Director & GB Executive Secretary
Sharyl	Byram	USNO	USA	Troposphere Working Group, Chair
VACANT	VACANT	VACANT	VACANT	Board Vice Chair

Table 1. Members of the IGS Governing Board, 2021.

Central Bureau Management:

Executive management of the IGS (Table 2) is carried out by the Central Bureau, whose office is hosted at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory, California Institute of Technology, in Pasadena, California, USA. It is funded principally by NASA, which generously contributes significant staff, resources, and coordination to advance the IGS. The mission of the IGS Central Bureau is to provide continuous management and technological resources in order to sustain the multifaceted efforts of the IGS in perpetuity. It functions as the executive office of the Service and responds to the directives and decisions of the IGS Governing Board. The Central Bureau coordinates the IGS tracking network and operates the Information System, the principal information portal where the IGS web, ftp (now https) and mail services are hosted. The Central Bureau also represents the outward face of IGS to a diverse global user community, as well as the general public.

The Central Bureau, as part of its work program carrying out the business needs of the IGS, implements actions defined by the GB. This includes routine analysis and refining of the IGS Terms of Reference, supporting the ongoing update of the associate membership and contributing organizations list, coordinating and facilitating GB elections, and ensuring successful organization of regular IGS Workshops, governance meetings, and community outreach events. Additionally, the Central Bureau works closely with members of the Governing Board's Executive Committee in developing and implementing the IGS Strategic Plan.

The IGS Central Bureau runs under the leadership of Ms. Allison Craddock, who was approved as Director by the Governing board in March 2018, and whose tenure has focused into developing a "resilient, interdisciplinary, and interoperable" IGS by ensuring successful completion of essential tasks, overseeing the procedures on IGS structure and governance and greatly increasing the IGS engagement and external relations. Craddock represents the Secretariat of the IGS in numerous stakeholder organizations, including GGOS, UN ICG, the International Federation of Surveyors (FIG), and supporting IGS contributions to IAG participation in the UN GGIM Subcommittee on Geodesy.

Since 2019, the Central Bureau has been fully-staffed, which has resulted in a steadfast advantage in supporting a growing IGS. In February 2019, Dr. Mayra Oyola (NASA JPL, USA) was appointed as the acting Deputy Director of the Central Bureau, having transitioned officially into the role after the 54th GB meeting in December 2019. She was also appointed as the Executive Secretary of the GB and a member of the Executive Committee. Oyola also acts as the IGS representative for the World Data System (WDS) and the IAG Inter-Commission Committee on "Geodesy for Climate Research" (ICCC). Besides supporting the organizational and administrative tasks of the IGS, Oyola's appointment leverages new connections and outreach opportunities to the Weather and Climate community given her background in both fields, a priority for the IGS. Additionally, Mr. Robert Khachikyan (Raytheon, USA), who had previously served as the Network Coordinator, was appointed as the new Information Systems Engineer. His reinstatement has allowed the development of the new IGS website, which became fully operational at the end of 2020. The Central Bureau has also received the support of Ms. Ashley Santiago (Raytheon, USA), who has been in charge of the new IGS website frontend development, and has been supporting all IGS communication efforts since June 2020. Table 2 lists the members of the current Central Bureau staff.

Name	*Affiliation*	*Role*
Allison Craddock	NASA Jet Propulsion Laboratory	Director
Mayra I. Oyola	NASA Jet Propulsion Laboratory	Deputy Director
David Maggert	UNAVCO	Network Coordinator
Robert Khachikyan	Raytheon Corporation	Information Systems Engineer
Ashley Santiago	Raytheon Corporation	User Interface Specialist
David Stowers	NASA Jet Propulsion Laboratory	Information Systems Advisor

Table 2 IGS Central Bureau Staff (as of May, 2021)

Summary of Accomplishments and Decisions 2019-2021:

Our global IGS community continues to adapt to the impacts of COVID-19, particularly with the newly introduced changes in work environment and travel limitations. The IGS Central Bureau and Governing Board were faced with challenges on how to best address the various options for holding meetings virtually, particularly accommodating for various time zones and technology bandwidths. Similarly, a major concern was how to best continue to support all of our data and products dissemination through the Information Systems, as members have been working from their respective residences in order to comply with the stay in place measures implemented across the United States since March, 2020.

The challenges imposed by this period have provided a number of lessons that can be apply to IGS future events and projects. We have explored and mastered a number of technology applications and practices that have improve data management and membership engagement. Despite the constraints and restrictions imposed by the novel COVID-19, the IGS was able to maintain all essential operations, including virtual round-the-world Governing Board and Working Group meetings.

IGS Operational Activities

With the assistance of the Central Bureau Network Coordinator and the Infrastructure Coordinator, the IGS network (Figure 3) added 5 new stations and identified 5 stations for decommissioned in 2020, bringing the current total to 506 stations. The number of muti-GNSS stations increased from 308 to 326; while real-time stations increased from 259 to 270. Additionally, 95 changes to the rcvr_ant.tab files were implemented with collaboration of the Antenna WG. At the end of the year, support for the Site Log Manager included 573 site log updates (~45 per month) and 41 antenna changes (11 of those at IGS14 core stations).

During 2020, 186 new user accounts were added to the Central Bureau real time caster, which as of January 2021, will be manned by the University Corporation for Atmospheric Research in Boulder, Colorado. The Central Bureau Network Coordinator also responded to over 140 inquiries about data, products, or general IGS information. Station information was updated to include new photos and SONEL and tide gauge information. In order to comply with security requirements for the transition of file transfer protocol (FTP) to secured FTP, the Central Bureau updated the internal scripts to use HTTPS/Curl for data collection.

Network Growth

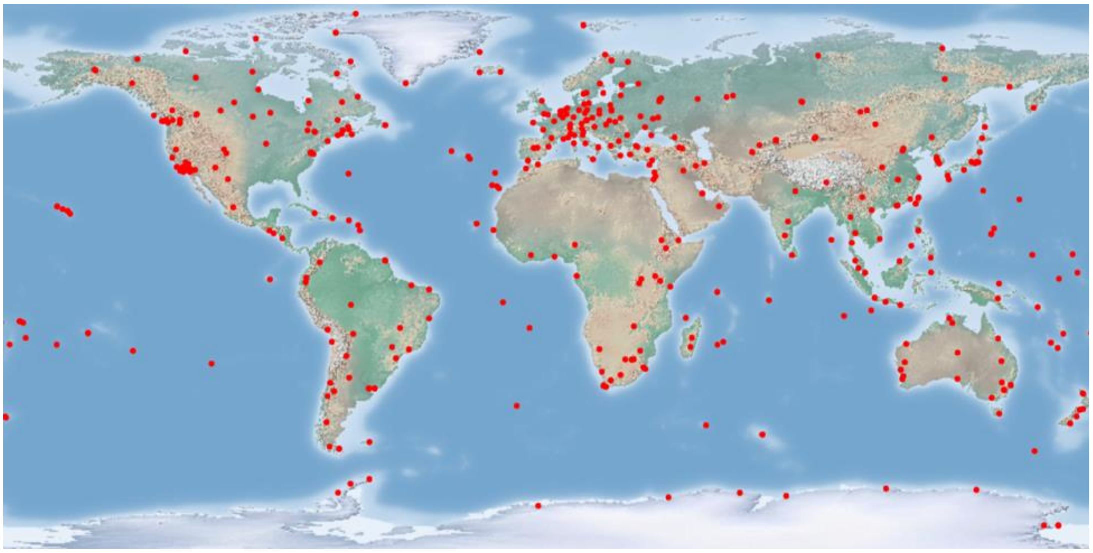


Figure 3 The 506 IGS stations as of January 31, 2021. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

Product Generation and Performance

Joint management of the IGS Analysis Center Coordinator by Michael Moore (Geoscience Australia, Australia) and Tom Herring (Massachusetts Institute of Technology, USA) continued, with operations based at Geoscience Australia in Canberra, Australia. The Analysis Center Coordinator combination software is housed on cloud-based servers located in Australia and Europe, and coordination of the IGS product generation continues to be carried out by personnel distributed between Geoscience Australia and the Massachusetts Institute of Technology. The IGS continues to maintain a very high level of product availability. At the end of 2020, Salim Masoumi of Geoscience Australia, succeeded Michael Moore as the IGS Co-Analysis Center Coordinator.

IGS Reprocessing Campaign 3 (repro3)

At the 2018 IGS workshop, it was decided to carry out a reprocessing that will lead to the third generation, in time for a contribution to the ITRF2020. The activities pertaining the third reprocessing (repro3) occurred during 2020.

A first set of daily and weekly combined terrestrial frame solutions from repro3 has been made available as preliminary IGS contribution to ITRF2020. The final IGS repro3 terrestrial frame solutions were released by the extended IERS deadline (10 April 2021). Most participating Analysis Centers have completed their reprocessing, and some minor issues identified in current contributions are being resolved. For now, the preliminary IGS repro3 terrestrial frame solutions are combinations of the following contributions:

Initial Available repro3 contributions:

Center	GPS Contribution	GLONASS Contribution from:	Galileo Contribution from:
COD	1994-01-02 to 2019-12-31	2002-01-01	2013-01-01
ESA	1995-01-01 to 2020-12-31	2009-01-01	2015-01-01
GFZ	1994-01-02 to 2020-12-31	2012-01-01	2013-12-21
GRG	2000-05-03 to 2020-12-31	2008-11-04	2016-12-31
JPL	1994-01-02 to 2019-12-28	None	None
MIT	2007-01-07 to 2019-12-28	None	2017-01-01
NGS	1994-01-02 to 2020-12-31	None	None
TUG	1994-01-02 to 2020-12-31	2009-01-01	2013-01-01
ULR	2008-01-01 to 2020-12-31	None	None
WHU	2008-01-01 to 2019-12-31	2010-09-28	None

Table 3 ACC repro3 initial contributions

Details about the available products, the modeling updates since the repro2 campaign and the combination strategy can be found in https://www.igs.org/news/repro3-solutions-now-available/ .

Data Management

The amount of IGS tracking data and products hosted by each of the four global Data Centers on permanently accessible servers increased from 2 TB to 11 TB (135 million files) over the last 5 years, supported by significant additional storage capabilities provided by Regional Data Centers.

Twelve Analysis Centers and a number of Associate Analysis Centers utilize tracking data from between 70 to more than 500 stations to generate precision products up to four times per day. Product coordinators combine these products on a continuous basis and assure the quality of the products made available to the users.

The collective effort of the IGS produces 700 IGS final, rapid, ultra–rapid and Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS)– only product files, as well as 126 ionosphere files weekly. Furthermore, troposphere files for more than 300 stations are produced on a daily basis.

Delivery of core reference frame, orbit, clock and atmospheric products continues strongly. The IGS has also seen further refinement of the Real Time Service with considerable efforts being targeted towards development of Standards. The transition to multi GNSS also continues apace within the IGS, with additional Galileo and Beidou satellite launches bringing those constellations closer to operational status.

The intense interest of users in IGS data and products is reflected in the 2020 user activity recorded by the Crustal Dynamics Data Information System at the NASA Goddard Space Flight Center.

- Total of 1.4B files equating to 121 TBytes GNSS data
- Total of 16M files equating to 43 TBytes GNSS products
- Average of 116M files equating to 10 TBytes GNSS data from 18.8K hosts per month
- Average of 16.4M files equating to 3.5 TBytes GNSS products from 13.8K hosts per month

Web Services

The IGS has ensured open access, high-quality GNSS data products since 1994. These products enable access to the definitive global reference frame for scientific, educational, and commercial applications – a tremendous benefit to the public, and key support element for scientific advancements. Most of these resources are available or introduced to the community via our webpage, which had become outdated and difficult to navigate over time. Based on its own internal assessment and following community feedback, the Central Bureau decided it was time to redesign the site and improve its User Experience and User Interface, focusing primarily on improving navigation, design and content. With this in mind, a new and secured https://igs.org was developed, with the intent to replace the functionality of the very complicated and unsecured previous site. A simplified domain was created under NASA's GovCloud to ensure the system is properly maintained, secured, and identified as a service within the NASA Jet Propulsion Laboratory.

The transition to the new website occurred in December 2020 along with the broadly advertised ftp to https transition. While the original transition date was scheduled for April 2020, the community requested for it to be extended to allow for additional time to deal with new COVID-related restrictions. In the meantime, the original site, which was located at http://igs.org continued to operate in parallel with the "beta site" https://igscb.org. As of 15 December 2020, the beta site (https://igscb.org) has transitioned into http://igs.org and the old website has been decommissioned.

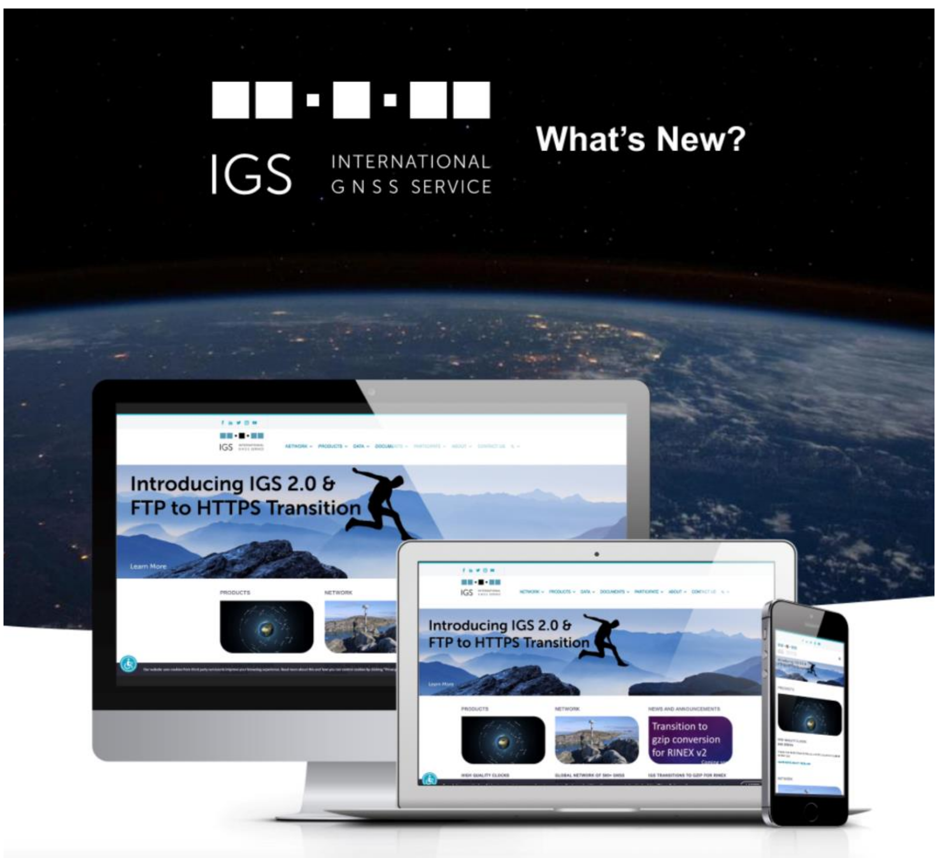


Figure 4 The New IGS.org

The new refresh focused on creating a more functional and easier to navigate platform by implementation of larger and more graphically descriptive menus, while matching the requirements of the stakeholders, IGS members and community in general. At the same time, the new portal focused on providing a platform that was easier to navigate than the previous website. The selected, platform (*Wordpress*), does not only offer a modern interface, but allows the website and its content to be optimized for different devices, browsers, data speed, search engines, and users. Some of the major areas that were improved include:

Front Page: The new igs.org home page has been enhanced for diverse community engagement, with an eye-catching banner for the latest news and announcements, a slider highlighting IGS working groups, and a *Twitter* feed to encourage users to follow us on social media to stay up to date [https://www.igs.org/]

Navigation: The old igs.org navigation menu had only had 5 top-level links with no dropdown menu. With the vast amount of information, the IGS currently has, it was difficult to navigate through the site without a significant time investment. Furthermore, users were relying on organic searches functions to be able to find their resources. The new "Mega Menu" navigation (as opposed to a traditional dropdown navigation), better supports the new and improved sitemap and ensures all links are clearly shown to users.

Contributing Organizations: Another important part of the IGS community are its contributing organizations. There is now a dedicated page that features contributing organizations where users can learn more about their role in the IGS as well as about that institution.

Events/News: Viewing IGS Events has been enhanced with a more user-friendly design, including the ability to search, change view from list to month, easily view key info about each event, and export events onto your Google or iCal calendars. To keep our users up to date with the latest news and announcements, the team also updated the news page design with added visuals and easy navigation.

Working Group and Pilot Project Pages: Working Groups and Pilot Projects are an important part of the IGS community. In this new website, IGS Working Groups and Pilot Projects are heavily featured, appearing on both the home page and its own dedicated page. Now users can find all the information about a particular working group or pilot project in one place. Additionally, working group chairs now have the ability to securely manage their respective pages to keep them up to date with the latest information. For more information, please visit: https://www.igs.org/working-groups-pilot-projects.

Scientific Applications of IGS Data and Analysis Products Session at AGU 2020

Between 2019-2020, the IGS has organized two sessions at the American Geophysical Union (AGU). While the 2020 Session was in person in San Francisco, CA, USA, the 2020 took place virtually due to COVID-19 travel restrictions. These Session, were convened by Governing Board Executive Committee member Rolf Dach of the University of Bern, Switzerland and Allison Craddock, Director of the IGS Central Bureau and the Jet Propulsion Laboratory. The description of the 2020 session is as follows:

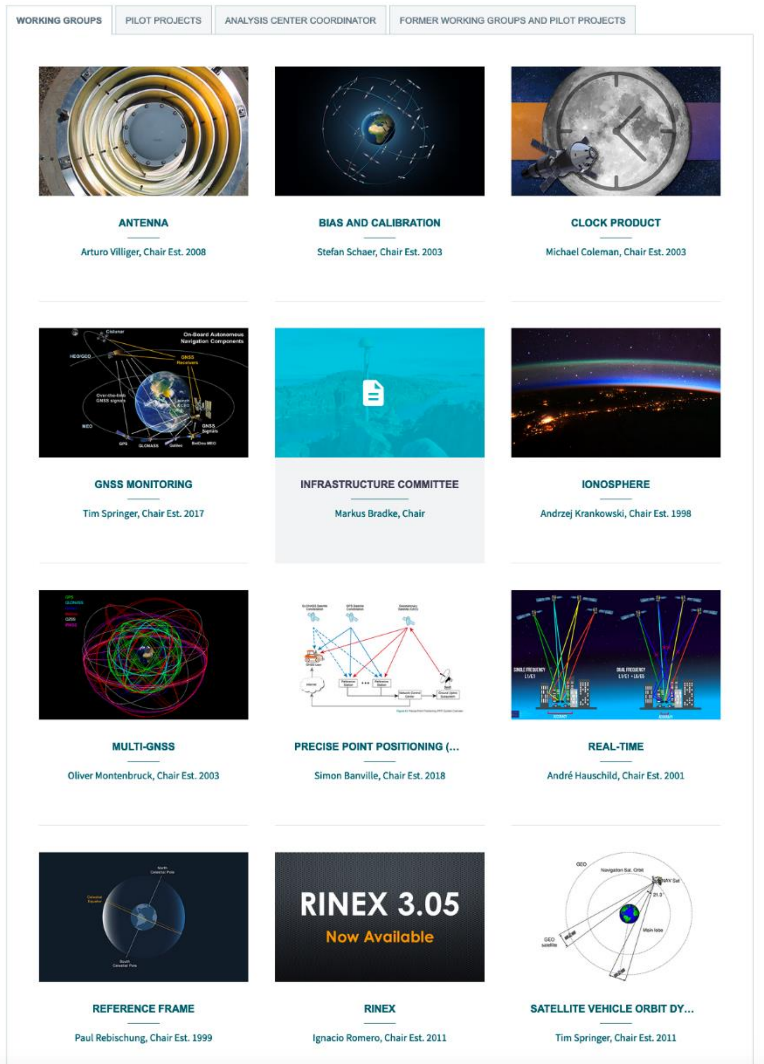


Figure 5 New Working Group Spaces on IGS.org

"The International GNSS Service (IGS) provides the scientific community with a broad range of high-precision products supporting a wide diversity of scientific applications. Currently three fully-deployed GNSS are analyzed by IGS Analysis Centers and included in the currently running reprocessing effort: GPS (USA), GLONASS (Russia), and Galileo (Europe). Developments including additional GNSS (Chinese BeiDou, Japanese QZSS, Indian NavIC, etc.) are ongoing within the IGS.

Several components of the IGS do already support a fully consistent processing of GPS, GLONASS, and Galileo in the operational chain as well as for the currently running reprocessing effort. The continuous improvement of IGS products in this fast-moving field with constantly evolving satellites, systems, signals, models, and data analysis methodology is a scientific challenge".

This session solicited presentations on scientific applications enabled by IGS products and new science enabled by improvements to quality and breadth of GNSS products.

IGS Governing Board Meetings 2019-2021

The GB meets regularly to discuss the activities and plans of the various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. Table 3, summarizes the 2019-2020 GB meetings.

Date	*Place*	*Comments*
December, 2019	San Francisco, CA, USA	Third Associate Member/Open WG Meeting, Prior to the American Geophysical Union Meeting
December, 2019	San Francisco, CA, USA	GB-54: Prior to the American Geophysical Union Meeting
May, 2020	TELECON	GB-55
August, 2020	TELECON	GB-56 (Meeting Focused on Strategic Planning)
December, 2020	TELECON	GB-57a
January, 2021	TELECON	GB-57b (Meeting Focused on Strategic Planning)

Table 3 2019-2020 GB Meetings

IGS 2021 Strategic Planning

Figure 6 Preliminary IGS Strategic Goals

The IGS was originally designed as Geodynamic Service -a mechanism to support people and institutions who needed GNSS at their national level, but required the global network to support their local applications.

Over twenty-five years later, the IGS is looking to redefine its role in an everchanging GNSS community. The most recent Strategic Planning cycle commenced with two in-person IGS Community Strategic Planning Dialogue sessions, held in April 2019. From July through October 2020, the IGS Central Bureau conducted an online community-wide strategic planning survey via igs.org, as part of the activities related to the development of a new decadal Strategic Plan for the organization, which initiation process was approved during the virtual IGS 55th Governing Board Meeting, in May 2020. The current comprehensive road map for the next iteration of the Strategic Planning Process is depicted on Fig. 5 and can be followed online at https://igs.org/strategic-planning . The questions included in the survey were selected under careful scrutiny by the members of the IGS Executive Committee, taking into consideration initial feedback from the community obtained during the first Strategic Planning Associate Member Meeting, which took place in April 2019 during the European Geophysical Meeting in Vienna, Austria.

The strategic planning survey was heavily advertised via social media platforms, web and IGS Mail, was available in two languages (English and Spanish) and consisted of three sections. The first section requested general information about the participant, GNSS applications and demographics. The second section asked the participant to rank the impact and relevance of the IGS role as facilitator, incubator, coordinator and advocate for the GNSS community. The last section allowed the participant to answer open questions in regards of the Strengths, Weaknesses, Opportunities and Threats (SWOT) the IGS is facing as we start the upcoming decade.

Upon analysis of both the 2020 Strategic Planning Survey the following three goals were identified for the 2021 Strategic Plan: 1) Multi-GNSS Technical Excellence, 2) Outreach and Engagement, 3) Sustainability and Resilience. This builds upon the four major community need categories that were outcomes of the 2019 Open Associate Member Strategic Planning Dialogue sessions: facilitation, coordination, incubation, and advocacy. The Strategic Plan is currently under final preparation by the Central Bureau, and will be released for GB consultation mid-2021.

Data Use, Contributions and Sharing (DUCks) Guidelines and Policies

Recently there have been a number of requests asking for clearer, more prescriptive, or otherwise better outlined policy regarding how members of the private sector may engage with, contribute to, and otherwise use/credit IGS data, products, and other resources. The Governing Board acknowledged that the current policy is in dire need of clarification and that there is a need to begin conversations to update such policies. A Task Force was established to lead this effort with new policies established and vetted by the Governing Board and reflected throughout igs.org and other IGS policy prescribing documents.

It was identified that DUCkS Guidelines should include organization of current data use, sharing, and contribution practices into a clear, impartial policy that forms parameters for consistent and transparent guidance to contributors and users. This should form a strong foundation that organizes and facilitates connection to existing specific information and guidance, including official IGS Policies, as well as established parameters and procedures for contributing to IGS components.

Following the GB support for a more comprehensive DUCkS suite of guidelines and policies, the Data and Product Disclaimer and Terms of Use was drafted by the Central Bureau and approved at the August 2020 GB meeting. Additional guidelines to address community needs and gaps in capacity building documentation are in development.

International Country Guidelines

The IGS Governing Board identified a need for a consistent and internationally-vetted and accepted list of country and territory names to be used for identifying IGS Network stations and in other applications. After significant research and discussion with similar international organizations regarding best practices, it was deiced that an internationally-accepted and standardized list would be the most inclusive and useful for IGS operations. In May 2020, the Governing Board decided to adapt use of the *International Organization for Standards (ISO)* standard "ISO 3166: Country Codes" for geographical names. Subsequently, the Central Bureau developed an IGS policy statement for consistent and standardized use of place names based on the *International Organization for Standards (ISO)* standard. More information about this Standard is available on the ISO website: https://www.iso.org/iso-3166-country-codes.html

Communications, Advocacy, and Public Information

The IGS is currently acting on a new communications plan that will be more inclusive to associate members and engaging across working groups. Communications efforts will and introduce a better and more diversified portfolio of outreach resources for the IGS community. This will be achieved by increasing the direct interaction with the community by virtual workshop, enhanced social network interactions, a regular circulation of *Constellations*, the newly introduced IGS newsletter, engaging with and celebrating our diverse community of contributors, enhancing our transdisciplinary collaborations (i.e with new or under-engaged scientific applications communities), and identifying opportunities for IGS engagement and support of the UN GGIM Subcommittee on Geodesy and UN International Committee on GNSS, as well as linkages to the UN Sendai Framework for Disaster Risk Reduction and UN Sustainable Development Goals.

Tour de'lIGS:

Figure 8 Promotion for the upcoming Tour de l'IGS

With the IGS workshop being postponed to 2022, the GB is looking forward to connect with the community in the form of a series of virtual talks or "mini-workshops" throughout 2021. The first is a session fully dedicated to the ITRF2020 and the outcomes of the activities of repro3. This event will take place on 02 June 2021 and it is open to 300 participants.

Highlighted Quarterly Publications:

Journals are a centerpiece of the scientific enterprise and serve as a platform to propel GNSS advancements. A new section of the IGS website is now focused on highlighting IGS-relevant publications for community awareness and access. The community is welcome to provide inputs and share upcoming publications in here: https://www.igs.org/pub-alerts/ .

Social Media and Targeted Campaigns:

Social media has been regularly maintained and continued to grow in followers, due in part by growing and maintaining mutually beneficial links to IGS Contributing Organization communications representatives and increased frequency of posting, as well as enhanced content. Increased cross-linking with IGS website and knowledge base content, as well as promoting video resources available on the IGS website, will continue in 2021. IGS Social Media accounts and follower statistics are as follows:

- Slack (For GB use)
- Twitter (1586 followers): https://twitter.com/igsorg
- Facebook (1743 followers): https://www.facebook.com/internationalGNSSservice
- LinkedIn Page: https://www.linkedin.com/company/igsorg/
- YouTube (150 subscribers, 2000+ views): http://www.youtube.com/igsorg

Numerous news pieces and social media posts covering IGS news, IGS activities, and other announcements were developed in collaboration with Governing Board members and contributing Working Groups. Many of these can be found on the IGS website under: https://www.igs.org/news/ and https://twitter.com/IGSorg/.

Some of the most recent social media campaigns have included:

- International Women Day (and month): https://www.igs.org/news/international-womens-day-womens-history-month/
- Repro3 solutions roll-out: https://www.igs.org/news/repro3-solutions-now-available/
- https://www.igs.org/news/international-day-of-human-space-flight/
- Introducing the New IGS.org: https://www.igs.org/news/introducing-igsorg-20-whats-new/

Engagement and External Participation

The IGS works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office. As representatives of the IAG, IGS members also participate actively in the United Nations Initiative on Global Geospatial Information Management (GGIM) Sub-Committee on Geodesy, Focus Group on Outreach and Communications http://ggim.un.org/UN_GGIM_wg1.html.

On behalf of the Governing Board, the Central Bureau Director ensures appropriate representation of the IGS on the GGOS Consortium and Coordinating Board, as well as working groups and focus areas. Significant progress was also made in supporting the development of a cooperative plan with the United Nations Office for Outer Space Affairs (UNOOSA), International Committee on Global Navigation Satellite Systems (ICG) to monitor performance and interoperability metrics between the different GNSSs, embodied by a joint IGS-ICG working group on monitoring and assessment. IGS continues to co-chair the ICG Working Group on Reference Frames, Timing and Applications jointly with IAG (Z. Altamimi; IGN France) and the International Federation of Surveyors (FIG, represented by S. Choy; RMIT University, Australia), in close collaboration with Bureau International des Poids et Mesures (BIPM, represented by G. Petit; France). The Central Bureau Deputy Director represents the IGS in the new IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC), as both IGS and GGOS representative; the Deputy Director is also the IGS representative to the International Science Council World Data System.

The Director continues to serve as a point of contact between IGS and the US Federal Advisory Board for Space-based Position, Navigation and Timing (PNT). Other IGS representatives presenting at the PNT Advisory Board meetings include IGS Founding Governing Board Chairman Professor Gerhard Beutler (University of Bern, Switzerland). The Central Bureau Deputy Director is a representative of the IGS to the ICG IGMA and Performance Standards Joint Monthly Meetings, along with Governing Board members T. Springer (ESA/ESOC, Germany) and S. Kogure (National Space Policy Secretariat, Cabinet Office, Japan).

Publications

- Craddock, A., Johnston, G., Perosanz, F., Dach, R., Meertens, C., Moore, M., Oyola, M. (2020) *Twenty-Five Years of the International GNSS Service*, [virtual conference] European Geosciences Union Virtual General Assembly, Austria
- Craddock, A., Oyola, M., Khachikyan, R., Santiago, S., Maggert, M., Stowers, S. (2020) *Improvements and Enhancements to the International GNSS Service Central Bureau Information Systems* [virtual conference] American Geophysical Union Fall Meeting, USA

Official IGS Citation

The IGS chapter in the 2017 *Springer Handbook of Global Navigation Satellite Systems* was recently deemed the official citation paper for those acknowledging the IGS in scholarly research and other work:

> Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. In **Teunissen**, Peter J.G., & **Montenbruck**, O. (Eds.), *Springer Handbook of Global Navigation Satellite Systems* (1st ed., pp. 967-982). Cham, Switzerland: Springer International Publishing
> DOI: 10.1007/978-3-319-42928-1

The book is currently available for purchase and download on the Springer website: https://www.springer.com/us/book/9783319429267

© 2017

Springer Handbook of Global Navigation Satellite Systems

Editors: **Teunissen**, Peter J.G., **Montenbruck**, Oliver (Eds.)

A state-of-the-art description of GNSS as a key technology for science and society at large

Outlook 2021 and beyond:

It was expected than in 2020 the IGS workshop participants will travel to Boulder, Colorado for the 2020 IGS Workshop hosted by UNAVCO and UCAR. The IGS is committed to minimizing the impact of COVID-19, therefore decided to postponed its IGS 2020 Workshop: Science from Earth to Space, to the first quarter of 2021, for which a virtual format was contemplated. However, after careful consideration, the Local Organizing Committee and the IGS decided to postpone it to an in-person workshop in 2022 in order to preserve the collaborative nature of the workshop. The location remains at Boulder, Colorado, USA.

Moving Forward

Following the results from the Strategic Planning survey, the IGS is focused in better serving the community as a platform for facilitation, coordination, incubation and advocacy. Looking forward, the the IGS will focus on supporting three major strategic goals identified in the 2021 Strategic Plan: achieve true multi-GNSS technical excellence, improve our outreach and engagement and improving our sustainability and resilience. The IGS 2021 *information systems* administrative goals are focused in providing support for dissemination of the results of the repro3 campaign and its contributions toward the ITRF2020. The IGS is also looking forward to upgrade the Site Log Manager to a more modern and accessible language, as well as continue upgrades on the IGS.org website that include a better Associate Member database.

The IGS will continue to be challenged by the growing stakeholder expectations for improved product timeliness, fidelity and diversity. As these are achieved reconsideration of the IGS mission and goals will need to be undertaken to ensure we don't become tangential to the needs of our key stakeholders, the associate members. Continued efforts to enhance advocacy for the IGS are needed, with the Governing Board and the Central Bureau playing key roles in this, but not at the exclusion of all associate members. Accordingly, presentations at a variety of forums within our discipline and outside of it will need to be given, ensuring that the efforts of all contributors are acknowledged. In this way the IGS will continue to build its user base resulting in enhanced sustainability.

Lastly, the Governing Board thanks all participants within the IGS for the efforts, with particular thanks going to those working group chairs ending their current terms. Without the contributions of all, the IGS could not have achieved the significant outcomes detailed in this report.

We would also like to express our thanks to everyone in the IGS Community for their patience and support during the COVID-19 pandemic. Special thanks to Ashley Santiago (IGS Central Bureau) for support in the graphical work for this report.

International Laser Ranging Service (ILRS)

https://ilrs.gsfc.nasa.gov

E. C. Pavlis[1], M. R. Pearlman[2], Claudia C. Carabajal[3], R. Ricklefs[4], C. Schwatke[5], M. Wilkinson[6], G. Kirchner[7], V. Luceri[8], T. Otsubo[9], J-M Torre[10], U. Schreiber[11]

[1] *Joint Center for Earth Systems Technology, UMBC and NASA GSFC, Baltimore, MD 21250, USA*
[2] *Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA 02138, USA*
[3] *SSAI, Inc. @ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[4] *Center for Space Research, The University of Texas at Austin, Austin, TX 78712, USA*
[5] *Technische Universität München, D-80333 München, Germany*
[6] *Natural Environment Research Council (NERC), Space Geodesy Facility (NSGF) Hailsham, East Sussex BN27 1RN, UK*
[7] *Austrian Academy of Sciences, Space Research Institute, A-8042 Graz, Austria*
[8] *Matera Space Center, 75100 Matera, Italy*
[9] *Hitotsubashi University, Tokyo, 186-8601 Japan.*
[10] *Observatoire de la Côte d'Azur, Nice, 06300 France*
[11] *Technische Universität München, D-93444 Bad Koetzting, Germany*

Overview

The ILRS is the international source that provides Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data and data products for scientific and engineering programs with the main focus on Earth and Lunar applications. The basic observables are the precise two-way time-of-flight of ultra-short laser pulses from ground stations to retroreflector arrays on satellites and the Moon and the one-way time-of-flight measurements to space-borne receivers (transponders). These data sets are made available to the community through the CDDIS and the EDC archives, and are also used by the ILRS to generate fundamental data products, including: accurate satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth’s gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters. SLR is one of the four space geodetic techniques (along with VLBI, GNSS, and DORIS) whose observations are the basis for the development of the International Terrestrial Reference Frame (ITRF), which is maintained by the IERS. SLR defines the origin of the reference frame, the Earth center-of-mass and, along with VLBI, its scale. The ILRS generates daily a standard product of station positions and Earth orientation based on the analysis of the data collected over the previous seven days, for submission to the IERS, and produces LAGEOS/Etalon combination solutions for maintenance and improvement of the International Terrestrial Reference Frame. The latest requirement is to improve the reference frame to an accuracy of 1 mm accuracy and 0.1 mm/year stability, a factor of $3-5$ improvement over the current product. To address this requirement, the SLR community is working to improve the quantity and quality of ranging to the geodetic constellation (LAGEOS-1 and -2, Etalon-1 and -2, and LARES) to support the definition of the reference frame, and to the GNSS constellations to support the global distribution of the reference frame.

The ILRS participates in the Global Geodetic Observing System (GGOS) organized under the IAG to integrate and help coordinate the Service activities and plans.

ILRS Structure

The ILRS Organization (see Figure 1) includes the following permanent components:

- Network of tracking stations
- Operations Centers
- Global Data Centers
- Analysis and Associate Analysis Centers
- Central Bureau
- Governing Board
- Standing Committees (SCs)
    - Analysis
    - Data Formats and Procedures
    - Missions
    - Networks and Engineering
    - Transponders
- Study Groups (SGs) and Boards
    - Laser Ranging to GNSS s/c Experiment (LARGE)
    - Quality Control Board
    - Software Study Group
    - Space Debris Study Group

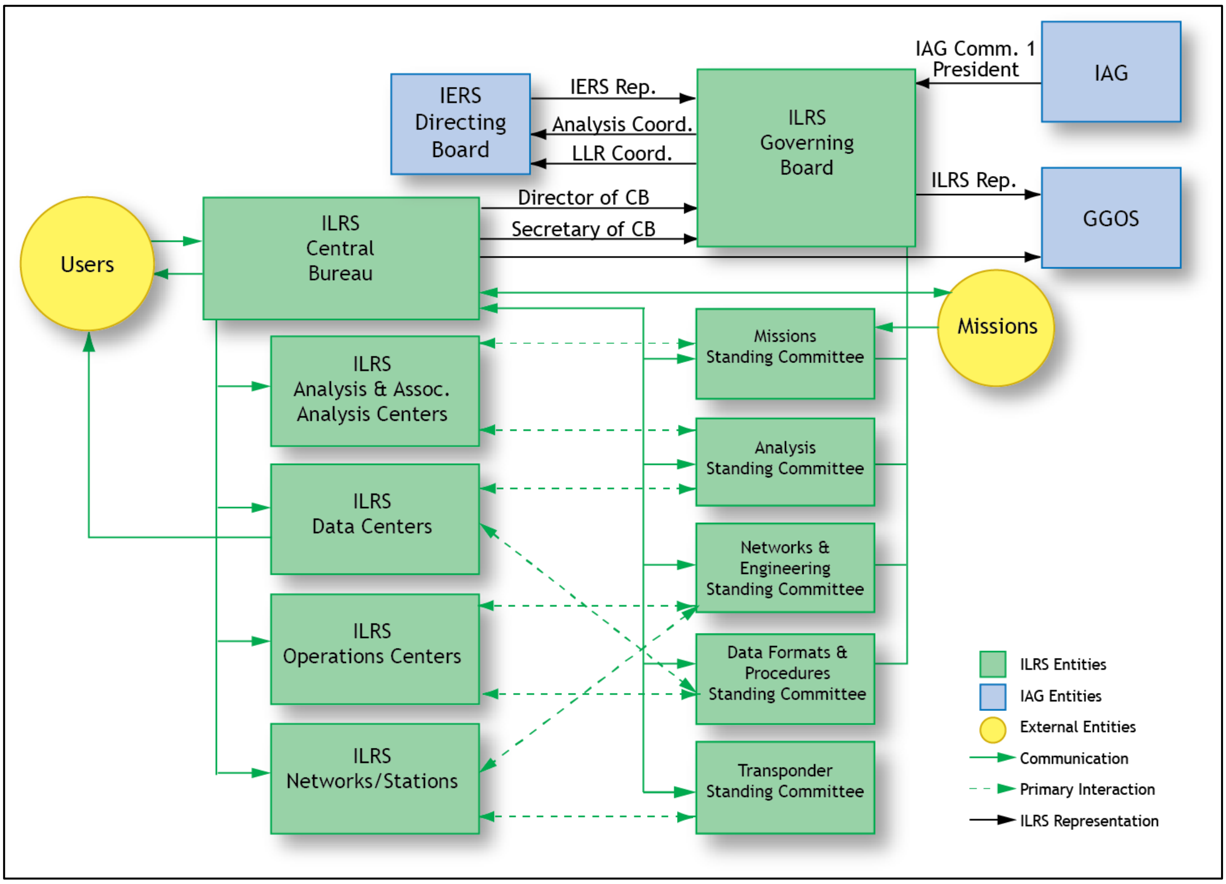


Figure 1. The organization of the International Laser Ranging Service (ILRS).

The role of these components and their inter-relationship is presented on the ILRS website (*https://ilrs.gsfc.nasa.gov/about/organization/index.html*).

The Governing Board (GB) is responsible for the general direction of the service. It defines official ILRS policy and products, determines satellite-tracking priorities, develops standards and procedures, and interacts with other services and organizations. The members of the current Governing Board, selected and elected for a two-year term, are listed in Table 1.

The Central Bureau (CB) is responsible for the daily coordination and management of the ILRS in a manner consistent with the directives and policies established by the Governing Board. The primary functions of the CB are to facilitate communications and information transfer within the ILRS and between the ILRS and the external scientific community, coordinate ILRS activities, maintain a list of satellites approved for tracking support and their priorities, promote compliance to ILRS network standards, monitor network operations and quality assurance of data, maintain ILRS documentation and databases, produce reports as required, and organize meetings and workshops. The CB operates the communication center for the ILRS. The CB performs a long-term coordination and communication role to ensure that ILRS participants contribute to the Service in a consistent and continuous manner and that they adhere to ILRS standards.

Permanent Standing Committees (SCs) and temporary Study Groups (SGs) provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the five SCs, led by a Chair and Co-Chair (see Table 1). The SCs continue to attract talented people from the general ILRS membership who contributed greatly to the success of these efforts.

Table 1. ILRS Governing Board (as of May 2021)

Name	Position	Country
Sven Bauer	Appointed,Eurolas Network	Germany
James Bennett	Appointed, WPLTN Network	Australia
Claudia Carabajal	Ex-Officio, Secretary, ILRS Central Bureau	USA
Evan Hoffman	Appointed, NASA Network	USA
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Italy
Stephen Merkowitz	Appointed, NASA Network	USA
Toshimichi Otsubo	Elected, At-Large, Governing Board Chair (2019-2020)	Japan
Erricos Pavlis	Elected, Analysis Representative, Analysis Standing Committee Chair	USA
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Jose Rodrigues	Appointed,Eurolas Network	Spain
Ulrich Schreiber	Appointed, At-Large, Transponder Standing Committee Chair	Germany
Christian Schwatke	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Krzysztof Sośnica	Appointed, At-Large	Poland
Daniela Thaller	Appointed, IERS Representative to ILRS	Germany
Jean-Marie Torre	Elected, Lunar Representative	France
Matt Wilkinson	Elected, At-Large, Networks and Engineering Standing Committee Chair	UK
Zhang Zhongping	Appointed, WPLTN Network	China
Former Governing Board Members during 2019-2021		
Giuseppe Bianco	Appointed, EUROLAS Network, Governing Board Chair (2015-2018)	Italy
Wu Bin	Appointed, WPLTN	China
Geoff Blewitt	Ex-Officio, Representative of IAG Commission 1	USA
Ludwig Combrinck	Elected, Lunar Representative	South Africa
Georg Kirchner	Appointed, EUROLAS Network	Austria
Rivers Lamb	Ex-Officio, Secretary, ILRS Central Bureau	USA
David McCormick	Appointed, NASA Network	USA
Jan McGarry	Appointed, NASA Network	USA
Jürgen Müller	Elected, Lunar Representative	Germany
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Andrey Sokolov	Appointed, At-Large	Russia

Data Products

The main ILRS analysis products consist of SINEX files of weekly-averaged station coordinates and daily Earth Orientation Parameters (x-pole, y-pole and excess length-of-day—LOD) estimated from 7-day arcs of SLR tracking of the two LAGEOS and two Etalon satellites. As of May 1, 2012, the official ILRS Analysis product is delivered on a DAILY basis by sliding the 7-day period covered by the arc by one day forward every day. This allows the ILRS to respond to two main users of its products: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single analysis per week, spanning the period Sunday to Saturday; the latter however requires as "fresh" EOP estimates as possible, that the "sliding" daily analysis readily provides. Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous one and constrained to an ITRF, which beginning on June 1, 2017, is ITRF2014. Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate these products of individual and combined solutions respectively. Both the individual and combined solutions follow strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide high quality products consistent with the IERS Conventions. This description refers to the status as of May 2021. Each official ILRS solution is obtained through the combination of seven solutions submitted by the seven official ILRS Analysis Centers:

ASI, Agenzia Spaziale Italiana
BKG, Bundesamt für Kartographie und Geodäsie
DGFI, Deutsches Geodätisches ForschungsInstitut
ESA, European Space Agency
GFZ, GeoForschungsZentrum Potsdam
JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
NSGF, NERC Space Geodesy Facility

Since 2016, the ILRS publishes online an additional operational product on a weekly basis: precision orbits in standard SP3c formatted files for the four satellite targets (LAGEOS-1, -2, and Etalon-1, -2). These orbits are strictly referenced to the ITRF2014 model.

Following the adoption of ITRF2014, the ASC issued an extended version of the reference frame, the SLRF2014, which includes some two-dozen additional SLR sites that were not part of ITRF2014 model. A number of these are historical sites from the early years of SLR, prior to ILRS, and the rest are new stations that were established either during the development of ITRF2014 or after its release; in either case these sites did not have enough data to support their inclusion in the new ITRF. The ILRS products are available, via ftp from the official ILRS Data Centers CDDIS/NASA Goddard Space Flight Center and EDC/TUM/DGFI:

http://cddis.nasa.gov/slr/products/pos+eop and
http://edc.dgfi.tum.de/pub/slr/products/pos+eop

The individual ILRS AC and CC product contributions as well as the combinations are monitored on a daily basis in graphical and statistical presentation of these time series through a dedicated portal hosted by the JCET AC/CC at:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

The efforts to identify, quantify and contain systematic errors in the SLR data have continued this period with many new initiatives that ILRS sees necessary in order to improve data quality. The main focus of the Analysis SC activities over the past five years was the estimation and monitoring of systematic errors in the SLR NP data and the generation of a model that would be applied a priori during the re-analysis for the development of the ITRF2020 ILRS contribution, (Luceri et al., 2019). All ACs made major efforts to comply with the newly adopted analysis standards and the IERS Conventions 2010 plus their recent modifications, e.g. the adoption of the new secular pole in 2019 (Pavlis, E. C., 2019a), the consistent modeling of low degree time-varying gravitation (Pavlis, E. C., 2019b), etc.. The preliminary version of the ILRS contribution to ITRF2020 (Pavlis et al., 2020), was delivered in mid-April 2021 and presented at the EGU 2021, (Luceri et al., 2021). Following that, the ASC focused on completing the final series with the inclusion of the historical LAGEOS data (1983.0 – 1993.0) and the correction of any entries that were found problematic in the preliminary combination.

It is anticipated that a follow up release will include LARES as an additional accurate target in developing the official products, which the ITRS will evaluate this time and will be hopefully included in the next ITRF model.

The ILRS "Quality Control Board", with members from all areas of expertise within the service, has continued it efforts to identify, quantify and correct any errors in the already collected SLR. Furthermore, it strives to generate tools and procedures that will help the station engineers identify with confidence and as quickly as possible, issues with their data, before they get too far down the production line. A manual on "best practices" for SLR data collection is now in preparation, as an aid to station personnel.

The LLR group is in the process of developing a unique data set of all available LLR data in the officially adopted CRD format, in order to better serve the community and to conform with the ILRS standards. The LLR community is now supported by their newly established Associate.

Satellite Laser Ranging

ILRS Network

The present ILRS network includes over forty stations in 24 countries (see Figure 2); some of these stations are undergoing refurbishment and upgrade. During the last five years, new stations joined the ILRS network in Badary, Baikonur, Irkutsk, Svetloe, Zelenchukskaya, (Russia), Sejong and Geochang (Korea), and Brasilia (Brazil) filling-in very important geographic gaps. The Russians have advanced the idea of co-locating two SLR stations at critical locations to help address the tracking load. A second new technology SLR station is in testing at Mendeleevo and Irkutsk and a Russian SLR They have co-located a second station at Mendeleevo and a Russian SLR station has been co-located with the NASA MOBLAS-6 at Hartebeesthoek (South Africa). The Russians are also planning installations of new SLR systems in Ensenada (Mexico), Java (Indonesia), and Grand Canary Island in the next 3 -5 years, and have offered to co-locate new systems at stations currently operated by other organizations. New systems and system upgrades have been delayed due to the Pandemic, budgetary constraints, and in some cases protracted importation restrictions. The core Argentine-German Geodetic Observatory (AGGO), formally TIGO in Concepción, Chile, has been relocated to La Plata (Argentina) and is being upgraded; operations are now expected to resume in late 2021. Work continues on the new station in Metsahövi (Finland) and the upgrade of the Chinese SLR station in San Juan (Argentina); both now planned for operations in late 2021. Two new stations, are underway at Ponmundi and Mt. Abu (India) and the new SLR station in Yebes (Spain) is now underway. The NASA Space Geodesy Project (SGP) is building new SGSLR stations (as part of Core sites) at McDonald TX, GSFC, and Ny Ålesund (Norway) in cooperation with the Norwegian Mapping Agency (NMA).. Operations are now projected for the 2024 timeframe. Planning is underway for additional SLR systems as part of core sites at other current NASA partner locations and new locations to help fill some of the current geographic gaps in the global space geodesy network.

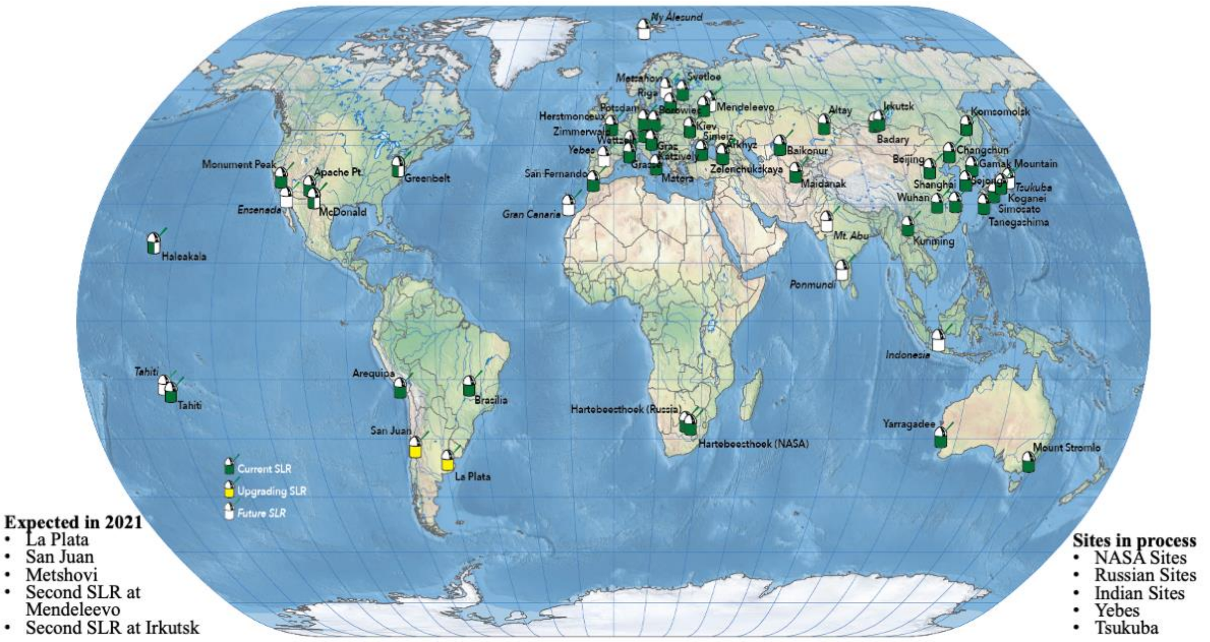


Figure 2. ILRS network (as of December 2020).

Large gaps are still very prominent in Africa and South America and discussions are underway with several groups in the hope of addressing this shortcoming.

Stations designated as operational have met the minimum ILRS qualification for data quantity and quality. In 2015, the ILRS Governing Board approved a new ILRS Pass Performance Standard of 3500 passes per year as an interim step toward a more comprehensive long-term strategy:

- 2 passes per week on each LEO satellite (2300 LEO passes per year)
- 4 passes per week on LAGEOS and LARES satellites (600 MEO passes per year)
- 2 passes per week on each HEO satellite (>3000 HEO passes per year)

In spite of the fact that SLR operations suffered due to the Pandemic in 2020, some stations continued to operate well; recent strong performers are shown in Figure 3. During 2020, seventeen stations met the updated ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

As shown in Table 2, many stations are now operating at 100 to kilohertz rates, thereby increasing data yield and allowing them to be more productive with pass interleaving, a critical step as the number of satellites being tracked with SLR has increased dramatically. Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

Table 2. High-Repetition Rate ILRS Stations (as of May 2021)

CDP ID#	Location	Laser Repetition Rate [Hz]
7816	Uhlandshoehe Research Observatory (UFO)	1000000
7359	Daedeok	5000
7394	Sejong	5000
7249	Beijing SLR Station	2000
7840	Herstmonceux	2000
7841	SLR Potsdam 3	2000
7865	NRL OPTICAL TEST FACILITY	2000
7249	Beijing SLR Station	1000
7396	JiuFeng	1000
7819	Kunming	1000
7821	Shanghai	1000
7827	Wettzell	1000
7838	Simosato	1,000
7840	Herstmonceux	1000
8834	Wettzell	400
1868	Komsomolsk-na-Amure	300
1874	Mendeleevo	300
1879	ALTAY	300
1886	Arkhyz	300
1887	Baikonur	300
1888	Svetloe	300
1889	Zelenchukskaya	300
1890	Badary	300
1891	Irkutsk	300
7407	Brasilia	300
7503	Hartebeesthoek Radio Astronomy Obs.	300
7810	Zimmerwald SLR	110

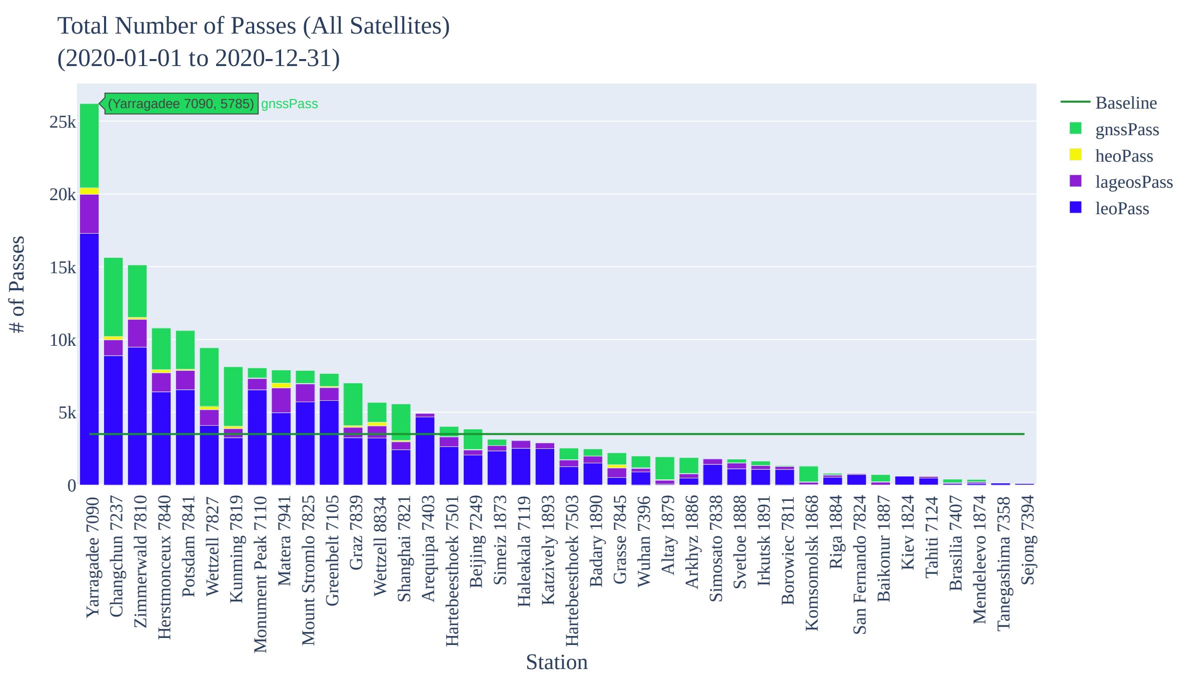


Figure 3. ILRS network performance (Total Number of Passes, all Satellites), January 1st, 2020 to December 31st. 2020.

Satellite Missions

The ILRS is currently tracking approximately 120 artificial satellites, including passive geodetic (geodynamic) satellites, Earth remote sensing satellites (e.g., altimetry, gravity field), navigation satellites (GNSS), and engineering missions (see Figure 4). Due to system limitations, some of the legacy stations are not able to track GNSS and other high satellites. The large list of satellites is saturating some stations that are not fully manned and strategies are being tried to maximize station data value. Some stations have implemented automated procedures to expand operating hours. The stations with lunar capability are also tracking the lunar reflectors. In response to this large roster of satellites, as well as for support of tandem missions (e.g., GRACE-A/-B, TanDEM-X/TerraSAR-X) and general overlapping schedules, most stations in the ILRS network are tracking satellites with interleaving procedures.

The ILRS assigns satellite priorities in an attempt to maximize data yield on the full satellite complex, while at the same time placing greatest emphasis on the most immediate data needs. Priorities provide guidelines for the network stations, but stations may deviate from these priorities to accommodate local conditions, support regional activities or national initiatives, and expand tracking coverage in regions with multiple stations. General tracking priorities are approved by the Governing Board, based on application to the Central Bureau and recommendation of the Missions Standing Committee (see

https://ilrs.gsfc.nasa.gov/missions/mission_operations/priorities/index.html).

Missions are added to the ILRS tracking roster as new satellites are launched and as new requirements are adopted; missions for completed programs are removed (see Figure 4). The ILRS provides restricted tracking procedures for satellites with time-varying array visibilities and optically vulnerable payloads (e.g. Sentinel satellites and ICESat-2), to limit ranging to authorized time periods. Some stations in the ILRS network track selected space debris objects to provide ephemerides and orientation data to help with trajectory/safety planning.

The tracking approval process begins with the submission of a Missions Support Request Form, which is accessible through the ILRS website:

(https://ilrs.cddis.eosdis.nasa.gov/docs/2016/ilrsmsr_1604.pdf).

The submitted form provides the ILRS with information to assess the appropriateness for ILRS support (does it fit into the ILRS/GGOS objectives) and the likelihood of tracking success, including any special procedures that the mission may require.

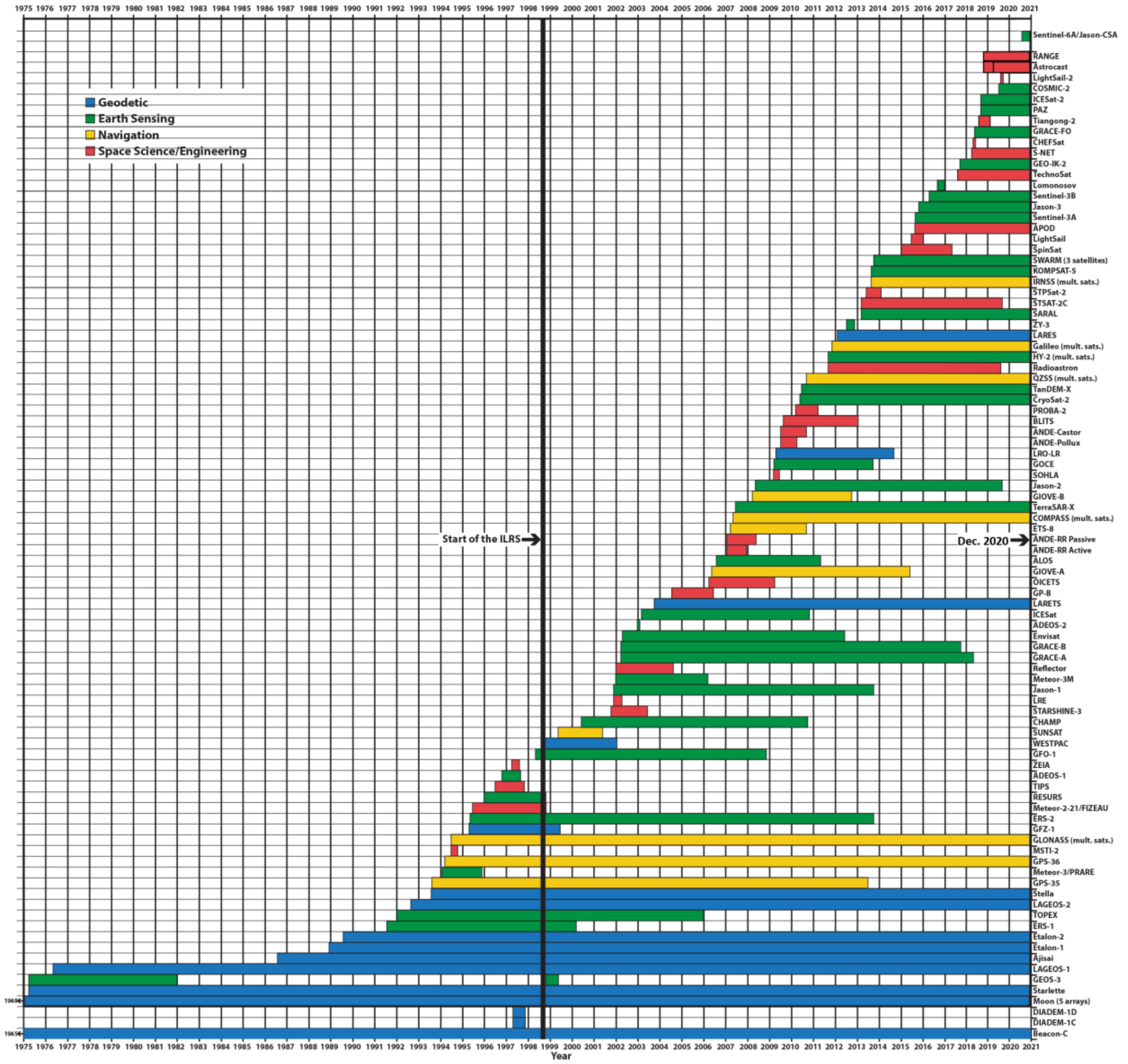


Figure 4. The past, current, and future ILRS satellite tracking list (as of December 2020).

Upcoming space missions that have requested ILRS tracking support is summarized in Table 3, along with their sponsors, intended application, and projected launch dates.

Table 3. Recently Launched and Upcoming Missions (as of May 2021)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Astrocast	ETH Zurich and Astrocast SA	Positioning information, precise orbit determination	1-Apr-19
Compass/BeiDou 3 IGSO, 3 GEO, 6 MEO (12 new, 42 total satellites)	Chinese Defense Ministry	Positioning, navigation, timing	2007- present
COSMIC-2	NSPO/NOAA/USAF	Meteorology, ionosphere, climatology, space weather	25-Jun-19
ELSA-d	Astroscale Pte Ltd (with HQs in Singapore) and SSTL (Surrey Satellite Technology Ltd. of Surrey, UK)	Orbital debris removal	22-Mar-21
Galileo. (Completed, 24 operational satellites)	ESA	Positioning, navigation, timing	2011- present
GLONASS 758, 759, 760 & 705 (4 new, 24 total satellites)	Russian Federation Ministry of Defense	Positioning, navigation, timing	1989-present
QZS (4 total satellites)	Cabinet Office, Government of Japan	Positioning, navigation	2005-present
H-2C, HY-2D	CNES, CNSA	Marine observation	9/21/2020, 5/19/2021
Sentinel-6A/Jason-CS-A	EUMETSAT/EC/ESA/NOAA/NASA	Oceanography	20-Nov
Approved by ILRS for Future SLR Tracking			
LARES-2	ASI, ESA	Relativity, geodesy	Late 2021
NISAR	NASA	Earth sensing	2022
SWOT	NASA, CNES	SAR altimeter	Late 2022
Future Satellites with Retroreflectors			
GPS-III 09	U.S. DoD, DoT	Positioning, navigation, timing	mid-2020s

New ILRS Tracking Strategy for GNSS

Since mid-2019, at the request of the IGS and supported by the ICG, the tracking strategy of the GNSS satellite have been changed. Each GNSS constellation is allowed to choose four of its satellites for the priority list; otherwise stations are requested to track ALL of the remaining GNSS satellites on an as time available basis; selection of targets should be determined by the stations for data yield, but stations are asked to try to diversify among all three constellations.

In addition, some users will request focused campaigns for eclipse studies to better model the effects of solar radiation pressure.

In the next several years, the GPS satellite constellation will commence launch, slated to eventually bring the GNSS population with retroreflectors to about 100 satellites.

Laser Ranging for High Accuracy Timing

Laser ranging has demonstrated significant capability for Precision Time Transfer with satellites. ILRS tracked the Jason-2 satellite, using the Time Transfer by Laser Link (T2L2) experiment to synchronize the clocks at ILRS stations, as well as to characterize the performance of the DORIS Ultra Stable Oscillator (USO) onboard the Jason-2 spacecraft. The data from T2L2, as well as other information, have been used to derive a detailed model of the DORIS USO behavior, including direct modeling of radiation effects, passage through the South Atlantic Anomaly (SAA) and natural aging of the oscillator. Applying this USO model it was possible to synchronize the clocks used in the Laser Ranging station to the same international time scale (UTC) at around 5 ns accuracy. The analysis of the T2L2 data has revealed that many stations exhibit time biases w.r.t. to UTC, sometimes as high as a few microseconds, well beyond the 200 ns limit requested by the ILRS, and yet still at a level that is hard to resolve from the orbit determination analysis. The past data from T2L2 and data from future similar systems will allow us to characterize station timing behavior and examine its impact on the reference frame and ILRS products. The T2L2 project team led by Dr. Pierre Exertier (Grasse SLR observatory) have provided timing bias estimates for SLR data to the ILRS analysis centers, based on analysis of data from T2L2 over the period 2008-2018.

The proper handling of local time is the key for the identification of station biases, which show up as additional, often variable measurement delays in the ranging process. Since time relates the measurement epoch to the phase angle of the clock frequency, any slip in the phase angle corresponds to a slip in the measured time interval during the ranging process, thus adding an unwanted bias to the measurement itself. Causes for such slips are manifold, like temperature changes in electronic amplifiers, timers and most importantly trigger circuits and impedance mismatches. In order to mitigate these effects, the phase of the clock signal has to be controlled in the ranging hardware over the entire ranging process in a two-way closed loop delay compensation process, which is currently pioneered by the Geodetic Observatory Wettzell. It is important to note that this process does not depend on accurate time itself, it is only concerned with the avoidance of additional biases in the handling of time intervals in the ranging process.

A precise clock in space provides a worldwide access to high performance ground clocks. Here SLR plays an important role, by providing accurate range and time between clearly defined reference points on ground and in space. This represents a two-way measurement technique, the main ingredient of the “Einstein Synchronization” process, the only technique that can compare and synchronize remote clocks with high accuracy. The European Space Agency (ESA) is developing the Atomic Clock Ensemble (ACES) (see https://earth.esa.int/web/eoportal/satellite-missions/i/iss-aces) experiment for flight on the International Space Station (ISS). The ELT (European Laser Timing) follows in the path of T2L2. The goal is to demonstrate an accuracy of time transfer at the level of 50 ps, with a perspective of 25 ps. The ELT payload consists of a corner cube retroreflector a SPAD detector, and an event timer. ELT will provide an alternative to time transfer via microwave link (MWL) and will provide superior accuracy.

The potential of SLR to transfer time with unprecedented accuracy over intercontinental distances and thus to tie a globally uniform timescale to the geodetic reference frames may one day together with the availability of accurate optical clocks create a uniform accurate observing system, which integrates the three pillars of geodesy, namely geometry, gravity and Earth rotation into one unified foundation, tied together by time.

Lunar Laser Ranging (LLR)

The LLR results are considered among the most important science return of the Apollo era; it certainly is the only active experiment still supporting science. There are currently four active ILRS observatories, which are technically in the position to track the lunar retro-reflector. These stations are APOLLO (USA), Grasse (France), Matera (Italy) and Wettzell (Germany). For several years, Grasse and Wettzell range in infrared (1064 nm), while Matera and APOLLO range in green (532 nm). New stations are under development in China (Kunming, and Shanghai) and in Russia (Altay Optical-Laser). Technical improvements have been made at Matera and Wettzell, with noted improved performance.

Lunar Analysis Centers

The LLR data analysis is performed by a few major LLR analysis centers, namely the Jet Propulsion Laboratory (JPL), Pasadena, USA, the Center for Astrophysics (CfA), Cambridge, USA, the Paris Observatory Lunar Analysis Center (POLAC), Paris, France, the Institute of Geodesy (IfE), University of Hannover, Germany and the Institute of Applied Astronomy Russian Academy of Sciences (IAARAS), Saint Petersburg, Russia. In the last few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. The six LLR analysis centers focus on different research topics (such as relativity, lunar interior, etc.). Various research projects have been successfully pursued, combining LLR, GRAIL and LRO data.

Since January, Dmitry Pavlov no longer works for IAA. He continues to communicate with his ex-colleagues and participate in ephemeris-related scientific activities, including lunar ephemeris, too. He also prepared the IAA RAS' LLR report for IRLS this year and he is willing to participate in preparing the lunar solution for the next version of our EPM ephemeris. He plans to resume his lunar tides/liquid core research in early 2021.

Lunar Laser Ranging Network:

- APOLLO, (USA): NASA took over responsibility for APOLLO station an added it to the NASA Space Geodesy Network.
- Grasse, (France): Waterproofing of the dome and calibration of the meteorological station.
- Matera, (Italy): They analyzed the problem of Luna17, which has never been observed by MLRO. The problem was related to the original MLRO software. For 2021, they expect a ≈70% increase in the number of returns. An optimization of the FOV is programmed.
- Wettzell, (Germany): no LLR observations after July, 2020, because the system is under refurbishment. Coming back online shortly.
- Kunming, (PR China): They purchased a 100 Hz frequency laser, 1064 nm wavelength and less than 100 ps pulsewidth this year. It will be sent to their station next year. They also purchased a SNSPD that is already at their station this year. They hope their system can provide better precision data next year.
- Shanghai, (PR China): They plan to use a 60 cm aperture for emission and 1.56 m telescope for reception.
- Altay Optical-Laser, (Russia): The completion date of the telescope has been postponed to the end of 2022. Work on the LLR is currently suspended due to the unavailability of the telescope. The completion date of the LLR is still expected after 2022.

LLR Science

Following the first series of successful two-way ranging on LRO (Mazarico et al., 2020), a new campaign is underway. This experiment provides a new method of verifying theories of dust accumulation over decades on the lunar retro-reflectors.

The LLR community is growing with new stations and new analysis centers. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface. LLR again has shown is strong capability to put Einstein's relativity theory to test and to improve the limits for a number of relativistic parameters. Also, lunar science and many quantities of the Earth-Moon dynamics could widely be studied. As the next step, a new structure in ILRS (e.g., a working group or standing committee) shall be created to link all LLR contributors, from observatories to science.

For 2020, the number of normal points decreased by a factor 2 compared to 2019. This is due to the COVID-19 restrictions, and the lack of information from APOLLO station.

New reflectors:

In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the lunar surface.

First Lunar Laser Ranging Meeting:

We had planned and organized a novel type of community meeting in order to reorganize the LLR activities more coherently and close the loop between the observation and the analysis side. An LLR-in-person meeting is in preparation and awaits the easing off from Covid-19 restrictions.

Website of the meeting: *https://llr2020.sciencesconf.org/*

Recent ILRS Activities

General

The ILRS Governing Board approved an update to the ILRS Terms of Reference (ToR) (*https://ilrs.gsfc.nasa.gov/about/termsofref.html*) in mid-2016; the IAG accepted the revision and the new Terms of Reference (ToR) was adopted in November 2016. The most significant change to the ILRS ToR was the addition of two At-Large members to the ILRS GB are chosen by the GB to additional technical expertise and geographic coverage the Board. Other changes addressed the addition of new SCs and clarifying terminology.

Standing Committees and Study Group Activities

All ILRS standing committees held meetings during ILRS workshops during this reporting period.

Analysis Standing Committee (ASC)

In addition to the production of the official ILRS ASC products, the ASC focused mainly on the timely completion of the Station Systematic Error Monitoring—SSEM Pilot Project (PP) during the reporting period. This PP was conceived and agreed at the 2015 ILRS Tech. Workshop in Matera, Italy, and the idea was to develop a robust and efficient analysis procedure that will monitor the long-term performance of systematic errors at the ILRS stations. These biases were adopted “a priori”, to be pre-applied in the reanalysis for the ITRF2020. The procedure will be eventually implemented as the standard in our operational series and the ASC will develop guidelines for identifying likely errors and notifying the affected stations. This step was completed by the end of 2020 and the results were captured in a new version of the “Data Handling File—DHF” which was delivered to the ACs to use in their ITRF2020 reanalysis. Another PP in progress is the introduction of LARES as the fifth target to be used for the development of the official ILRS products and at the same time, the delivery of weekly averaged low-degree spherical harmonic coefficients of the gravitational field model. This PP is expected to be completed by the end of 2021.

Based on simulation studies that indicated the role that increased Etalon 1 & 2 data could play in the enhancement of ILRS EOP products (Andritsch, 2020), the ASC called for an intensive tracking campaign that was held from February 15 to May 15, 2019. The amount of range data (NPs) that was collected nearly doubled from that over the same period a year ago. The ASC evaluated the benefit from these additional data on the EOP products and recommended that the network make every effort to increase the Etalon 1 & 2 data yield. As a result, we now collect on a regular basis ~35 passes on each of the Etalon targets per week, up from ~20 in the past years.

The co-chairs of the ASC were two of the guest-editors for the special issue (SI) of the Journal of Geodesy dedicated on Laser Ranging. The SI was completed and published online in November 2019 (Pavlis et al., 2019) with 20 contributions.

Data Formats and Procedures Standing Committee (DFPSC)

The DFPSC, especially the "Data Format Update" study group, released the latest version 2.0 of the ILRS standard CRD (data) and CPF (prediction) formats in September 2019. Since then, predictions providers, stations and analysis started implementing the new format in their software. All prediction providers have completed their transition to the new format and are submitting CPFs of version 1.0 and 2.0 to the DCs. Additionally, nine SLR stations are also ready and submit their CRD data in version 1.0 and 2.0 to the DCs. It is planned to finish the transition to the new formats by the end of 2021.

The ILRS operates two global data and operation centers. In order to achieve homogeneous data centers, the applied quality checks by the OCs have to be identical. The harmonization of quality checks has been completed.

A new open source normal point software has been developed by the Herstmonceux station. It was extensively tested and appears to produce normal points as good or better than official station normal points. The new software will be made available on the ILRS website.

Missions Standing Committee (MSC)

The Missions Standing Committee (MSC) has reviewed mission support requests from BLITS-M. LARES-2. Sentinel-6A/Jason-CSA. HY-2C. NXD-1-SLAG. and ELSA-d. All six requests were approved by the GB. The committee reviewed ILRS policy towards supporting commercial and non-science missions like ELSA-d and found no need to update the policy at this time. The committee also agreed to periodically follow-up with missions to update their tracking needs and assess the value of continued ILRS support.

Networks and Engineering Standing Committee (NESC)

The NESC exists in the ILRS to draw on the experience, knowledge and creativity in the global SLR network in order to advance the technique and boost the performance of every station. It aims to strengthen the network links to promote collaboration, information sharing and best practice. It also provides a practical source of advice to other areas of the ILRS.

In place of its regular meetings at ILRS Workshops the NESC is now meeting every two months online using Microsoft Teams. While this isn't a perfect substitute for in person meetings it does have the advantages of being low-cost, more accessible and more varied in subject matter.

To run alongside these meetings, an online forum exists for the NESC, and for the wider ILRS community, (*http://sgf.rgo.ac.uk/forumNESC*) to encourage knowledge sharing, collaboration and community support.

Transponders Standing Committee (TSC)

Optical time transfer remains to be the main objective of the TSC. In the past few years two-way ranging was successfully demonstrated to the LRO spacecraft orbiting the moon. In a major campaign effort the successful asynchronous transponder ranging between ground stations in Australia, Japan and Europe and the Hayabusa 2 spacecraft at a distance of about 10 mio. km has been achieved. The launch of the ACES clocks to the ISS is still awaited. Issues with the major during flight tests, have deferred the launch further. Within the TSC we have explored methods of accurate optical time transfer from ground to ground via a diffuse passive (zero-delay) reflector in space. In this operation one station is transmitting, while more than one station is detecting and timing the the transferred laser pulses. A elaborate tumbling motion model links the cooperating observing stations together. This concept works surprisingly well. For the near future it is intended to extend this concept for reciprocal laser transmission.

Quality Control Board (QCB)

The ILRS Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR system biases and other data issues that have degraded the ILRS data and their derived products. The board is a joint activity under the ASC and the NESC and meets by telecon on a bimonthly basis. Current activities include reviewing the results from the ASC's "Station Systematic Error Monitoring Pilot Project" and the development of tools for the stations to view system performance and examine systematic errors. Several of these tools are now available to the users, with the intention to have the complete ensemble of these web-based diagnostic tools online by the latter part of 2019. Four ACs have been routinely examining the incoming SLR data and providing rapid feedback to the stations on suspect performance using the "Rapid Response" exploder (Otsubo et al., 2018). The Board is also evaluating tools and procedures that would enhance data scrutiny at the stations.

Issues that the Board had been dealing with recently include: the influence of local data screening procedures, minimum full rate NP content; lapses in station operating procedures, lapses in reporting procedures, more stress on long- and short-term stability rather than NP rms, the need for proper backup and redundancy (timing, barometer, etc.) and engineering scrutiny of data results. Erricos Pavlis and Toshi Otsubo have operational on-line tools and diagnostic assessment for use in reviewing station performance; Van Husson has been performing station by station performance assessments starting with the NASA stations and he has now begun working on other network stations. The Board has been urging stations to be more rigorous in their use of our History Logs so that data inconsistencies can be better diagnosed. The QCB meeting notes are posted on the ILRS website.

Software Study Group (SSG)

The SSG works to identify existing software of use to ILRS stations. The SSG has worked with the ILRS CB to provide links to these software packages on the ILRS website. A set of lunar prediction, filtering, and normal pointing software has been added to the software available on the website. Also, an SLR normal pointing program has been added and is available for testing and implementation. A program showing sky plots of available satellites from any given station is another package now accessible from the ILRS website. Updated sample software for the new version 2 of the CPF and CRD formats is now available.

Space Debris Study Group (SDSG)

The SDSG was formed in 2014 to coordinate and assist stations in laser ranging to space debris targets. The SG also acts as an interface between the ILRS and the space debris activities within ESA. Early on, the SG organized several campaigns on TOPEX, Envisat, and other SD targets. Over the last three years, the number of stations tracking space debris has increased significantly. Measurements in multi-static/bi-color debris ranging measurements are being taken to uncooperative targets. "Stare and Chase" is another method for tracking uncooperative targets and has also been successfully tested. Significant results have been seen for science, POD, attitude motion, pre-entry data, and other applications. Work continues to extend debris laser ranging time into full daylight and during full night.

A dedicated server has been set up in Graz, where stations can deposit their laser ranging data from space debris targets; stations can also use this server to download updated CPF/TLE files for space debris targets. First successful daylight space debris laser ranging results have been recently published.

Participants within the space debris laser ranging community (Zimmerwald, Borowiec, Potsdam) meet frequently. Currently, there two different project teams that meet regularly: Tumbling motion and Expert Center.

Mission Campaigns

GREAT

Monthly campaigns were conducted on Galileo-201 with Galileo-202 as a backup, to study the behavior of on-board clocks and the gravitational redshift predicted by General Relativity. Launch problems placed in elliptical orbits which induced a periodic modulation of the gravitational redshift at the orbital frequency. In response to a Galileo mission request, the ILRS conducted monthly, week-long campaigns for a period of one year in support of the Galileo gravitational Redshift Experiment with eccentric sATellites (GREAT) experiment.

GASTON Project

The Paris and Cote d'Azur Observatories and the Royal Observatory of Belgium organized the GASTON project (Galileo Survey of Transient Objects Network) to search for evidence of Dark Matter (DM) in the universe. The experiment used the large network of atomic clocks and electromagnetic links from the Galileo constellation as a gigantic detector of 50,000 km aperture to search for Dark Matter (DM). Evidence of DM transients would be in distant clock correlations with the delay predicted by the trajectory of our Solar System within the dark matter halo. The experiment relied on the ILRS network to help maintain the metrology of the aperture over the period January – March 2021. Many of the network stations participated and maintained concentrated coverage on the Galileo constellation. Tracking priorities were adjusted to put heavy concentration on the Galileo constellation, while at the same time maintaining acceptable coverage on the other network priorities.

We give special thanks to all of the stations that put extra effort to make this all work. We now await the experiment results.

Sentinel-6/Jason-3 Tandem Campaign

The Sentinel-6 mission was launched into orbit on November 21, 2020. It is the latest mission to be launched to synoptically measure ocean surface topography (including the change in Global Mean Sea Level) along the TOPEX reference ground track at an inclination of 66°, and a repeat period 9.9156 days. Since December 18, 2020, Sentinel-6 has been flying in the same orbit, 30 seconds behind Jason-3. This tandem mission mode allows a direct inter-calibration of the instruments on the two spacecraft, including the radar altimeters and the water vapour radiometers. The geophysical corrections to the data from the different instrumentation on the two spacecraft, such as the ionosphere correction and the significant wave height (SWH) corrections can also be directly compared. These comparisons are necessary in order to connect the time series of sea surface height measurements from Sentinel-6 with the data from the previous satellites (TOPEX and Jasons 1,2,3). This tandem period will last approximately one year (compared to about nine months for the previous tandem missions (Jason-2+Jason-3 in 2016, and Jason-2+Jason-1 in 2008-2009). During this tandem mission, the ILRS stations are asked to interleave their tracking between the two spacecraft. If the stations prefer not to rapidly move between the targets, then the stations are asked to alternate their tracking passes evenly between the two spacecraft. The SLR data contribute by directly measuring the radial orbit error for the two missions during this important mission phase.

ILRS Meetings

Workshops

The ILRS holds bi-annual International Workshops on Laser Ranging which cover a wide range of topics throughout the service including scientific, engineering, mission, and infrastructure presentations. In addition, in recent years, the ILRS has conducted Technical Workshops in the intervening years to focus on a few timely topics that impact the quality of ILRS data products and service operations. These workshops are oriented more toward the SLR practitioners and are intended to provide more time to articulate the issues carefully, allow for in-depth discussion, and formulate a path forward.

In 2019 an ILRS Technical Workshop, sponsored by the DLR and the ILRS, was held in Stuttgart Germany, October 21 – 25 with the theme "Laser ranging: To improve economy, performance, and adoption for new applications". The workshop focused on addressing the following questions:

- What are the current and anticipated laser ranging requirements for the various satellites and have we defined them properly?
- How do we evaluate our current performance and is it adequate?
- What factors are currently limiting our network performance?
- What operational steps and tools would help us to better meet satellite ranging accuracy and scheduling requirements?
- What automation capabilities have been implemented or are planned for implementation, and what automation capabilities should stations consider?
- Novel concepts to improve the SLR network

With its 150 participants from more than twenty countries and more than seventy presentations (oral and poster), the workshop illustrated the importance of SLR and its application to international scientific research. For more detail on this Workshops see *https://cddis.nasa.gov/2019_Technical_Workshop/*

Prior to the 2019 ILRS Workshop, the ILRS scheduled a one-day introductory course to give non-practitioners in SLR an opportunity to broaden their knowledge about laser ranging to Earth-orbiting satellites and the Moon. More information about the "SLR School" can be found at: *https://ilrs.gsfc.nasa.gov/docs/2019/SLRschool_20191020.pdf*

An International Workshop was scheduled to take place in Kunming China in 2020; a Technical Workshop was scheduled for Arequipa, Peru in 2021. Both were delayed by two years (2022 and 2023) due to the Pandemic. In place of the Kunming event, the ILRS held a 5 day, 2 hours a day, tour of five SLR stations. The format also included an SLR related talk from each site to round out the program. These programs are available by access through the front page of the ILRS website at ilrs.gsfc.nasa.gov. A similar program is being planned for 2022.

ILRS Components Meetings

Meetings of the Governing Board and standing committees are typically held in conjunction with these ILRS workshops. The GB meeting in December 2020 was held virtually. The meeting Agenda and presentations can be found on the ILRS web site under About/Organizations/ILRS Governing Board/Meetings.

The ILRS Central Bureau meets monthly to review network station operations and performance, as well as to coordinate support of upcoming missions, monitor and manage the ILRS infrastructure, and plan future directions and activities. The ILRS Central Bureau continues to maintain the ILRS website, installed on a CDDIS webserver at NASA GSFC. The website, *https://ilrs.gsfc.nasa.gov*, is updated several times per week as required. A bibliography of laser ranging publications is maintained on this website. Then ILRS CB meets monthly; meeting notes are available upon request.

The Standing Committees meet periodically in person or virtually as required. See individual briefs above.

A summary of recent and planned ILRS meetings is shown in Table 4. Minutes and presentations from the workshops and these splinter meetings are available from the ILRS website (*https://ilrs.gsfc.nasa.gov/about/reports/workshop/index.html* and *https://ilrs.gsfc.nasa(.gov/about/reports/meeting_reports.html*).

Table 4. Recent and future ILRS Meetings (as of May 2021)

Timeframe	Location	Meeting
October 2019	Stuttgart, Germany	2019 ILRS Technical Workshop, "Laser ranging: To improve economy, performance, and adoption for new applications" ILRS Governing Board meeting ILRS Standing Committee meetings
November 2020	Virtual Meeting	Virtual Station Tour (in place of the original scheduled Workshop)
December 2020	Virtual Meeting	ILRS Governing Board meeting
October 2021 (Canceled/Postponed to 2022)	Kunming, China	22nd International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee/Study Group meetings
October 2022 (Canceled/Postponed to 2023)	Arequipa, Peru	23rd International Technical Workshop ILRS Analysis Standing Committee meetings ILRS Standing Committee/Study Group meetings

Publications and Reports

The Special Issue of the Journal of Geodesy, Volume 93, Issue 11, dated November 2019 (Pavlis et al, 2019) consists of a collection of articles on Laser Ranging, covering a variety of topics from ILRS operations, to science, and to other applications.

The ILRS issues periodic reports summarizing activities within the service over the reporting period. The latest report, for the period 2016 – 2019, is available on the ILRS website, and can be references as:

International Laser Ranging Service (ILRS) 2016-2019 Report, edited by C. Noll and M. Pearlman, NASA/TP-20205008530, NASA Goddard Space Flight Center, Greenbelt, MD, USA, 2020.

Detailed reports from past meetings can be found on the ILRS website. ILRS Biannual Reports summarize activities within the service over the period since the previous release. They are available as hard copy from the CB or online at the ILRS website.

The ILRS Central Bureau continues to maintain the ILRS website, installed on a CDDIS webserver at NASA GSFC. The website, *https://ilrs.gsfc.nasa.gov*, is updated several times per week as required. A bibliography of laser ranging publications is maintained on this website.

ILRS Analysis Center reports and inputs are used by the Central Bureau for review of station performance and to provide feedback to the stations when necessary. Special weekly reports on on-going campaigns are issued by email. The CB also generates monthly and quarterly Performance Report Cards and posts them on the ILRS website (*https://ilrs.gsfc.nasa.gov/network/system_performance/index.html*). These Report Cards evaluate data quantity, data quality, and operational compliance for each tracking station relative to ILRS minimum performance standards. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, and minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the ILRS website. Plots, updated frequently, of multiple satellite normal point RMS and number of full-rate points per normal point as a function of local time and range have been added to the ILRS website station pages.

While the "Report Cards" show in tabular form the performance of the network for a 3-month (short-term) or 1-year (long-term) period, to better visualize the evolution of each station's performance in time, JCET has developed a database that is accessed from our portal:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

by selecting the "ILRS Report Card" option and then selecting the station of interest and period of performance. Depending on the choice, monthly or quarterly reports, this tool generates a month-by-month or quarter-by-quarter graph of the performance and its measure of confidence.

Issues and Challenges

Several challenges are on the horizon for the ILRS as it moves forward. Some of the new stations underway and planned will help address geographic gaps in the network, but many gaps remain, primarily in Latin America, Africa, and Oceania. The ILRS network still consists of a mix of new and old technologies and levels of financial support, and the lack of standardization in system hardware and operations introduces data issues that require attentions. The number of satellite targets, particularly in the GNSS constellations, continues to increase. The ILRS has implemented a new GNSS tracking strategy (see sections on Satellite Missions) to address the increase in the number of GNSS satellites and the increase in user requirements. The Furthermore, there is a need to be more selective on the time spent on each target. Data quality issues continue to affect the ILRS products; rapid data review feedback to the stations continues to improve and on-line data evaluation software tools have been implemented. The progress made in the improvement of the geodetic satellite center of mass corrections has been significant, and techniques to address sources of data biases have been much improved.

References

Akentyev A.S., Sokolov A.L. (2020). "Retroreflector Complexes for Determining the Spacecraft Spatial Orientation Parameters", *BMSTU Journal of Mechanical Engineering*, 11, 73-82, DOI: 10.18698/0536-1044-2020-11-73-82. (Text of paper in Russian).

Andritsch F., Grahsl A., Dach R., Schildknecht T., Jaeggi A. (2020). "Simulation of tracking scenarios to LAGEOS and Etalon satellites", *J. Geodesy*, 94(4), 40, DOI: 10.1007/s00190-019-01327-w.

Arnold, D., Montenbruck, O., Hackel, S., Sośnica, K. (2019). "Satellite laser ranging to low Earth orbiters: orbit and network validation", *J. Geodesy*, 93, 2315-2334, DOI: 10.1007/s00190-018-1140-4.

Arnold D.A. (2020). "Thermal-optical design of a geodetic satellite for one millimeter accuracy", *Adv. Space Res*., 65(10), 2276-2289, DOI: 10.1016/j.asr.2020.01.031.

Bloßfeld M., Zeitlhofler J., Rudenko S., Dettmering D. (2020). "Observation-Based Attitude Realization for Accurate Jason Satellite Orbits and Its Impact on Geodetic and Altimetry Results", *Remote Sensing*, 12(4), 682, DOI: 10.3390/rs12040682.

Boisits J., Landskron D., Boehm J. (2020). "VMF3o: the Vienna Mapping Functions for optical frequencies", *J. Geodesy*, 94(6), 57, DOI: 10.1007/s00190-020-01385-5.

Bury, G., Sośnica, K., Zajdel, R. (2019). "Multi-GNSS orbit determination using satellite laser ranging", *J. Geodesy*, 93, 2447-2463, DOI: 10.1007/s00190-018-1143-1.

Bury, G., Sośnica, K., Zajdel, R. (2019). "Impact of the Atmospheric Non-tidal Pressure Loading on Global Geodetic Parameters Based on Satellite Laser Ranging to GNSS", *IEEE Transactions on Geoscience and Remote Sensing*, 57(6), DOI: 10.1109/TGRS.2018.2885845.

Bury, G., Sośnica, K., Zajdel, R., Strugarek D., Hugentobler, U. (2021). "Determination of precise Galileo orbits using combined GNSS and SLR observations", *GPS Solutions*, 25 (11), DOI: 10.1007/s10291-020-01045-3.

Chen, J.L., Ries, J.C., Tapley B.D. (2021). "Assessment of degree-2 order-1 gravitational changes from GRACE and GRACE Follow-on, Earth rotation, satellite laser ranging, and models", *J. Geodesy*, 95(4), 38, DOI: 10.1007/s00190-021-01492-x.

Ciufolini, I. C. Paris, E. C. Pavlis, B. Negri, G. Bianco, S. Pirrotta, A. Bursi, K. F. Hussain (2020). "LARES 2: status of the mission", 71st Int. Astronautical Congress, The CyberSpace Edition,12-16 October, 2020, Dubai, *IAC-20-A2.1.2 (60750)*.

Ciufolini, I., R. Matzner, A. Paolozzi, E. C. Pavlis, G. Sindoni, J. Ries, V. Gurzadyan, and R. Koenig (2019). "Satellite Laser-Ranging as a Probe of Fundamental Physics", *Scientific Reports*, 9 (1):15881. DOI: 10.1038/s41598-019-52183-9.

Ciufolini, I., A. Paolozzi, E. C. Pavlis, G. Sindoni, J. Ries, R. Matzner, R. Koenig, C. Paris, V. Gurzadyan, and R. Penrose (2019). "An improved test of the general relativistic effect of frame-dragging using the LARES and LAGEOS satellites", *The European Physical Journal C.* 79 (10): 872. DOI: 10.1140/epjc/s10052-019-7386-z.

Cordelli E., Vananti A., Schildknecht T. (2020). "Analysis of laser ranges and angular measurements data fusion for space debris orbit determination", *Adv. Space Res.*, 65(1), 419-434, DOI: 10.1016/j.asr.2019.11.009.

Couhert A., Bizouard C., Mercier F., Chanard K., Greff M., Exertier P. (2020). "Self-consistent determination of the Earth's GM, geocenter motion and figure axis orientation". *J. Geodesy*, 94 (113), DOI: 10.1007/s00190-020-01450-z.

Courde, C. et al. (2017). "Lunar laser ranging in infrared at the Grasse laser station", Astronomy & Astrophysics, 602, A90, DOI: 10.1051/0004-6361/201628590.

Dequal D., Agnesi C., Sarrocco D., Calderaro L., Amato L.S., de Cumis M.S., Vallone G., Villoresi P., Luceri V., Bianco G. (2021). "100 kHz satellite laser ranging demonstration at Matera Laser Ranging Observatory", *J. Geodesy*, 95(2), 26, DOI: 10.1007/s00190-020-01469-2.

Eckl J.J., Schreiber K.U., Schuler T. (2019). "Lunar laser ranging utilizing a highly efficient solid-state detector in the near-IR", in Quantum Optics and Photon Counting, ed. by I. Prochazka, R., Sobolewski, R.B. James, P. Domokos, & A. Gali, Proceedings of SPIE, Volume 11027, UNSP 1102708, DOI: 10.1117/12.2521133.

Ferrándiz J. M., Modiri S., Belda S., Barkin M., Bloßfeld M., Heinkelmann R., Schuh H.: "Drift of the Earth's Principal Axes of Inertia from GRACE and Satellite Laser Ranging Data". *Remote Sensing*, 12(2), 314, DOI: 10.3390/rs12020314, 2020 (Open Access).

Glaser, S., König, R., Neumayer, K.H. et al. (2019). "Future SLR station networks in the framework of simulated multi-technique terrestrial reference frames", *J Geodesy*, DOI: 10.1007/s00190-019-01256-8.

Glaser, S., König, R., Neumayer, K. H., Nilsson, T., Heinkelmann, R., Flechtner, F., Schuh, H. (2019). "On the impact of local ties on the datum realization of global terrestrial reference frames", *J. Geodesy* , DOI: 10.1007/s00190-018-1189-0.

Hattori A., Otsubo T., (2019). "Time-varying solar radiation pressure on Ajisai in comparison with LAGEOS satellites", *Adv. Space. Res.* 63, 63-72, DOI: 10.1016/j.asr.2018.08.010.

Kehm A., Bloßfeld M., König P., Seitz F. (2019), "Future TRFs and GGOS – where to put the next SLR station?", *Advances in Geosciences*, 50, 17-25, DOI: 10.5194/adgeo-50-17-2019, (Open Access).

König, R., Glaser, S., Ciufolini, I., Paolozzi, A. (2019)," Impacts of the LARES and LARES-2 Satellite Missions on the SLR Terrestrial Reference Frame". - In: Novák, P., Crespi, M., Sneeuw, N., Sansò, F. (Eds.), IX Hotine-Marussi Symposium on Mathematical Geodesy, (International Association of Geodesy Symposia ; 151), Cham : Springer International Publishing, 57-65. DOI: 10.1007/1345_2019_84.

Kucharski D., Kirchner G., Otsubo T., et al. (2020). "Quanta Photogrammetry of Experimental Geodetic Satellite for remote detection of micrometeoroid and orbital debris impacts", *Acta Astronautica*, 174, 24-31, DOI: 10.1016/j.actaastro.2020.04.042.

Lim H.C., Zhang Z.P., Sung N.P., et al. (2020). "Modeling and Analysis of an Echo Laser Pulse Waveform for the Orientation Determination of Space Debris", *Remote Sensing*, 12(10), 1659, DOI: 10.3390/rs12101659.

Löcher, A., Kusche, J. (2021). "A hybrid approach for recovering high-resolution temporal gravity fields from satellite laser ranging", *J. Geodesy*, 95(6), DOI: 10.1007/s00190-020-01460-x.

Long M.L., Zhang H.F., Men L.L., Wu Z.B., Deng H.R., Qin S., Zhang ZP. (2021). "Satellite laser ranging at 10 kHz repetition rate in all day", J. *Infrared and Millimeter Waves*, 39(6), 778-785. DOI: 10.11972/j.issn.1001-9014.2020.06.016.

Loomis B.D., Rachlin K.E., Wiese D.N., Landerer F.W., Luthcke S.B. (2020), "Replacing GRACE/GRACE-FO C_{30} With Satellite Laser Ranging: Impacts on Antarctic Ice Sheet Mass Change", *Geopys. Res. Lett.*, 47(3), e2019GL085488, DOI: 10.1029/2019GL085488.

Luceri V., Pirri M., Rodríguez J., Appleby G., Pavlis E. C., Müller H. (2019). "Systematic errors in SLR data and their impact on the ILRS products", *J. Geodesy*, 93, 2357-2366, https://link.springer.com/article/10.1007/s00190-019-01319-w.

Luceri, V., Pavlis, E. C., Basoni, A., Sarrocco, D., Kuzmicz-Cieslak, M., Evans, K., and Bianco, G. (2021). "The ILRS Contribution to ITRF2020", EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14739, https://doi.org/10.5194/egusphere-egu21-14739.

Luchessi, D., Anselmo, L., Bassan, M., Magnafico, C., Pardini, C., Peron, R., Pucacco, G., Visco, M. (2019). "General Relativity Measurements in the Field of Earth with Laser-Ranged Satellites: State of the Art and Perspectives", *Universe*, 2, DOI: 10.3390/universe5060141.

Lucchesi D., Visco M., Peron R., Bassan M., Pucacco Gl., Pardini C., Anselmo L., Magnifico C. (2020). "A 1% Measurement of the Gravitomagnetic Field of the Earth with Laser-Tracked Satellites", *Universe*, 6(9), 139, DOI: 10.3390/universe6090139.

Lyons, P., Lyons J.J., Dogoda, P. et al. (2020). "Alignment and Verification Testing of the GPS LRA Test Bed", in Optical System Alignment, Tolerance and Verification XIII (Proceedings of SPIE), edited by J. Sasian and R.N. Youngworth, Volume 11488 (114880I), DOI: 10.1117/12.2569160.

Mazarico, E., X. Sun, J.-M. Torre, et al. (2020). "First Two-way Laser Ranging to a Lunar Orbiter: infrared observations from the Grasse station to LRO's retro-reflector array", *Earth, Planets and Space*, 10.1186/s40623-020-01243-w.

Meyer, U., Sośnica, K., Arnold, D., Dahle, C., Thaller, D., Dach, R., Jäggi, A. (2019). "SLR, GRACE and Swarm gravity field determination and combination", *Remote Sensing*, 11 (8), art. no. 956, DOI: 10.3390/rs11080927.

Otsubo, T., Müller, H., Pavlis, E.C., Torrence, M.H., Thaller, D., Glotov, V.D., Wang, X., Sośnica, K., Meyer, U., Wilkinson, M.J. (2019). "Rapid response quality control service for the laser ranging tracking network, *J. Geodesy*, DOI: 10.1007/s00190-018-1197-0.

Paolozzi, A., Sindoni, G., Felli, F. Pilone, D., Brotzu, A., Ciufolini, I., Pavlis, E. C., Paris C. (2019). Studies on the materials of LARES 2 satellite, *J Geod, Springer-Verlag GmbH*, https://doi.org/10.1007/s00190-019-01316-z

Paris C., Sindoni G. (2019). "Comparison of Optical Quality of Some Passive Laser Ranged Satellites", Proceedings of the 2019 Photonics and Electromagnetics Research Symposium, pp. Rome, Italy, June 17-20, pp. 3483-3489.

Pavlis, E. C., (2019a). "The ILRS ASC Planned Contribution to ITRF2020", GGOS/IERS Unified Analysis Workshop 2019, October 2-4, Paris Observatory.

Pavlis, E. C., (2019b). "Gravity Modeling Changes for the ILRS Reanalysis for ITRF2020", GGOS/IERS Unified Analysis Workshop 2019, October 2-4, Paris Observatory.

Pavlis, E. C., V. Luceri, O. Toshimichi, U. Schreiber (Editors) (2019). "Special Issue: Satellite Laser Ranging", Journal of Geodesy, Volume 93, issue 11, https://doi.org/10.1007/s00190-019-01305-2.

Pavlis, E. C., V. Luceri, M. Kuzmicz-Cieslak, A. Basoni, D. Sarrocco, K. Evans, and G. Bianco, (2020). "Status Report of the Reprocessing for the ILRS Contribution to ITRF2020" AGU Fall 2020 Meeting, Presentation Abstract *G025-06*.

Pearlman, M., Arnold, D., Davis, M., Barlier Fl, Biancale R., Vasiliev V., Ciufolini I., Paolozzi A., Pavlis E., Sośnica K. (2019). "Laser geodetic satellites: a high-accuracy scientific tool, *J. Geodesy*, 93, 2181-2194, DOI: 10.1007/s00190-019-01228-y.

Pearlman, M., Brachet G., Lefebvre M., Barlier F., Exertier P. (2019). "The Smithsonian Astrophysical Observatory (SAO) and the Centre National d'Études Spatiales (CNES): contributions to the international laser ranging network", *J. Geodesy*, 93, 869-875, DOI: DOI: 10.1007/s00190-018-1209-0.

Pearlman, M., Noll C., Pavlis E., Lemoine F., Combrink L., Degnan J., Kirchner G., Schreiber U. (2019). "The ILRS: approaching twenty years and planning for the future", *J. Geodesy*, 93, 2161-2180. DOI: 10.1007/s00190-019-01241-1.

Porcelli L., Tibuzzi M., Mondaini C., et al. (2019). "Optical-Performance Testing of the Laser RetroReflector for InSight", *Space Sci. Reviews*, 215(1),1, DOI: 10.1007/s11214-018-0569-3.

Prochazka I., Bimbova R., Kodet J., Blazej J., Eckl J. (2020). "Photon counting detector package based on InGaAs/InP avalanche structure for laser ranging applications", *Review of Scientific Instruments*, 91(5), DOI: 10.1063/5.0006516.

Riepl, S., Müller, H., Mähler, S. et al. (2019). "Operating two SLR systems at the Geodetic Observatory Wettzell: from local survey to space ties", *J. Geodesy*, 93, 2379-2387, DOI: 1007/s00190-019-01243-z.

Sagnières L.B.M., Sharf I., Deleflie F. (2019). "Simulation of long-term rotational dynamics of large space debris: A TOPEX/Poseidon case study", *Adv. Space Res.*, 65(4), 1182-1195, DOI: 10.1016/j.asr.2019.11.021.

Schillak, S., Lejba, P., Michałek, P. (2021). "Analysis of the Quality of SLR Station Coordinates Determined from Laser Ranging to the LARES Satellite", *Sensors*, 21(3), 737. DOI: 10.3390/s2103073.

Sliwinska J., Nastula J., Winksa M. (2021). "Evaluation of hydrological and cryospheric angular momentum estimates based on GRACE, GRACE-FO and SLR data for their contributions to polar motion excitation", *Earth, Planets and Space*, 73(1), 71, DOI: 10.1186/s40623-021-01393-5.

Steindorfer M.A., Kirchner G., Koidl F., Wang P., Jilate B., Flohrer T. (2020). "Daylight space debris laser ranging", *Nature Communications*, 11(1), 3735, DOI: 10.1038/s41467-020-17332-z.

Strugarek, D., Sośnica, K., Jäggi, A. (2019), "Characteristics of GOCE orbits based on Satellite Laser Ranging", *Adv. Space Res*., 63 (1), pp. 417-431. DOI: 10.1016/j.asr.2018.08.033.

Strugarek D., Sośnica, K., Arnold D., Jäggi A., Zajdel R., Bury G. (2021). "Determination of SLR station coordinates based on LEO, LARES, LAGEOS, and Galileo satellites", *Earth Planets and Space*, 73(1), 87, DOI: 10.1186/s40623-021-01397-1.

Thomas T.C., Luthcke S.B., Pennington T.A., Nicholas J.B., Rowlands D.D. (2021). "ICESat-2 precision orbit determination". *Earth and Space Science*, 8, e2020EA001496. DOI: 10.1029/2020EA001496.

Varghese, T., R. L. Ricklefs, E.C. Pavlis, M. Kuzmicz-Cieslak and S. M. Merkowitz (2019). Transitioning the NASA SLR network to Event Timing Mode for reduced systematics, improved stability and data precision, *J Geod, Springer-Verlag GmbH,* https://doi.org/10.1007/s00190-019-01326-x.

Wang P.Y., Steindorfer M.A, Koidl F., Kirchner G., Leitgeb F. (2021). "Megahertz repetition rate satellite laser ranging demonstration at Graz observatory", *Optics Letters*, 46(5), 937-940, DOI: 10.1364/OL.418135.

Yang H.L., Xu T.H., Nie W.F., Fang Z.L., Li M., Guan M.Q. (2021). "GLONASS precise orbit determination based on L-band and SLR data", *Measurement and Science Technology*, 32(4), 045007, DOI: 10.1088/1361-6501/abd1fe.

Yang W., Zhao Y., Fan C., Kang Z., Liu P. (2021). "Real-time range gate control of a satellite laser ranging system based the on heterogeneous processor architecture," *Applied Optics*, 60, 296-305, DOI: 10.1364/AO.408434.

Zhao S.S., Steindorfer M., Kirchner G., et al. (2020). "Attitude analysis of space debris using SLR and light curve data measured with single-photon detector", *Adv. Space Res.*, 65(5), 1518-1527, DOI: 10.1016/j.asr.2019.12.005.

International VLBI Service for Geodesy and Astrometry (IVS)

https://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Rüdiger Haas (Sweden)
Director of the Coordinating Center: Dirk Behrend (USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2019−2021. Due to COVID-19 the IVS General Meeting and splinter meetings were cancelled in 2020. The IVS Directing Board developed an Infrastructure Development Plan 2030. Rüdiger Haas was elected IVS Chair for the period from February 2021 through February 2025, succeeding Axel Nothnagel in this position. In July 2020, Stuart Weston succeeded Ed Himwich as IVS Network Coordinator. The IVS contributed with results from eleven Analysis Centers to the ITRF2020 effort. In January 2020 the fledgling VGOS network of 8–10 stations was declared operational.

Structure

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, are:

- to provide a service to support geodetic, geophysical and astrometric research and operational activities;
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique; and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

They are realized through seven types of components (Network Stations, Operations Centers, Correlators, Analysis Centers, Data Centers, Technology Development Centers, and the Coordinating Center). The structure of the IVS and the interaction among the various components and external organizations is shown in Figure 1.

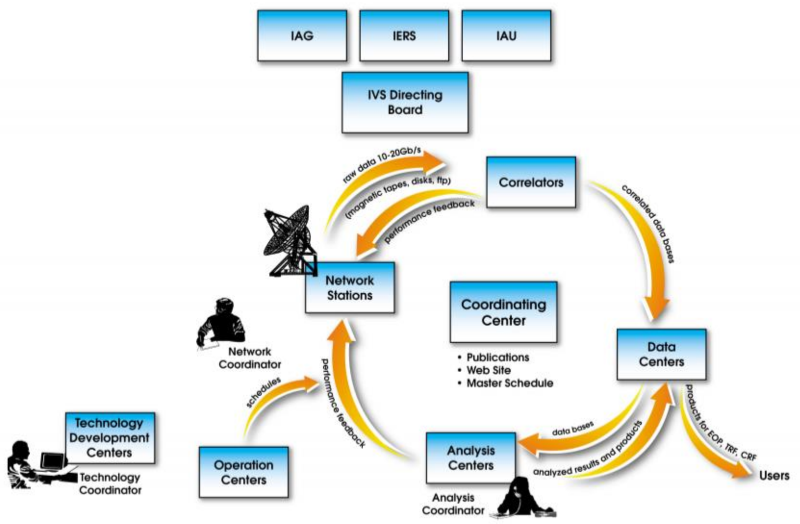


Figure 1. Organizational diagram of the IVS.

Being tasked by IAG and IAU with the provision of timely and highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Activities

Meetings and Organization

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 1 gives an overview of the IVS meetings during the report period.

Table 1. IVS meetings during the report period (2019─2021).

Time	**Meeting**	**Location**
18–20 November 2019	8th International VLBI Technology Workshop	Sydney, Australia
~~22 March 2020~~	~~IVS Stakeholders Meeting~~	~~Annapolis, MD, USA~~
~~22–26 March 2020~~	~~11th IVS General Meeting~~	~~Annapolis, MD, USA~~
~~27 March 2020~~	~~21st IVS Analysis Workshop~~	~~Annapolis, MD, USA~~
15–18 March 2021	EVGA Working Meeting 2021	Cyberspace
18 March 2021	22nd IVS Analysis Workshop	Cyberspace
3–5 May 2021	11th IVS Technical Operations Workshop	Cyberspace
6–7 May 2021	VGOS Correlation Workshop	Cyberspace

The Eleventh IVS General Meeting plus several splinter meetings were planned for the last week of March 2020. The meetings were canceled two weeks prior to commencement due to the onset of the coronavirus pandemic with travel bans and lockdowns. There were extensive discussions undertaken whether the event could be organized in a virtual setting or postponed to a later date. Eventually it was decided to outright cancel the General Meeting proper but hold part of the splinter meetings virtually.

The Directing Board corresponded with the IVS stakeholders about the service’s future and its mandate for the next ten years. The deliberations resulted in a planning document that was finally called the “IVS Infrastructure Development Plan 2030.” Based on feedback received, more than 80 percent of the stakeholders saw their agencies’ involvement in the IVS driven by service considerations (as opposed to science). See more information below.

The subsequent meetings until the end of the report period were all organized in Cyberspace. This includes the European VLBI meeting as well as workshops to train the station personnel and correlators. The latter two workshops ensured that the gap between hands-on training events did not become too large. But it became also apparent that the virtual workshops cannot replace any in-person, hands-on knowledge exchange.

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Board members are listed in Table 2.

Table 2. Members of the IVS Directing Board during the report period (2019−2021).

a) *Current Board members (May 2021)*

Directing Board Member	Institution, Country	Functions	Recent Term
James Anderson	GFZ Potsdam, Germany	Analysis and Data Centers Representative	Feb 2019 − Feb 2023
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Johannes Böhm	TU Vienna, Austria	IAG Representative	—
Patrick Charlot	Bordeaux Observatory, France	IAU Representative	—
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	IERS Representative, Chair	—
David Hall	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Sep 2019 − Feb 2023
Hayo Hase	BKG & AGGO, Argentina	Networks Representative	Feb 2019 − Feb 2023
Nancy Kotary	Haystack Observatory, USA	Office for Outreach and Communications	—
Chet Ruszczyk	Haystack Observatory, USA	Technology Development Centers Representative	Feb 2019 − Feb 2023
Nadia Shuygina	Institute of Applied Astronomy, Russia	At Large Member	Feb 2021 − Feb 2023
Yu Takagi	Geospatial Information Authority, Japan	At Large Member	Feb 2021 − Feb 2023
Oleg Titov	Geoscience Australia, Australia	Analysis and Data Centers Representative	Feb 2021 − Feb 2025
Gino Tuccari	IRA/INAF, Italy	Technology Coordinator	—
Pablo de Vicente	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2021 − Feb 2025
Stuart Weston	Auckland University of Technology, New Zealand	Network Coordinator	—
Alet de Witt	Hartebeesthoek Radio Astronomy Observatory, South Africa	At Large Member	Feb 2021 − Feb 2023

b) *Previous Board members in 2019−2021*

Francisco Colomer	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2017 − Feb 2021
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Laura La Porta	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2019 − Sep 2019
Jinling Li	Shanghai Astronomical Observatory, China	At Large Member	Feb 2019 − Feb 2021
Evgeny Nosov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2019 − Feb 2021
Axel Nothnagel	TU Vienna, Austria	Analysis and Data Centers Representative	Feb 2017 − Feb 2021
Oleg Titov	Geoscience Australia, Australia	IAG Representative	—

In July 2020, Stuart Weston of Auckland University of Technology (AUT) in New Zealand took over the position of IVS Network Coordinator from Ed Himwich of NVI, Inc./NASA Goddard Space Flight Center. In November–December 2020, the IVS held Directing Board elections. Following the elections, the new Board elected Rüdiger Haas from Chalmers University of Technology, Onsala Space Observatory, Sweden as chair of the IVS for the four-year term from February 2021 to February 2025.

IVS Infrastructure Development Plan 2030

Based on the discussions with the IVS stakeholders, the IVS Directing Board developed an IVS Infrastructure Development Plan 2030. The main goal is to provide overall planning guidelines and to give the stakeholders and IVS Associates reasonable indications for the investments and activities needed. It is hoped that the plan will trigger serious considerations for additional components in order to establish and sustainably maintain elements identified as missing for further progress. Not only should this document motivate existing IVS components but also provide necessary arguments to new players for a serious need for additional contributors and contributions.

UT1−UTC, the highly variable Earth's phase of rotation, is needed for a variety of important applications such as positioning, navigation and environmental monitoring, preferably in real-time. Since the VLBI technique is the only one to determine this parameter with sufficient accuracy and due to the need for low latency results, regular UT1−UTC determinations have the highest priority in the IVS's endeavours and justify the maintenance of global critical infrastructure. However, the other components of EOP, as well as those of terrestrial and celestial reference frames, though with different latency requirements, are equally essential for numerous applications in science and technology. These products are highly correlated with each other and need to be monitored diligently with the same level of energy.

Starting from its current level of operations, the IVS embarks on organizing IVS observing networks in operation for 24 hours, seven days a week and on producing products with reasonable accuracies and latencies. Within these observing sessions, it will be warranted that all products, i.e., the complete set of EOP components including UT1−UTC as well as terrestrial and celestial reference frames, are produced with the same level of quality.

The IVS relies on voluntary contributions of national agencies and institutions acting in a global context. The workload is large and the investments are costly. At present, not all of the resources needed for the targets named above, such as coordination, data transfer and *Level 1 Data Analysis*, have been committed in full or even in part. For this reason, much of the progress to be seen in the next ten years will heavily depend on increased commitments and investments of active and new IVS contributors.

Observing Program

The observing program for 2019–2021 with the legacy S/X system (production system) included the following sessions:

- EOP: Daily 1-hour UT1 Intensive measurements: Int1 sessions on five weekdays (Monday through Friday) using the Wettzell (Germany) to Kokee Park (Hawaii, USA) baseline; Int2 sessions on Saturday and Sunday, using the Wettzell (Germany) to Ishioka (Japan) baseline; and Int3 sessions on Monday mornings in the middle of the 36-hour gap between the Int1 and Int2 series with the Wettzell (Germany), Ny-Ålesund (Norway), and Ishioka (Japan) network. Two rapid-turnaround 24-hour sessions each week designed to measure all components of EOP. These mostly used networks of 10–12 globally distributed stations, depending on station availability. In 2020, extended R1 sessions with up to 14 stations were observed roughly every other week. These networks were designed with the goal of having comparable x_p and y_p results. Data is available within 15 days after each session ends.
- TRF: Bi-monthly TRF sessions with 14–18 stations using all stations at least two times per year.

- CRF: Bi-monthly sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus astrometric sessions to observe mostly southern sky sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. On average, a total of about 1650 station days per year were used in around 200 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

In January 2020, the VGOS network was officially declared operational (and vgosDB files were made available on the data centers for sessions from January 2019 onward). The goal was to schedule 24-hour VGOS sessions every two weeks. This goal was largely successful with 26 sessions scheduled and correlated each in 2019 and 2020. These sessions generally involved all of the VGOS antennas which were available at a given time. Although we continued to observe at roughly a bi-weekly cadence during 2020 there was a backup in correlating these sessions due to COVID-19. The IVS is still working through the backlog.

Analysis

Diurnal and Semidiurnal EOP Variation

Several IVS Analysis Centers participated in the work of the IERS Working Group on Diurnal and Semi-diurnal EOP Variation. Ten different models were evaluated by members of the IVS, the ILRS, and the IGS. Each technique used metrics appropriate to their technique. For example, the IVS looked at baseline repeatability and goodness of fit. The general consensus of all the techniques was that the two best models were *2017a_astro*, an empirical model derived from VLBI data by John Gipson, and a model by Desai and Sibois of JPL derived from a TPX08, an altimetry model due to Egbert. Both models were improvements over the current IERS models, and each model had advantages and disadvantages. In order to avoid technique-specific signals, the working group recommended the use of the Desai and Sibois model which is the new IERS standard and is used in ITRF2020.

Gravitational Deformations of Radio Telescopes

VLBI antennas are structures, traditionally with a typical size of 30 m or larger, although modern VGOS antennas have dish diameters of 12–13 m. The VLBI antennas deform due the effect of gravity, and the deformation is a function of the elevation angle. In 1988 Per Thomsen and Tom Clark built a finite-element model for the 26-m diameter Gilcreek VLBI antenna and showed that the change in path length could be up to 2.4 mm. This causes a change in the observed differential delay, which in turn causes a change in the estimated geodetic parameters, particularly local Up. Beginning in the early 2000s the deformation of several VLBI antennas was directly measured using surveying techniques, leading to a total of six antennas for which we had models. The change in path length can be as large as 97 mm (as for the 100-m antenna at Effelsberg). First measurements on VGOS antennas show that the path length changes of these modern antennas are on the order of just 1 mm. In preparation for ITRF2020, all IVS Analysis software was modified to be able to incorporate modelling the effect of gravitational deformation.

Loading Effects

The standard IVS analysis includes the effect of pressure loading. Since the other space geodetic techniques do not routinely include these effects, this meant that our estimates of station position were not consistent with other techniques. This is an issue when you are trying to combine data from several techniques. After consultation with the IERS, the IVS came up with the following compromise. We would do our analysis as we normally do, but we would modify the SINEX files that we produced so that loading effects could be removed *a posteriori*. This essentially involves adding in an additional normal equation vector which is due entirely to pressure loading.

ITRF2020

Much of the focus of the last two years was related to the preparation for and participation in the IVS submission for ITRF2020. Eleven Analysis Centers using seven software packages submitted SINEX files. The IVS 2020 submission differed from the 2014 submission in several key ways, mostly modeling changes:

- ITRF2014 used a model from 1996 for High-Frequency EOP. This model had begun to show its age, and the IERS recommended use of a new model due to Desai and Sibois (2016), based on Topex data.
- The IVS also adopted the new IERS pole-tide model.
- This submission included the effects of galactic aberration using the model recommended by IVS Working 8 on Galactic Aberration (MacMillan et al., 2019).
- This submission included models for the effects of gravitational deformation for six antennas: EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60, and YEBES40M. Unfortunately, we were not able to include the model for NYALES20 which became available too late.
- Unlike previous submissions, this submission included the effect of pressure loading. In order to be able to combine the results with other techniques that do not routinely apply pressure loading effects, the SINEX files were modified so that pressure loading could be backed up.
- Source positions. The IVS contribution to ITRF2020 included source coordinates.

Source Structure

The ideal VLBI source is strong and point-like. In reality all sources have structure. This causes changes in the observed delay. If not correctly accounted for, this will show up as noise in the measurements. In the past few years, several groups have looked at the effect of source structure. Although this is still very much an R&D effort, the results look promising. We anticipate that future VLBI analysis software will include the effect of source structure.

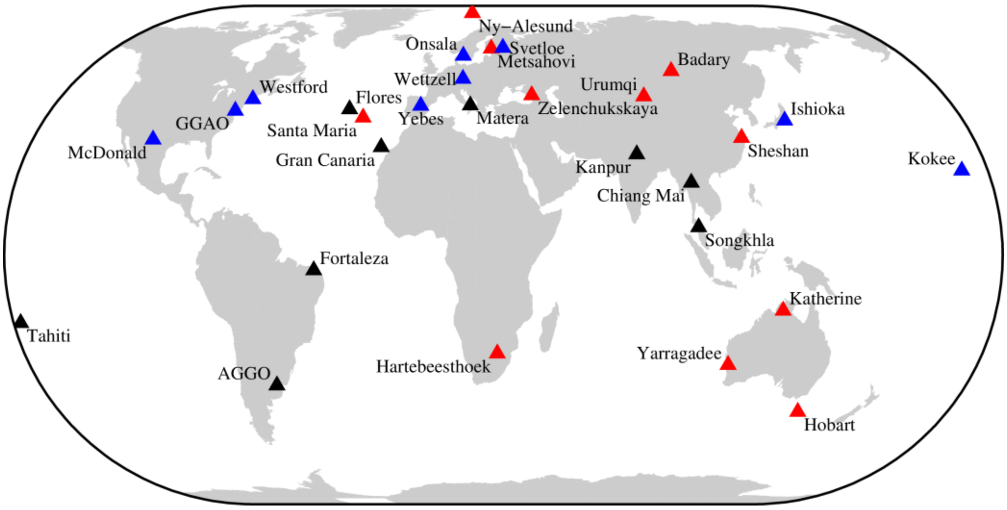


Figure 2. Rollout status of the VGOS station network: ▲ operational station, ▲ antenna built, signal chain work in progress, and ▲ in planning stage.

Technology Development

Progress was made in realizing the goals of the next-generation VLBI system, the VLBI Global Observing System (VGOS). A fledgling network started observing in operational IVS sessions with the beginning of 2020; 24-hour VGOS sessions were observed on a two-week basis. The network of 8–10 stations has matured enough to make the results available on the Data Center. It is anticipated that the global network will grow in the coming years to almost 30 stations (and possibly beyond) and will eventually replace the legacy S/X system as the IVS production system.

As part of the modernization process, other infrastructure components of the VLBI processing chain have been further developed as well, including the VGOS correlation and post-processing capabilities as well as VGOS data analysis. At the end of 2020 and the beginning of 2021, several correlators (Washington, Bonn, Vienna, Shanghai) began processing VGOS sessions in addition to the Haystack correlator.

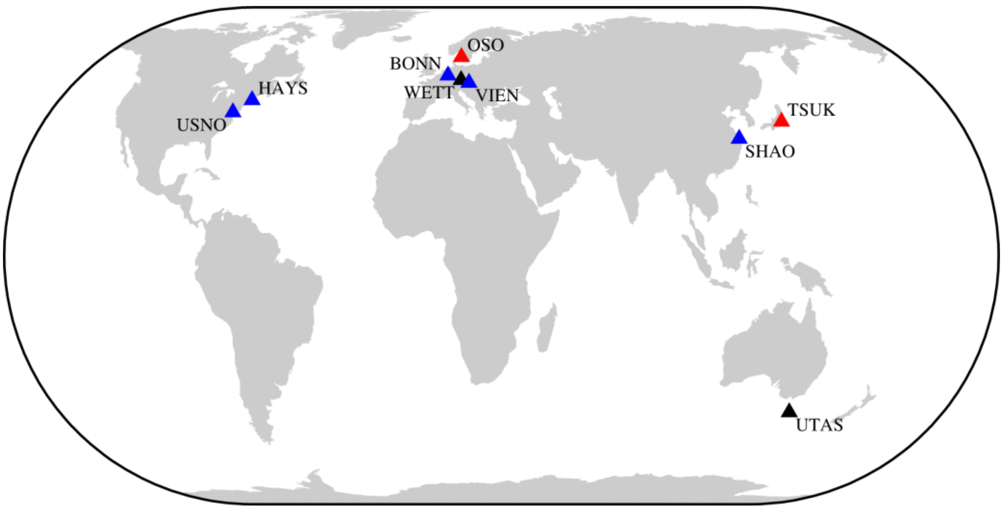


Figure 3. Rollout of VGOS correlation capabilities: ▲ operational correlator, ▲ under verification, and ▲ future correlation center.

References

K. Armstrong, D. Behrend. K.D. Baver (editors): IVS 2018 General Meeting Proceedings, NASA/CP-2019-219039, Greenbelt, MD, USA, 2019.
https://ivscc.gsfc.nasa.gov/publications/gm2018/

K.L. Armstrong, K.D. Baver, D. Behrend (editors): IVS 2017+2018 Biennial Report, NASA/TP-2020-219041, Greenbelt, MD, USA, 2020.
https://ivscc.gsfc.nasa.gov/publications/br2017+2018/

K.L. Armstrong, K.D. Baver, D. Behrend (editors): IVS 2019+2020 Biennial Report, in preparation.
https://ivscc.gsfc.nasa.gov/publications/br2019+2020/

D. Behrend, C. Thomas, J. Gipson, E. Himwich, K. Le Bail, "On the organization of CONT17." J. Geod., 94:100, 2020. doi:10.1007/s00190-020-01436-x
https://rdcu.be/b8q0I

D. S. MacMillan, A. Fey, J. M. Gipson, D. Gordon, C. S. Jacobs, H. Krásná, S. B. Lambert, Z. Malkin, O. Titov, G. Wang, M. H. Xu, "Galactocentric acceleration in VLBI analysis – Findings of IVS WG8." A&A 630, A93 (2019). doi:10.1051/0004-6361/201935379

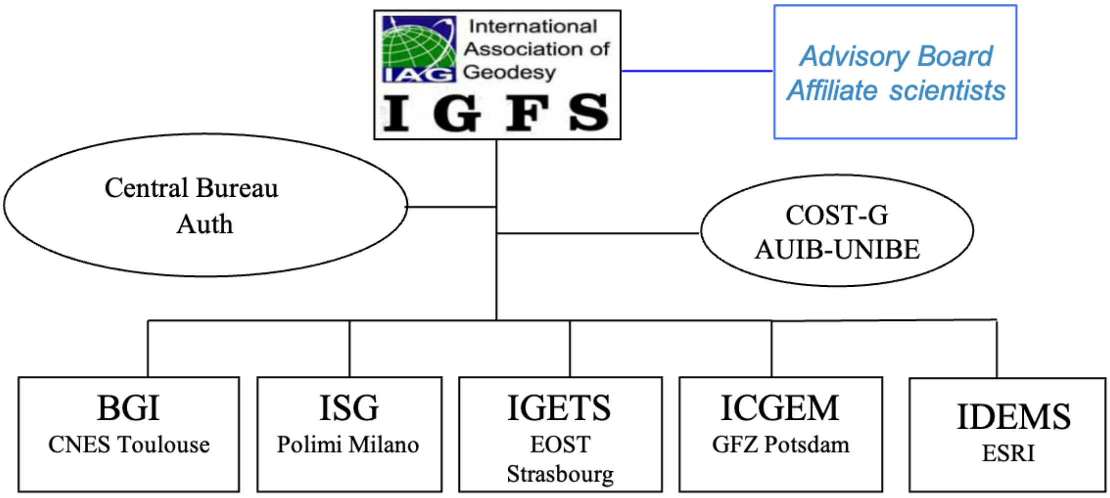
A. Nothnagel, J. Anderson, D. Behrend, J. Böhm, P. Charlot, F. Colomer, A. de Witt, J. Gipson, R. Haas, D. Hall, H. Hase, E. Himwich, N. Wolfe Kotary, J. Li, E. Nosov, C. Ruszczyk, G. Tuccari: "IVS Infrastructure Development Plan 2030." In: K.L. Armstrong, K.D. Baver, D. Behrend. (eds.), International VLBI Service for Geodesy and Astrometry 2019+2020 Biennial Report, in preparation. Also accessible via the IVS website at:
https://ivscc.gsfc.nasa.gov/about/strategic/IVS-InfrastructureDevelopmentPlan2030_2020-09-28.pdf

International Gravity Field Service - IGFS

http://igfs.topo.auth.gr/
Chairman: Riccardo Barzaghi (Italy)
Director of the Central Bureau: Georgios Vergos (Greece)

The IGFS structure

The present day IGFS structure is summarized in the following chart



BGI (Bureau Gravimetrique International), Toulouse, (F)
ISG (International Service for the Geoid), POLIMI, (I)
IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg, (F)
ICGEM (International Center for Global Earth Models), GFZ, Potsdam, (D)
IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA (USA)
COST-G (International Combination Service for Time-variable Gravity Fields), AIUB, Bern (CH)
Auth (Aristotle University of Thessaloniki), Thessaloniki (GR)

IGFS coordinates the activities of the Gravity Services (BGI, ISG, IGETS, ICGEM, IDEMS) and of its Product Center COST-G via its Central Bureau at the Aristotle University of Thessaloniki (Greece) and its Advisory Board. In the 2020-2023 period, the members of the IGFS Advisory Board are:

- H. Abd-Elmotaal (Egypt)
- J.-P. Barriot (French Polynesia)
- S. Bonvalot (France)
- S. Bettadpur (USA)
- R. Forsberg (Denmark)
- Y. Fukuda (Japan)
- T. Gruber (Germany)
- J. Huang (Canada)
- E. S. Ince (Germany)
- A. Jäggi (Switzerland)

- K. Kelly (USA)
- U. Marti (Switzerland)
- T. Otsubo (Japan)
- R. Pail (Germany)
- M. Reguzzoni (Italy)
- M. G. Sideris (Canada)
- L. Sanchez (Germany/Columbia)
- I. N. Tziavos (Greece)
- L. Vitushkin (Russia)
- Y. Wang (USA)
- H. Wziontek (Germany)

This structure of IGFS proved to be effective for managing the interaction among the Gravity Services that were able to provide the required gravity products.
IGFS was also active in promoting the contacts among the Gravity Services and GGOS, namely with the GGOS Bureau of Products and Standards, the GGOS Bureau of Networks and Observations and the GGOS Focus Area on Unified Height System.
Finally, IGFS is also involved in the activities of the following IAG Joint Working and Study Groups

- JWG GGOS 0.1.3: Implementation of the International Height Reference Frame (IHRF) (joint with GGOS, Commission 1, Commission 2, ICCT)
- JWG GGOS: Towards a consistent set of parameters for the definition of a new GRS (joint with GGOS, Commissions 1, Commission 2, ICCT, IERS Committee on EGV)
- JSG T.26: Geoid/quasi-geoid modelling for the realization of the geopotential height datum (joint with Commission 2, GGOS, ICCT)
- JSG T.37: Theory and methods related to the combination of high resolution topographic/bathymetric models in geodesy (joint with ICCT, IDEMS)

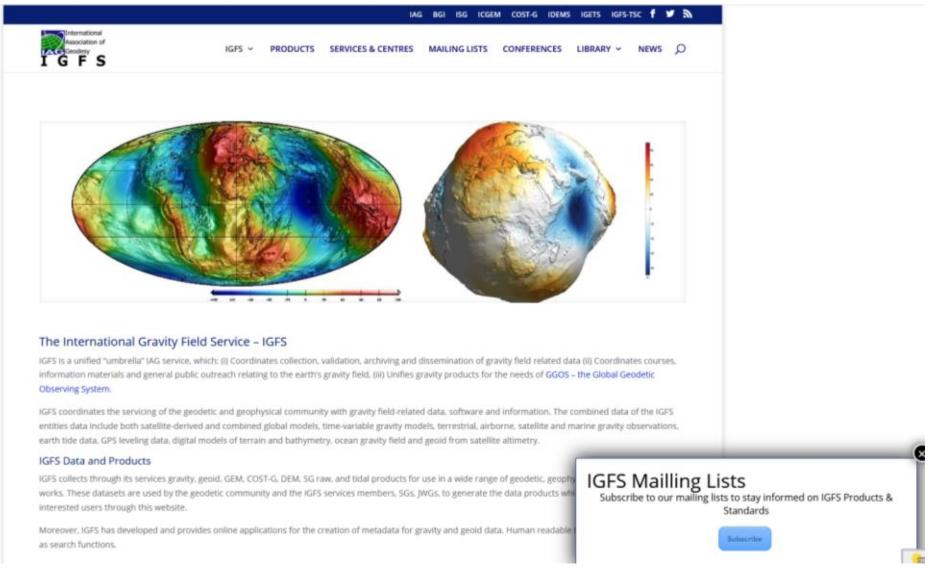
Overview

In the period 2020-2021, the main IGFS activities have been addressed to the improvements of the internal communication among the Gravity Services, to strengthen the connection with GGOS and Commission 2 and to manage the organization of projects and conferences. At the same time, some other standard activities within IGFS have been carried out, such as e.g. the coordinate exchange of software and data for gravity field estimation.
While these activities have been performed in a direct way by the related Gravity Services, though supervised and harmonized by IGFS, the International Combination Service for Time-variable Gravity Fields **(**COST-G) has produced its solutions directly on behalf of IGFS. This is a remarkable activity, providing time variable gravity field solutions that are stored at ICGEM.
As mentioned, another fundamental part of the IGFS actions is performed in connection with GGOS. IGFS actively participates to the GGOS Consortium and its Chair is one of the GGOS-CB members. Through these connections, the Gravity Services activities are documented to GGOS also in order to have a closer cooperation with the Geometric Services of IAG. This also led to the establishment of standards on gravity metadata (based on the GGOS Bureau of Products and Standards recommendations) that were implemented in the IGFS web page. IGFS actions in GGOS were also performed within the framework of the

Focus Area on “Unified Height System” for the ongoing definition and establishment of the International Height Reference System/Frame (IHRS/IHRF).
As previously mentioned, the cooperation between IGFS and IAG Commission 2 is based on the activities of Joint Working and Study Groups that have been established at the last IAG/IUGG Assembly in Montreal (2019) (see the list above).
Also, IGFS and Commission 2 planned to co-organize the 3rd Joint Commission 2 and IGFS Meeting, the “Gravity, Geoid and Height Systems 2020”. This is the meeting usually held every two years, following those in Thessaloniki, Greece (September 19-23, 2016) and in Copenhagen, Denmark (September 17-21, 2018). Contacts were established with the University of Texas at Austin and a possible date and a tentative program were discussed. However, due to the COVID pandemic, the meeting was postposed to 2022, as agreed with the LOC.
Finally, IGFS is managing the GEOMED2 project, an ESA supported project. This project, based on the co-operation among the IGFS Services (i.e. BGI, ISG, ICGEM and IDEMS), aims at computing the geoid and the DOT in the Mediterranean Sea.

The IGFS Central Bureau and the IGFS web page

With the International Gravity Field Service (IGFS) Central Bureau (CB) being hosted at the Department of Geodesy and Surveying (DGS) of the Aristotle University of Thessaloniki (AUTH) since April 2016, in the period 2020-2021 an effort was put forth in order to update its presence in the web and make the IGFS data and products more visible to the interested scientific and user community. To that respect, the IGFS webpage (igfs.topo.auth.gr) has been updated targeting especially the available IGFS services products.



The first update of the IGFS webpage since May 2021.

Given the need to promote the work carried out by IGFS Services and Centers, a new updated webpage has been recently created focusing more on the data and products availability, so that interested users can acquire them directly from the available portals (see figures below). In the new webpage layout, the availability of gravity, geoid, time-variable gravity, GEM, DEM, SG and tide data through the IGFS services portal is more visible, while a news section has been created as well to direct to IGFS related conferences, updates, etc..

The recently updated IGFS webpage, since May 2021

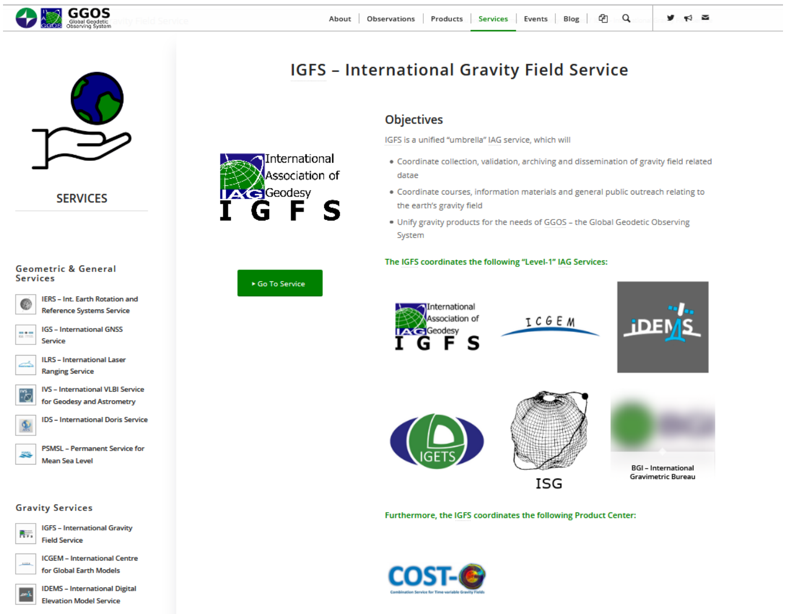
Moreover, given the update of the GGOS webpage and web front end, the IGFS CB has updated the IGFS presence, as well as that of all IGFS Services and Product Center.

Furthermore, two mailing lists have been developed within IGFS CB:

igfs-products@lists.auth.gr: the scope of this list if to provide updated information on the new data and products that become available from the IGFS Services. New data and products such as GEMs, DEMs, gravity, geoid, SG, tide, etc. will be posted and shared to all list members. Subscription to the list is free. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-products

igfs-standards@lists.auth.gr: the scope of this list is to provide a forum for idea exchange within the IGFS CB, AB and IAG Commission2 SC, towards the introduction of new and the update of old IGFS conventions and standards. The igfs-standards mailing list is open to all, but pending approval of the IGFS CB, given the more administrative nature of the list. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-standards

Finally, IGFS has gained presence in public media, both in Facebook (@InternationalGravityFieldService) and Twitter (@igfscb) in order to increase both its visibility and the influence of its products.



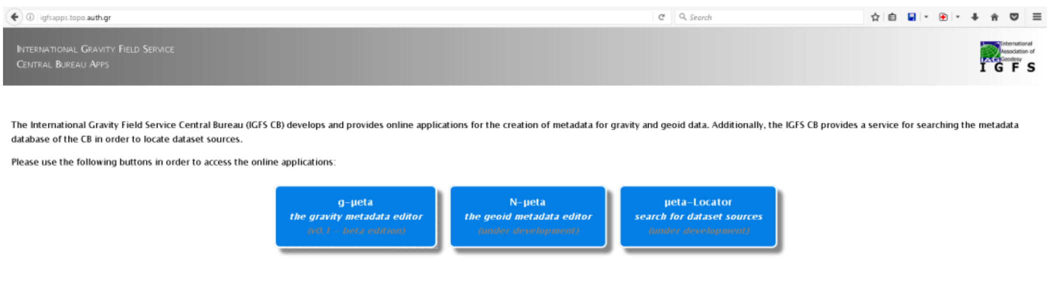
The recently updated IGFS presence in the GGOS webpage, online since May 2021

IGFS and GGOS

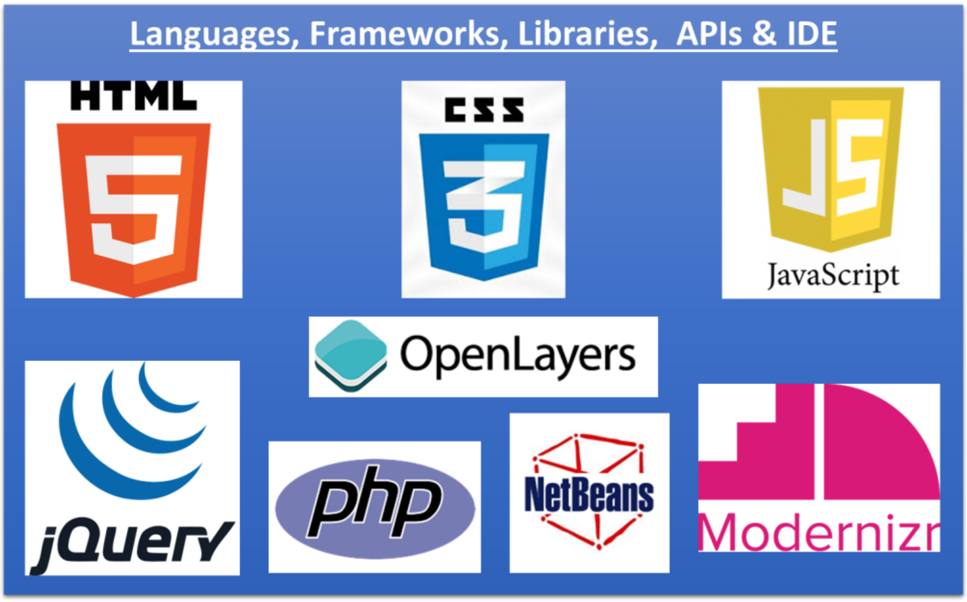
- Gravity metadata structure g-μeta

The IGFS CB has developed, within the IGFS web-page, an IGFS-applications front-end where three main components have been established. The first one refers to the generation of metadata for both relative and absolute gravity observations, either original and gridded ones. The rest refers to metadata for geoid models as well as a geodatabase and geolocator for the visualization of all products offered by IGFS and its services.

IGFS generated a dedicated web-server hosted by a Virtual Machines Host (VMWare) of the Aristotle University of Thessaloniki targeting at minimum downtime, automatic backup and being monitored automatically for threats. The main technologies and modules employed for the metadata generation are HTML5, CSS3, java scripting, jquery, php, netbeans and Modernizr. The application has succeeded to be lightweight, compatible with portable devices, adhere to user needs and extensible.



The IGFS applications front-end (g-μeta, N-μeta and μeta-Locator)



Technologies and modules used for the development of the IGFS metadata

Moreover, it provides code in popular programming languages for integrating the functionality of g-μeta and N-μeta in existing applications. The g-μeta includes both mandatory and optional fields related to the gravity data acquisition standards, processing methodology, tide corrections applied, owner information, geospatial referencing etc.. It requires a complicated validation procedure carried out both on the client and the server side.

Five main categories have been foreseen as: 1) Identification information, 2) Standards and conventions, 3) Data and Data quality information, 4) Distribution information and 5) Metadata reference information. All categories comply with ISO19115-1 adopted also by GGOS. The sub-categories within each main field are presented in the following figures.

1.Identification Information
Citation
Description
Time Period of Content
Status
Spatial Domain
Keywords
Constraints
Points of Contact
Security Information

2.Standards and Conventions
General Standards and Conventions
Earth's Gravity Field
Earth Orientation Parameters
Tidal Conventions
Station Coordinates and corrections for absolute gravity

3.Data and Data Quality Information	
Attribute Accuracy	Gravity Data Type
Logical Consistency	Gravity Accuracy
Completeness Report	Position Accuracy

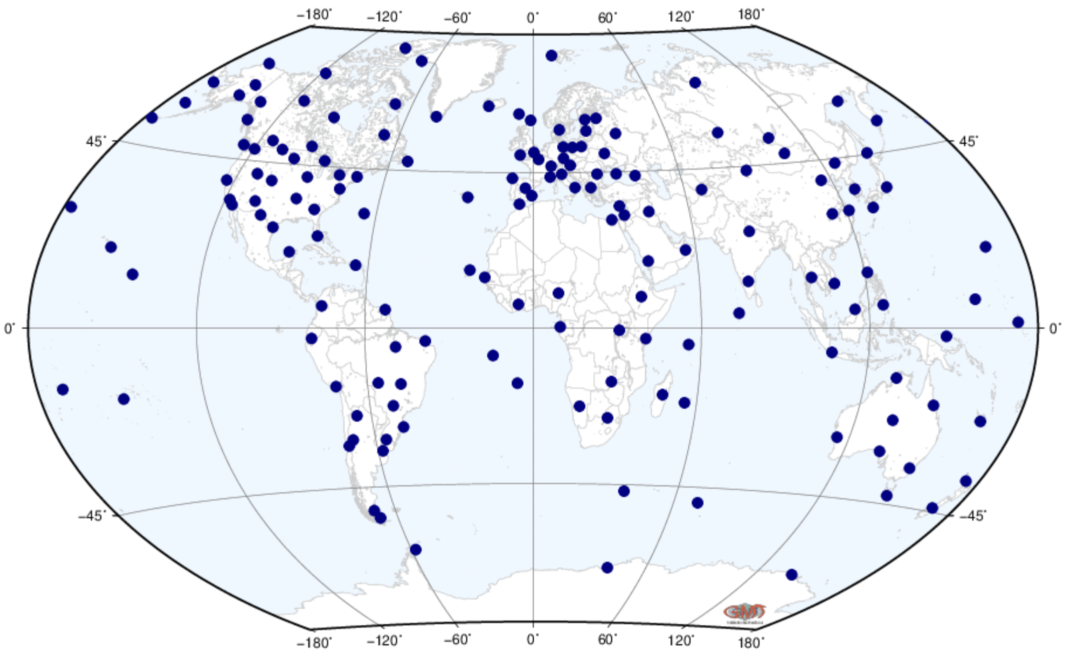
4.Distribution Information
Distributor
Standard Order Process

5.Metadata Reference Information
Metadata Creation Date and Creator Information
Metadata Prototype Information

Implemented categories within the IGFS g-μeta metadata generator.

- The International Height Reference System/Frame

The International Height Reference System/Frame (IHRS/IHRF) is one of the key issues in IAG and GGOS. As it is well known, IAG provides the scientific community with the ITRSnn/ITRFnn. This global reference frame is a fundamental infrastructure that allows monitoring e.g geodynamical phenomena such as deformations of the Earth crust in seismogenic areas. On the other hands, a corresponding global physical height reference system/frame is still missing. In 2015, at the IAG/IUGG General Assembly in Prague, IAG established the IHRS/IHRF through its resolution n°1. From that moment on, this project started and is ongoing. At the IAG/IUGG General Assembly in Montreal (2019), the project was further implemented and is now in its realization phase. The draft design of the IHRS/IHRF has been set up (see the figure below) and the computation of the W(P) values in the network points is currently performed.



The IHRF network design (https://ggos.org/item/height-reference-frame/#learn-this)

IGFS has been actively involved in the definition of such a system and strictly co-operated with GGOS focus area on "Unified Height System" and Commission 2 for that. IGFS contributed also to the papers that have been published on this subject (see reference below). At the same time, IGFS is involved in the definition of the Global Geodetic Reference System/Frame (GGRS/GGRS) that includes the definition of the new global gravity reference system that will replace IGSN71, a project that is strictly connected to the IHRS/IHRF topic.

References

Definition and Proposed Realization of the International Height Reference System (IHRS).
J. Ihde1, L. Sanchez, R. Barzaghi, H. Drewes, Christoph Foerste, Thomas Gruber, Gunter Liebsch, Urs Marti, Roland Pail, Michael Sideris, Surv. Geophys. (2017), DOI 10.1007/s10712-017-9409-3.

The Worldwide Physical Height Datum Project
R. Barzaghi, C. I. De Gaetani, B. Betti. Rend. Fis. Acc. Lincei (2020), https://doi.org/10.1007/s12210-020-00948-0

Strategy for the realization of the International Height Reference System (IHRS)
L. Sánchez, J. Ågren, J. Huang, Y. M.Wang, J. Mäkinen, R. Pail, R. Barzaghi, G. S. Vergos, K. Ahlgren, Q. Liu. Journal of Geodesy (2021), 95:33, https://doi.org/10.1007/s00190-021-01481-0.

Recent IGFS activities

- 3rd Joint IGFS and Commission 2 Meeting "Gravity, Geoid and Height Systems 2022"

As previously mentioned, the organization of the 3rd Joint IGFS and Commission 2 Meeting to be held in September 2022 in Austin, Texas, is ongoing. According to what was stated for the agenda of the 2020 meeting, the topics of the forthcoming meeting will be:

- Current and future satellite gravity missions
- Global Gravity Field Modelling
- Local/regional gravity field modelling
- Absolute, Relative and Airborne Gravity - Instrumentation, Analysis, and Applications
- Height systems and vertical datum unification
- Satellite altimetry and applications
- Gravity for Climate & Natural Hazards: Inversion, Modeling, and Processes

It is foreseen that the call for abstract will be available by the end of September 2021.

- The Geomed2 Project

IGFS has proposed and managed the GEOMED2 Project that started in 2015. Although the project end was planned at the beginning of 2020, its deadline was shifted to the end of 2021 due to the COVID pandemic.
The main aim of the proposed GEOMED2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea using land and marine gravity data, the most recent Global Geopotential Models and an *ad hoc* DTM/bathymetry model. The processing methodology is based on the well-known remove-compute-restore method following both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data. The main accomplishments of the project have been documented in the paper *GEOMED2: high-resolution geoid of the Mediterranean*

(International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, IAG, Kobe. DOI: https://doi.org/10.1007/1345_2018_33) by Barzaghi et al.
Further activities are planned in 2021 that will be focused on refining the gravity database, computing new geoid solutions and deriving an updated estimate of the Mean Dynamic Sea Surface Topography over the whole Mediterranean Sea.
The project is based on the cooperation between IGFS related Services (BGI, ICGEM, ISG) and the following scientific institutions:

- Politecnico di Milano, Italy
- Aristotle University of Thessaloniki, Greece
- GET UMR 5563, Toulouse, France
- SHOM, Brest, France
- OCA/Géoazur, Sophia-Antipolis, France
- DTU Space, Kopenhagen, Denmark
- General Command of Mapping, Ankara, Turkey
- University of Zagreb, Zagreb, Croatia
- University of Jaén, Jaén, Spain

- *The COST-G status and its activities*

The International Combination Service for Time-variable Gravity Fields (COST-G) is the Product Center of IGFS for time-variable gravity fields. COST-G provides consolidated monthly global gravity models in terms of spherical harmonic (SH) coefficients and global grids by combining existing solutions or normal equations from COST-G analysis centers (ACs) and partner analysis centers (PCs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from GRACE/GRACE-FO low-low satellite-to-satellite tracking (ll-SST), high-low satellite-to-satellite tracking (hl-SST), Satellite Laser Ranging (SLR).
COST-G performs a quality control of the individual contributions before combination and provides:

i) Combined gravity field solutions in SH coefficients (Level-2 products) derived from a weighted combination of individual normal equations (NEQs) supplied by the different ACs,
ii) Spatial grids and other high-level products (Level-3 products) of the Combined Solutions for hydrological, oceanic and polar ice sheets applications.

The Level-2 products are made available through the International Center for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de), the Level-3 products by the Information System and Data Center (ISDC, https://isdc.gfz-potsdam.de). The Level-3 products can be visualized at the COST-G Plotter (https://cost-g.org) and the Gravity Information Service (GravIS, http://gravis.gfz-potsdam.de) at GFZ Potsdam.
The initial Analysis Centers (AC), in charge of computing time-variable gravity field solutions from GRACE and GRACE-FO are: the Astronomical Institute at University of Bern (AIUB); the Centre National d’Etudes Spatiales (CNES); the German Research Centre for Geosciences (GFZ); the Institute of Geodesy, Graz University of Technology (IFG).

The current Partner Analysis Centers (PAC) are the Center for Space Research (CSR), and NASA's Jet Propulsion Laboratory (JPL).
Just recently, the Institut für Erdmessung of the Leibniz University of Hannover was selected to become also an AC and discussions with various Chinese processing centers such as IGG, SUSTech, Tongji, HUST or Whuhan to be become COST-G ACs are ongoing.

International Centre for Global Earth Models (ICGEM)

http://icgem.gfz-potsdam.de/home

Director: E. Sinem Ince (Germany)

Overview

International Centre for Global Earth Models (ICGEM) is one of the five services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG) and is a part of Global Geodetic Observing System (GGOS). The primary objective of the ICGEM service is to collect and archive all existing static and temporal global gravity field models and provide an online interactive calculation service for the computation of gravity field functionals freely available to the general public. The ICGEM Service has been hosted and funded by the GFZ-Potsdam German Research Centre for Geosciences and is supported by model developers and service users at an international level.

During 2019 to 2021, the ICGEM service continued to support scientific activities with additional features and Level 2 research data made publicly available. New satellite-only and combined static global gravity field models and operational temporal gravity field models have been the highlights of the last two years. Previously reported COST-G (https://cost-g.org, Jaeggi et al. 2020) operational GRACE-FO series are now available in the temporal gravity field models page (http://icgem.gfz-potsdam.de/series/02_COST-G/Grace-FO) and made publicly available with a DOI number assigned by the GFZ Library and Information Services (LIS). Other models published are: new release of satellite-only models from ESA's GOCE mission, new release of satellite-only mean global gravity field model from CNES, combined static gravity field models expanded up to very high degree/order (5440) from Technical University of Munich, monthly solutions from ESA's Swarm mission, GRACE-FO operational monthly series and GAX products, and finally topographic gravity field models of the Moon.

During the reporting period, we received Release 06 GRACE-FO models from the three Science Data System centers and **operational** monthly solutions from other groups and COST-G. The growing interest in models for other celestial bodies has also increased the number of the models submitted to ICGEM in 2019-2020. Similar to the previous ones, all recently submitted models are provided in the standardised format (Barthelmes and Förste, 2011) and in the form of spherical harmonic coefficients with possible DOI number assignment via GFZ Library and Information Services (Ince et al. 2019). At the moment, **177** static gravity field models, **22** different kinds of temporal gravity field models from GRACE, GRACE-FO, Swarm and SLR measurements, and **10** topographic gravity field models are made available in the ICGEM service. The models are developed by different institutions and agencies and ICGEM keeps track of the references by the support of model developers and GFZ Library and Information Services.

In this documentation, the developments and activities during 2019-2021 have been summarised. For more information on the ICGEM Terms of References and Services, please refer to our previous IAG reports, our paper published in the Earth System Science Data (Ince et al. 2019, https://www.earth-syst-sci-data.net/11/647/2019) and the Geodesist's Handbook 2020: Poutanen M, Rózsa S (2020): The Geodesist's Handbook 2020. J Geod 94, 109, https://doi.org/10.1007/s00190-020-01434-z.

Activities during the period of 2019-2021

1. Models

In 2016, the ICGEM Service was renewed from technical, administration and presentation perspectives. Via this renewed platform, development of a new flexible service for future applications will be possible also applicable for the GRACE-FO mission. Following the launch of GRACE-FO and collection of new data, new products provided by the model developers have been made available under the temporal gravity field models page.

The static models (http://icgem.gfz-potsdam.de/tom_longtime), temporal models (http://icgem.gfz-potsdam.de/series) as well topographic gravity field models (http://icgem.gfz-potsdam.de/tom_reltopo) can be found under Gravity Field Models. For the static gravity field models, users can access any reference related to the model that was provided to ICGEM on the same page in column 6 and can access the links to download the model coefficients in column 7, calculate the gravity functionals in column 8 and also visualise the geoid and gravity anomalies using the link provided in column 9 corresponding to the model. For the temporal models that are assigned DOI numbers, references and citation information can be found in the header part of the page. Relevant links to the model developer institution's page are indicated when available.

Newly available models since the last reporting period are the following:

Static Gravity Field Models (http://icgem.gfz-potsdam.de/tom_longtime):

- SGG-UGM-2 (d/o* 2190): Developed based on Altimetry, EGM2008, GRACE and GOCE data (Liang, W. et al. 2020)
- XGM2019e_2159 (d/o 5540, 2190, 760): Developed based on Altimetry, satellite-only combined model GOCO06s, ground measurements and topography information.
  Please note that to comply with the ICGEM standards, the model coefficients are provided by the model developers in the spherical harmonic domain. To simplify the utilization of the model, coefficients are precalculated in three different spectral resolution scales (in the spheroidal harmonic domain, then converted back to spherical harmonics, thus, avoiding truncation errors near the spheroidal surface (Zingerle et al. 2019).
- GO_CONS_GCF_2_TIM_R6e (d/o 300): Developed based on GOCE-only and ground measurements in the polar areas (Zingerle et al. 2019).
- ITSG-Grace2018s (d/o 200): Developed based on GRACE measurements only (Mayer-Gürr, T. et al. 2018).
- EIGEN-GRGS.RL04.MEAN-FIELD (d/o 300): Developed based on satellite-only data (Lemoine J.M. et al. 2019).
- GOCO06s (d/o 300): Developed based on satellite-only data (Kvas, A. et al. 2021).
- GO_CONS_GCF_2_TIM_R6 (d/o 300): Developed based on GOCE only data (Brockmann JM et al. 2021.
- GO_CONS_GCF_2_DIR_R6 (d/o 300): Developed based on satellite-only data (Förste et al. 2019).

*(d/o refers to degree and order).

Temporal Gravity Field Models:

- Monthly GRACE-FO solutions from the 3 Science Data System (SDS) centers CSR (60x60, 96x96), GFZ (60x60, 96x96), and JPL (60x60, 96x96) are operational and updated monthly on the following links:
  http://icgem.gfz-potsdam.de/series/01_GRACE/CSR/CSR Release 06 (GFO)
  http://icgem.gfz-potsdam.de/series/01_GRACE/GFZ/GFZ Release 06 (GFO)
  http://icgem.gfz-potsdam.de/series/01_GRACE/JPL/JPL Release 06 (GFO)
- Relevant GAX products are made available on the same pages
- Monthly GRACE-FO series (60x60, 96x96, 120x120) developed at the Institute of Theoretical Geodesy and Satellite Geodesy, TU GRAZ (Technical University of Graz) are operational and updated monthly on http://icgem.gfz-potsdam.de/series/03_GRACE_other/ITSG/ITSG-Grace_op
- Monthly reprocessed GRACE series (60x60, 96x96, 120x120) from TU GRAZ are made available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/ITSG/ITSG-Grace2018/monthly
- Monthly GRACE-FO series developed at LUH (Leibniz University Hannover) are operational and updated monthly on http://icgem.gfz-potsdam.de/series/03_GRACE_other/LUH/LUH-GRACE-FO-2020
- Monthly GRACE series developed at LUH are made available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/LUH/LUH-Grace2018
- COST-G (International Combination Service for Time-variable Gravity Field
  - Combined solutions and GAX products for GRACE are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Grace
  - Combined solutions for GRACE-FO operational series are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Grace-FO
  - Swarm monthly solutions and GAX products are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Swarm
- Monthly operational series developed at AIUB (Astronomical Institute of University Bern) are available on: http://icgem.gfz-potsdam.de/series/03_GRACE_other/AIUB/AIUB-GRACE-FO_op
- Hybrid models (6 different versions) developed in the Institute of Geodesy and Geoinformation, University Bonn based on SLR data are available on http://icgem.gfz-potsdam.de/series/04_SLR/IGG_SLR_HYBRID
- Monthly series (60x60, 90x90) developed at the Institute of Geophysics, HUST (Huazhong University of Science and Technology) are available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/HUST/HUST-Grace2020
- Monthly series of combined HLSST and SLR solutions developed at Quantum Frontiers are available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/QuantumFrontiers/HLSST_SLR_COMB2019s
- Monthly series developed at Tongji University are available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/Tongji/Tongji-Grace2018
- Monthly series developed at CNES based on GRACE and SLR data are available on http://icgem.gfz-potsdam.de/series/03_GRACE_other/CNES/CNES_GRGS_RL04

*References can be found under the links.

Topographic Gravity Field Models (http://icgem.gfz-potsdam.de/tom_reltopo)

- ROLI_EllApprox_SphN_3660 (ROLI_EllApprox_SphN_3660_plusGRS80): The models is developed at Department 1: Geodesy, GFZ-Potsdam based on Earth2014 is available on http://icgem.gfz-potsdam.de/tom_reltopo (Abrykosov O. et al. 2019).

Other Celestial Bodies (http://icgem.gfz-potsdam.de/tom_celestial)

- AIUB-GRL350A and AIUB-GRL360B (d/o 350): Gravity field models of the Moon derived from GRAIL measurements are available (Bertone S. et al. 2021)
- densityMoon (d/o 89): Moon density model derived from GRAIL measurements (Sprlak M. et al 2020)
- STU_MoonTopo720 (STU_MoonTopo720_plusNormalField) (d/o 2160): Moon gravity field model developed based on the Runge-Krarup theorem (Bucha B. et al 2019)
- sphericalRFM_MOON_2519 (SphericalRFM_MOON_2519_plusNormalField) (d/o 2519): Forward modelled gravity field model of the Moon (Sprlak M. et al. 2020)
- sphericalRFM_CERES_2519 (d/o 2519): Forward modelled gravity field model of Ceres (Sprlak M. et al. 2020)

Statistics of the ICGEM visits in 2019-2021, papers per year citing the recently published ICGEM paper (https://essd.copernicus.org/articles/11/647/2019/) in May 2019 as the main reference of the service and its activities, and model downloads for 2020 are presented in Figures 1 to 5. Figure 1 shows the total ICGEM visits during the last 2,5 years, whereas Figure 2 represents the research papers per year citing 67 in total. ICGEM has been continuously active and used for model download and calculation and visualisation services during the reporting period.

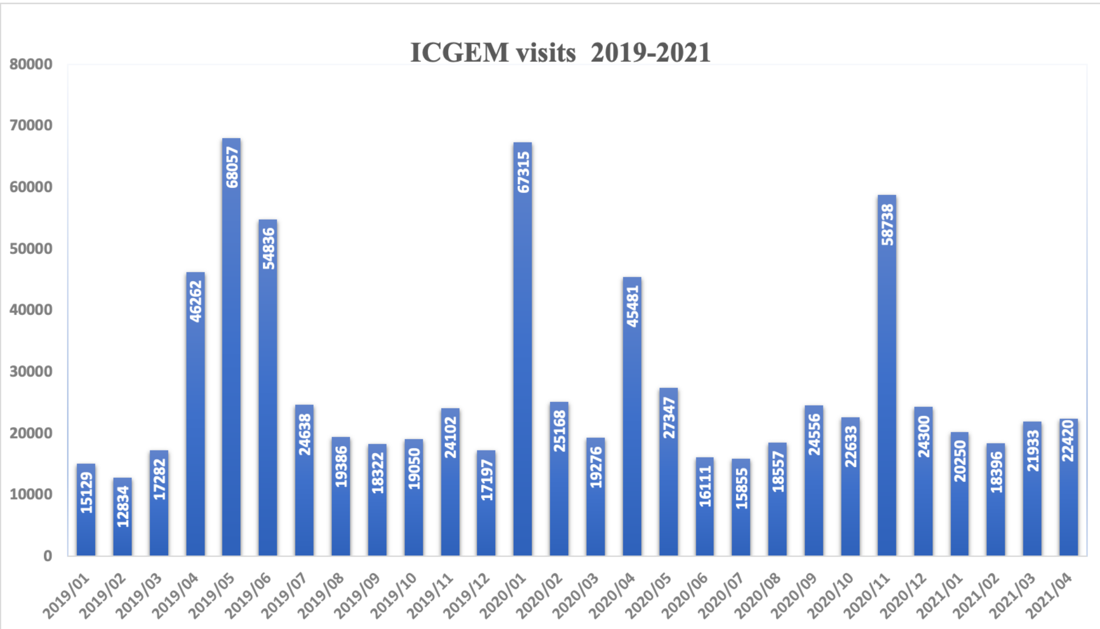


Fig. 1: Statistics of ICGEM visits in 2019-2021

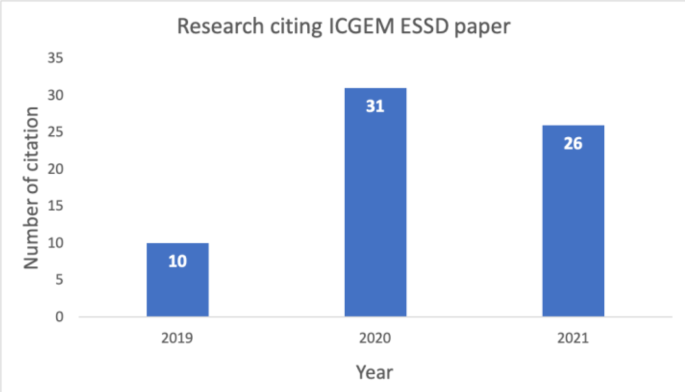


Fig. 2: Research citing ICGEM (Source: Googlescholar)

Figure 3 shows the list of downloaded static gravity field models and number of downloads. It shows that the topographic models are now also downloaded with increasing rate. Moreover, high degree order combined static gravity field models are the most downloaded models for geodetic and geophysical research.

Figure 4 shows the downloads of temporal gravity field models generated by different institutions. There are indications that the users prefer to test and use different models in different applications. One needs to note that COST-G is a recent product centre of IAG, and its products are available since 2019. Finally, Figure 5 shows that the ICGEM is particularly important in collecting temporal gravity field models developed by different institutions and agencies in addition to the three 3SDS. The users can download 3SDS models from different platforms (e.g. ISDC, GravIS) but the models from other groups are collected uniquely in the ICGEM. ICGEM provides access to Level 2 temporal gravity field models. Users who are interested in Level 3 products can refer to other services such as GravIS (http://icgem.gfz-potsdam.de/tom_reltopo) and the COST-G plotter (http://plot.cost-g.org/index.php?p=timeseries).

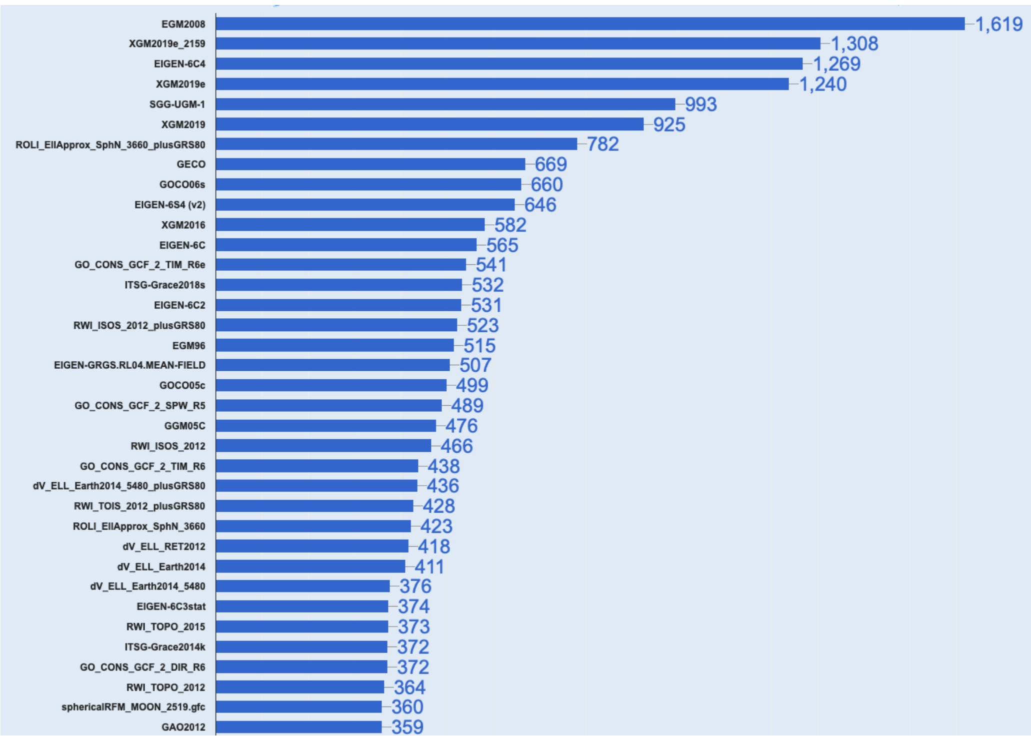


Fig 3: Download of static and topographic gravity field models in 2020. The total number is 68294.

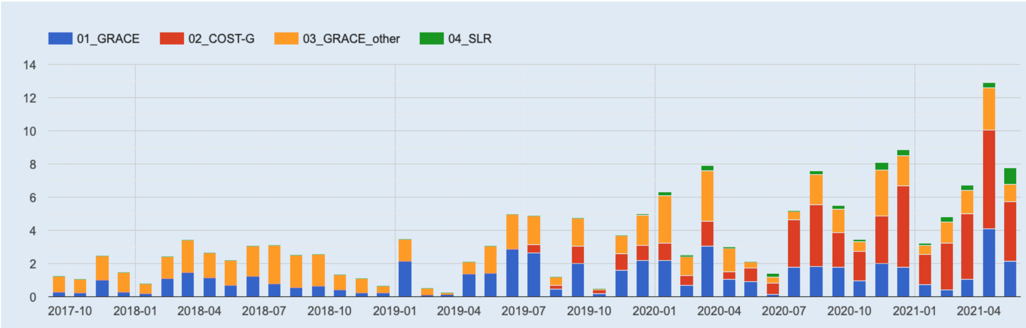


Fig 4: Downloads of temporal gravity field models in 2017-2020. Note that COST-G started its activities in 2019. The stats show the complete download of series.

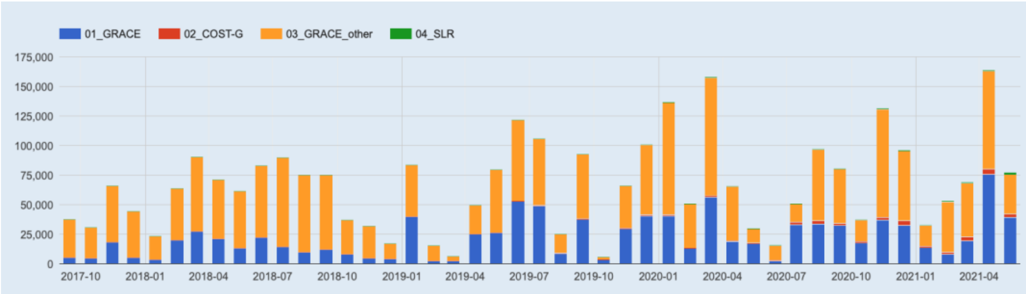


Fig 5. Downloads of temporal gravity field models in 2017-2020. Note that COST-G started its activities in 2019. The stats show the download of singles files.

2. Calculation Service

Beside collecting and archiving Level 2 gravity field models, ICGEM provides gravity field functionals computed based on these models. Such functionals can be considered as Level 3 products that are indispensable for many Earth science related research. ICGEM offers both gridded and user defined point calculations. Figure 5 shows the distribution of the most frequently calculated gravity field functionals in the Grid calculation service in 2020. Geoid, gravity anomaly, height anomaly, Bouguer gravity anomaly and gravity disturbance are the most frequently calculated functionals. ICGEM plans to provide readily computed high resolution grids of these gravity field functionals.

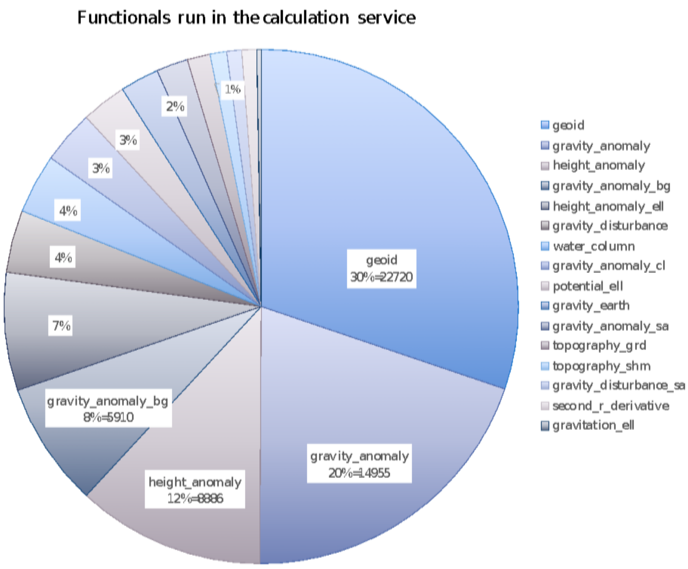


Fig 5: Gravity field functionals calculated in the grid calculation in 2020.

3. Evaluation

Our evaluations for the static gravity field models are in both spectral domain and w.r.t. GNSS/levelling derived geoid undulations. Spectral comparisons of the models with respect to one of the latest combined models, EIGEN-6C4 can be found under “Spectral domain” (http://icgem.gfz-potsdam.de/evalm). The GNSS/levelling derived geoid undulation comparisons w.r.t. 7 different datasets for different countries and continents (USA, Canada, Europe, Australia, Japan, Brazil and Mexico) are provided in “GNNS/Levelling” (http://icgem.gfz-potsdam.de/tom_gpslev). The columns can be re-ordered by clicking on the title of the column.

In 2021, the comparison of geoid/quasi-geoid heights derived from the models with GNS/Levelling derived values from Australia, Brazil, and Canada has been updated and GNSS/Levelling comparisons w.r.t. Mexican benchmarks have been added in the table representation (http://icgem.gfz-potsdam.de/tom_gpslev). The USA data will be updated after quality check analysis before the end of the year. The references for the GNSS/Levelling data used in the ICGEM Static gravity field model evaluation are as follows:

- USA; Milbert, 1998
- Canada; Marc Veronneau, Canadian Geodetic Survey, Natural Resources Canada, 2019
- Europe; Ihde et al., 2002
- Australia; W. E. Featherstone, N. J. Brown, J. C. McCubbine & M. S. Filmer (2018): Description and release of Australian gravity field model testing data, Australian Journal of Earth Sciences, DOI: 10.1080/08120099.2018.1412353
- Japan; Tokuro Kodama, Geospatial Information Authority of Japan
- Brazil; Roberto Teixeira Luz and Sonia Costa, Brazilian Geography and Statistics Institute (IBGE), 2019
- Mexico; National Institute of Statistics and Geography (INEGI), 2019

We acknowledge the contribution of these institutions to the scientific evaluation of the static global gravity field models and we welcome similar datasets from all interested colleagues.

4. DOI Service

DOI Service was developed as a request by the user community in cooperation with GFZ Data Services. To reduce the heterogeneity in data documentation for static global gravity field models, standardised metadata templates for describing the models were developed. At the moment, all models with assigned DOIs are published under the Creative Commons Attribution 4.0 International Licence (CC BY 4.0). Since its implementation in late 2015, we have assigned DOIs to 24 static and 12 temporal global gravity field models, mostly at the time of their first publication via ICGEM.

5. Documentation

The documentation section of the ICGEM Service brings five subsections together to support the scientific community and user interaction. These five subsections are: Frequently asked questions, theory, references, latest changes, and a discussion forum with regular updates. Moreover, ICGEM also provides documentation of the models. New model releases, new documentation, conference and symposium presentations and ICGEM’s recent activities can be found in the ICGEM Home page and in the list of latest changes. for the convenience of the users, all relevant sources are listed in the references. This will ensure that the service and its components are available at the same place.

6. User e-mail list

ICGEM user e-mail list has been active since July 2019 and has more than 60 subscribers. The User mailing list is indented to be used to update the community with the new products and changes and stimulate communication especially with early career scientists and users from diverse backgrounds. Users are welcome to send their questions and updates to the e-mail list at icgemusers@gfz-potsdam.de. We hope this platform will support the gravity field community and use of gravity field products and make each people feel more involved especially when it is not possible to meet in person. Please feel free to send your gravity related questions, comments, ideas to this e-mail list icgemusers@gfz-potsdam.de or to us directly icgem@gfz-potsdam.de. Please spread the word to graduate students and encourage them to sign up for the mailing list.

7. Scientific events and presentation

ICGEM is a member of:

- Global Geodetic Observing System (GGOS),
- Member of GGOS DOI Working group with regular attendance to monthly meetings,
- Member of COST-G Directing Board and member of Essential Geodetic Variables.

Other scientific activities in 2019-2021 are as follows:

Elger K, Angermann D, Bock Y, Bonvalot S, Botha R, Bradke M, Bradshaw E, Bruyninx C, Carrion D, Coetzer G, Elger K, Fridez P, Ince ES, Lamothe P, Navarro V, Noll C, Reguzzoni M, Riley J, Roman D, Soudarin L, Thaller D, Yokota Y, Members A, Amponsah, G, Blevins S, Craddock A, Craymer M, Michael P, Miyahara B, Pearlman M, Romero N, Schwatke C, Sehnal M, Tyahla L (**2021**): News from the GGOS DOI Working Group - Abstracts, EGU General Assembly 2021 (Online 2021). https://doi.org/10.5194/egusphere-egu21-15081

Ince ES, Reißland S, Barthelmes F (**2020**): Sirgas Americas Symposium 2020, Gravimetry and Geoid, https://www.youtube.com/watch?v=VUeQvaHW1AY, invited talk.

Förste C, Ince ES, Reißland S, Elger K, Flechtner F, Barthelmes F (**2020**): The International Centre for Global Earth Models (ICGEM) - Abstracts, EGU General Assembly 2020 (Online 2020). https://doi.org/10.5194/egusphere-egu2020-3511

Ince ES, Reißland S, Barthelmes F and Elger K (**2019**): ICGEM- International Centre for Global Earth Models, Implemenation of the Global Geodetic Reference Frame (GGRF), Sep 16-19, 2019, invited talk

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F (**2019**): ICGEM – 15 years of Successful collection and Distribution of Gravity Field Models, Association Services and Future Plans, IUGG General Assembly, Montreal, Canada, July 8-18

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F (**2019**): New Features and Future Plans of the International Centre for Global Earth Models (ICGEM), (Geophysical Research Abstracts, Vol. 21, EGU2019-15513), General Assembly European Geosciences Union (Vienna 2019).

Data Policy

Access to global gravity field models, derived products and tutorials, once offered by the centre, is unrestricted for any external user.

ICGEM Team: The staff is allocated part-time and responds to queries on a best-effort basis.

Elmas Sinem Ince
Sven Reißland

Point of Contact

ICGEM-Team
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
Telegrafenberg, D-14473 Potsdam, Germany
E-mail: icgem@gfz-potsdam.de,

References

Barthelmes F (2013): Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM). Scientific Technical Report STR09/02, Revised Edition, January 2013. Deutsches GeoForschungZentrum GFZ, http://doi.org/10.2312/GFZ.b103-0902-26.

Barthelmes F, Förste C (2019): The ICGEM-format. Potsdam: GFZ German Research Centre for Geosciences, URL: http://icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf, last access 30 January.

Barthelmes F, Koehler W (2012): International Centre for Global Earth Models (ICGEM). In: Dreves: The Geodesists Handbook 2012, Journal of Geodesy, 86(10): 932-934, https://doi.org/10.1007/s00190-012-0584-1.

Barthelmes F, Ince ES, Reissland S (2017): International Centre for Global Earth Models, International Association of Geodesy, Travaux, Volume 40, Reports 2015-2017, https://iag.dgfi.tum.de/fileadmin/IAG-docs/Travaux_2015-2017.pdf,. 2017, last access 30 January.

Bertone S, Arnold D, Girardin V, Lasser M, Meyer U, Jäggi A (2021): Assessing Reduced-Dynamic Parametrizations for GRAIL Orbit Determination and the Recovery of Independent Lunar Gravity Field Solutions. Earth and Space Science. doi: 10.1029/2020EA001454.

Brockmann JM, Schubert T, Schuh WD (2021): An Improved Model of the Earth's Static Gravity Field Solely Derived from Reprocessed GOCE Data Surveys in Geophysics, doi: 10.1007/s10712-020-09626-0.

Bucha B, Hirt C, Kuhn M (2019): Divergence-free spherical harmonic gravity field modelling based on the Runge-Krarup theorem: a case study for the Moon. Journal of Geodesy 93, 489-513, https://doi.org/10.1007/s00190-018-1177-4.

Förste C, Abrykosov O, Bruinsma S, Dahle C, König R, Lemoine JM (2019): ESA's Release 6 GOCE gravity field model by means of the direct approach based on improved filtering of the reprocessed gradients of the entire mission (GO_CONS_GCF_2_DIR_R6). GFZ Data Services. https://doi.org/10.5880/ICGEM.2019.004

Ince ES., Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F, Schuh H (2019): ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services, and future plans, Earth Syst. Sci. Data, 11, 647-674, https://doi.org/10.5194/essd-11-647-2019.

Jäggi A. et al. (2020) International Combination Service for Time-Variable Gravity Fields (COST-G). In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, https://link.springer.com/chapter/10.1007%2F1345_2020_109.

Kvas A, Brockmann, JM, Krauss S, Schubert T, Gruber T, Meyer U, Mayer-Gürr T, Schuh WD, Jäggi A, Pail R. (2021): GOCO06s - a satellite-only global gravity field model, Earth System Science Data, 13(1), 99–118. https://doi.org/10.5194/essd-13-99-2021.

Lemoine JM, Bourgogne S, Biancale R (†), Reinquin F and Bruinsma S (2019): EIGEN-GRGS.RL04.MEAN-FIELD – Mean Earth gravity field model with a time-variable part from CNES/GRGS RL04.

Liang W, Li J, Xu X, Zhang S, Zhao Y (2020): A High-Resolution Earth's Gravity Field Model SGG-UGM-2 from GOCE, GRACE, Satellite Altimetry, and EGM2008. Engineering, 860-878, doi: 10.1016/j.eng.2020.05.008.

Mayer-Gürr T, Behzadpur S, Ellmer M, Kvas A, Klinger B, Strasser S, Zehentner N, ITSG-Grace2018 - Monthly, Daily and Static Gravity Field Solutions from GRACE. GFZ Data Services, doi: 10.5880/ICGEM.2018.003.

Sprlak M, Han S-C, Featherstone W (2020): Spheroidal Forward Modelling of the Gravitational Fields of 1 Ceres and the Moon. Icarus 335, doi: https://doi.org/10.1016/j.icarus.2019.113412.

Sprlak M, Han S-C, Featherstone W (2020): Crustal Density and Global Gravitational Field Estimation of the Moon from GRAIL and LOLA Satellite Data, Planetary and Space Science, 192, 105032, doi: https://doi.org/10.1016/j.pss.2020.105032.

Zingerle P, Brockmann JM, Pail R, Gruber T, Willberg M (2019): The polar extended gravity field model TIM_R6, doi: 10.5880/ICGEM.2019.005 2019.

Zingerle P, Pail R, Gruber T. et al. (2020): The combined global gravity field model XGM2019e.J Geod 94, 66, https://doi.org/10.1007/s00190-020-01398-0.

International Digital Elevation Model Service (IDEMS)

https://idems.maps.arcgis.com/home/index.html

Director, **Mr Kevin M. Kelly** (USA)

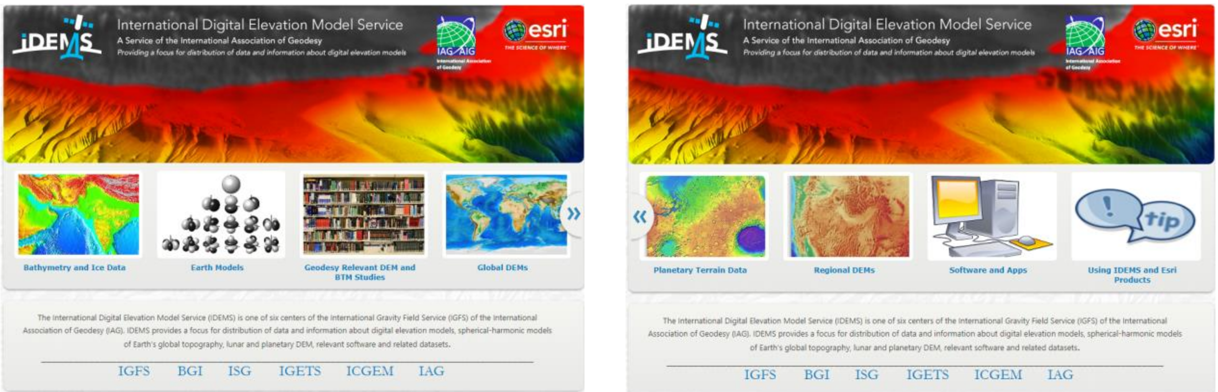
Structure

The Governing Board (GB) of IDEMS consists of five members who oversee the operation and general activities of the service. The GB is structured as follows:

Director of IDEMS:	Mr Kevin M Kelly
Deputy Director of IDEMS:	Dr Fei Wang
IAG/IGFS representative:	Dr Riccardo Barzhagi
Advisory member:	Dr Christian Hirt
Advisory member:	Dr Michael Kuhn

Overview

IDEMS is a service of IAG operated by Environmental Systems Research Institute (Esri) (http://www.esri.com/). The service became operational in 2016. The IDEMS website was developed and is maintained by Mr Kevin M. Kelly of Esri, and scientific content provided by Dr Christian Hirt of TU Munich. IDEMS provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth’s global topography, lunar and planetary DEM, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain.



Screenshot of home page of IDEMS showing DEM and related content categories.

IDEMS Products

IDEMS currently hosts 33 sources of terrestrial and planetary DEM data providers (see Table 1) and 126 references of DEM and bathymetry research papers relevant to geodesy and Earth sciences. The IDEMS bibliography is updated regularly (currently two times per year) to provide the user community with an up-to-date overview over key developments in DEM production, validation and applications. The IDEMS bibliography includes recent and seminal papers describing relevant data sets of Earth's topography, bathymetry, ice data and composite elevation models. Some DEM sources appear in multiple categories to facilitate source discovery for the researcher. IDEMS serves as a repository of links to DEM data providers rather than a DEM data storage facility. The site also provides access to Esri's free ***ArcGIS Earth*** (https://www.esri.com/en-us/arcgis/products/arcgis-earth/overview) which is fully integrated with the ArcGIS platform for accessing, sharing, and publishing maps and data.

The IDEMS website is continually updated with new terrestrial and planetary DEM datasets and related Earth models as they become available. Table 1 lists the current content available through the IDEMS website.

Table 1. DEM and Related Data Sources Hosted on IDEMS

Bathymetry and Ice Data (14)	Antarctica CryoSat-2 DEM
	Bedmap2
	BOEM Northern Gulf of Mexico Bathymetry
	Elevation Coverage Map (Esri)
	Flight MH370 Bathymetry
	Global Bathymetry BTM (Esri)
	Global Water Body Map (G3WBM)
	Ice, Cloud, and Land Elevation (ICESat / GLAS Data)
	MH370 Bathymetry
	Polar Geospatial Center
	Randolph Glacier Inventory (RGI 6.0)
	SRTM30_PLUS (30 arc-sec grid), 2014
	SRTM15 V2.0
	Svalbard time-lapse terrain data
Global DEMs (15)	ALOS/PRISM AW3D30
	ASTER GDEM v2
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	ETOPO1 (60 arc-sec grid), 2009
	Global Terrain DEM (Esri)
	Global Water Body Map (G3WBM)
	MERIT DEM (SRTM-based Bare-Earth model), 2017
	NASADEM (reprocessed SRTM model), 2017
	SRTM v3 (NASA)
	SRTM v4.1 (CGIAR-CSI)
	SRTM15 V2.0
	SRTM30_PLUS (30 arc-sec grid), 2014
	TanDEM-X DEM
	Viewfinder Panorama DEMs (2014)
Regional DEMs (7)	Antarctica CryoSat-2 DEM
	Arctic DEM Explorer
	OpenTopography
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	Polar Geospatial Center
	Svalbard Time-Lapse Terrain Model
Planetary Terrain Data (3)	NASA Planetary Data System (PDS) Geosciences Node
	Planetary topography data archive
	USGS Astrogeology Science Center
Earth Models (5)	Earth2014 (60 arc-sec), 2014
	ICE-6G GIA Model
	Preliminary Reference Earth Model (PREM)
	Topographic Earth Models (LMU Munich)
	SRTM2gravity(2018)

IDEMS Website Usage

Table 2 below shows IDEMS activity from 2016 to 2021. Over the past five years the site has received reasonably good use for the small community it serves. Among the 11 most popular IDEMS content, these items collectively received a total of 14,950 views. This represents an additional 8,517 views over the 2016-2019 period, an increase of 232%.

Table 2. IDEMS activity by number of views of most popular content.

Data Type	**No. of item views**
ALOS/PRISM AW3D30	
Antarctica CryoSat-2 DEM	
ArcGIS Earth (Esri)	
Arctic DEM Explorer	
ASTER GDEM v2	247
BedMap2	
BOEM Northern Gulf of Mexico Bathymetry	
DEM and BTM Research Papers	186
Earth2014 (60 arcsec), 2014	221
Elevation Coverage Map (Esri)	1,043
Esri Elevation Layers	
ETOPO1 (60 arc-sec grid), 2009	
Getting Started with IDEMS	73
Global bathymetry (Esri)	1,240
Global Geospatial Data from Earth Observation (2016)	
Global Terrain DEM (Esri)	11,306
Global Water Body Map (G3WBM)	
IAU Cartographic Coordinates and Rotational Elements (WGCCRE)	
Ice, Cloud, and Land Elevation (ICESat / GLAS Data)	
ICE-6G GIA Model	
MERIT DEM (SRTM-based Bare-Earth model), 2017	
MH370 Bathymetry	
NASA Planetary Data System (PDS) Geosciences Node	
NASADEM (reprocessed SRTM model), 2017	
OpenTopography	
Planetary topography data archive	
Polar Geospatial Center	
Preliminary Reference Earth Model (PREM)	143
Randolph Glacier Inventory (RGI 6.0)	
SRTM v3 (NASA)	198
SRTM v4.1 (CGIAR-CSI)	144
SRTM30_PLUS (30 arc-sec grid), 2014	
Svalbard Time-Lapse Terrain Model	
TanDEM-X DEM	149
Topographic Earth Models	
USGS Astrogeology Science Center	
Total	**14,950**

IDEMS Research Activities

Although work has not commenced as of this writing, IDEMS will participate in JSG T.37: *Theory and methods related to the combination of high-resolution topographic/bathymetric models in geodesy*, which aims at studying the available topographic and bathymetric models and at exploring their limitations, in particular concerning the transition along the coasts.

International Geodynamics and Earth Tide Service (IGETS)

http://igets.u-strasbg.fr/

Chair of the Directing Board: Hartmut Wziontek (Germany)
Director of the Central Bureau: Jean-Paul Boy (France)

Structure

- Directing Board: H. Wziontek, J.-P. Boy, V. Palinkas, J.-P. Barriot, C. Förste, H.-P. Sun, C. Voigt, D. Crossley, J. Hinderer, B. Meurers, S. Pagiatakis, S. Bonvalot, N. Sneeuw
- Central Bureau: J.-P. Boy
- Data Center: C. Förste, C. Voigt

Overview

The primary objective of the International Geodynamics and Earth Tide Service (IGETS) is to provide a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS continues the activities of the Global Geodynamic Project since it was established at the IUGG general assembly in Prague 2015.

Status of the IGETS Data Center

The IGETS data sets are stored on an FTP server and are freely available after user registration. The number of IGETS users is still increasing steadily since the launch in summer 2016 (see Fig. 1). The new data base server is hosted by GFZ Potsdam (Germany) and is accessible via http://igets.gfz-potsdam.de.
Currently data from 44 stations and 63 sensors are available, globally distributed, provided by 30 producers covering a time span of up to 30 years. New stations were included since 2019: Helgoland, Zugspitze (Germany) and Rochefort (Belgium). Records from superconducting gravimeters made by GWR of compact (CT) and observatory (OSG) type are predominant, while the number of GWR iGrav transportable superconducting gravimeter data has grown at most.

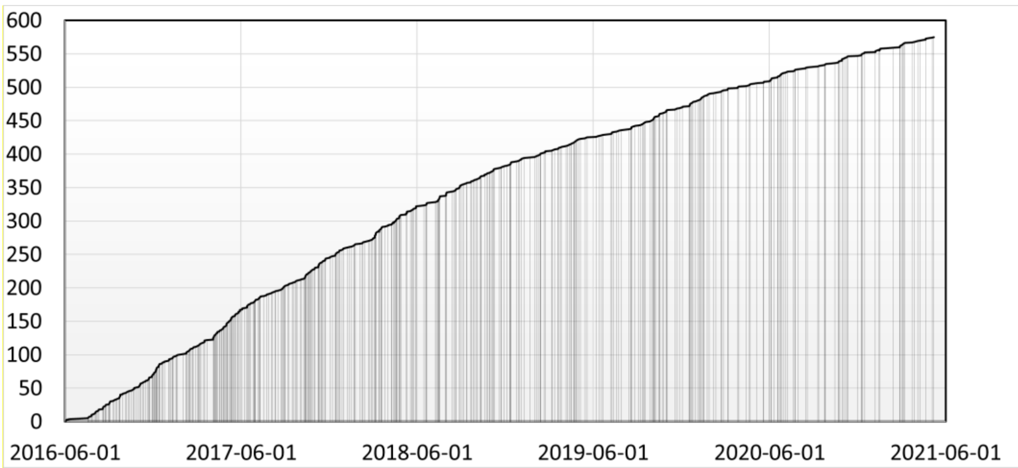


Fig. 1: Number of IGETS data base users since the launch in summer 2016.

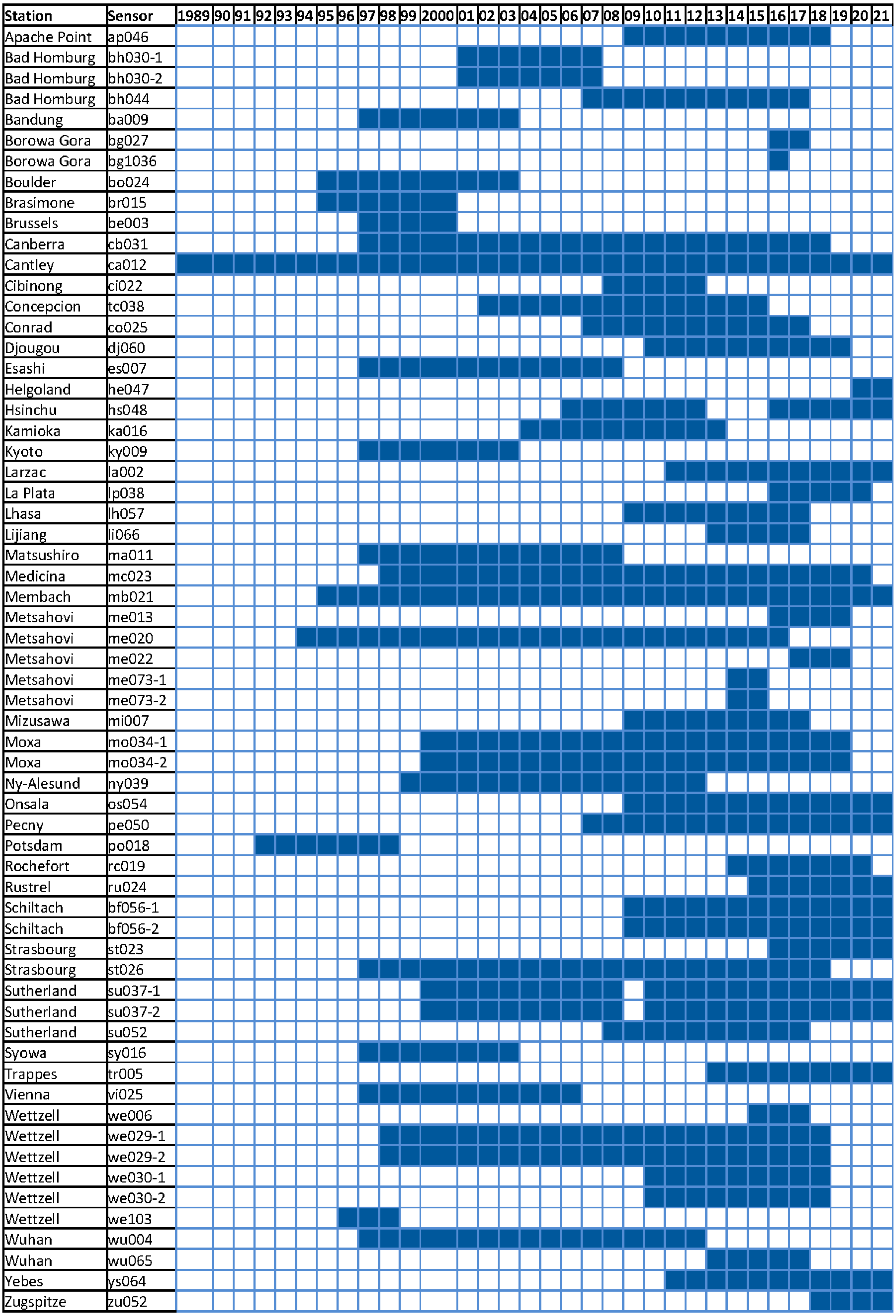


Fig. 1: Time span of the data coverage of the IGETS data base until 2021.

All relevant information on the IGETS data base were compiled in the scientific technical report Voigt et.al. (2016), comprising station and sensor information, available data sets, directory structure, file name convention, repair codes and file formats. Data descriptions originating to a large part from Global Geodynamics Project (GGP) were updated and extended for IGETS.

Status of the Analysis Centers

Different product levels are derived from the gravity and atmospheric pressure data recorded with the superconducting gravimeters. Products of Level-1 are the raw data without pre-processing which are down-sampled to 1 min. resolution but also provided at the original resolution of 1 sec. for 17 stations (for a total of 22 different time series). The pre-processing of these data, i.e. elimination of gaps, spikes, steps and disturbance is continued as a Level-2 product.

Two IGETS Analysis Centers, at the University of French Polynesia (Tahiti) and at the University of Strasbourg/ EOST (Strasbourg, France) provide different products. While the first is in charge of processing Level-2 data from the raw Level-1 data, i.e. gravity and pressure data corrected for all major disturbances, the second center is mainly in charge of producing the Level-3 data, i.e. gravity residuals after correction of all major geophysical signals, but also produces alternate Level-2 data.

The Level-2 data, i.e. gravity and pressure, are corrected for major instrumental disturbance using a remove/restore technique based on a local tide model.

The Level-3 data, i.e. gravity residuals sampled at 1 minute, are derived from the Level-2 data produced by EOST, by subtracting solid Earth tides, tidal ocean loading using FES2014 (Lyard et al., 2021), Polar Motion and Length-Of-Day induced effects, including a static ocean response, atmospheric loading based on MERRA2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) reanalysis (Gelaro et al., 2017) assuming an inverted barometer ocean response to pressure forcing and an instrumental drift. Loading models are also available on the EOST Loading Service (Boy and Lyard, 2008; Boy and Hinderer, 2006; http://loading.u-strasbg.fr/).

Table 1 provides all the data (Level-1, various Level-2 and Level-3) available at the IGETS datacenter.

		Level-1			Level-2 (station)			Level-2 (UPF)			Level-2 (EOST)			Level-3 (EOST)		
		nb month	start	end	nb month	start	end	nb month	start	end	nb month	start	end	nb month	start	end
Apache-Point	ap046	116	200902	201809	102	200904	201809	101	200904	201808	94	201001	201809	94	201001	201809
Bad-Homburg	bh030-1	75	200102	200704	64	200201	200704	75	200102	200704	75	200102	200704	75	200102	200704
Bad-Homburg	bh030-2	75	200102	200704				75	200102	200704	75	200102	200704	75	200102	200704
Bad-Homburg	bh044	122	200702	201703	113	200702	201606	122	200702	201703	122	200702	201703	122	200702	201703
Bandung	ba009	67	199712	200306				16	199712	200001						
Borowa-Gora	bg027				10	201606	201702	39	200002	200306						
Boulder	bo024	103	199504	200310				82	199701	200310						
Brasimone	br015	46	199512	200001				46	199512	200001						
Brussels	be003	39	199707	200009												
Canberra	cb031	257	199707	201812				248	199804	201812	257	199707	201812	258	199707	201812
Cantley	ca012	321	198911	202104				227	199707	201701	264	199707	202103	265	199707	202102
Cibinong	ci022	33	200811	201205				33	200811	201205	32	200812	201205	32	200812	201205
Concepcion	tc038	132	200212	201504				131	200212	201504	149	200212	201504	149	200212	201504
Conrad	co025	98	200711	201703				98	200711	201703	113	200711	201703	113	200711	201703
Djougou	dj060	103	201007	201901				99	201007	201810	101	201007	201811	101	201007	201811
Esashi	es007	138	199707	200812				117	199707	200703						
Helgoland	he047	14	202003	202104												
Hsinchu	hs048	82	200604	202009				33	200604	200812						
Kamioka	ka016	106	200410	201307				106	200410	201307	106	200410	201307	106	200410	201307
Kyoto	ky009	72	199707	200306												
La-Plata	lp038	60	201601	202012				38	10601	201912	60	201601	202012	60	201601	202012
Larzac	la002	120	201105	202104							100	201105	202103	99	201105	202102
Lhasa	lh057	91	200912	201706	89	200912	201706	89	200912	201706	91	200912	201706	91	200912	201706
Lijiang	li066	52	201303	201706	52	201303	201706	50	201304	201706	51	201304	201706	51	201304	201706
Matsushiro	ma011	133	199705	200806				132	199705	200807						
Medicina	mc023	275	199801	202011	218	199801	201602	256	199801	201904	256	199801	201904	256	199801	201904
Membach	mb021	308	199508	202103				206	199702	201209	308	199508	202103	307	199508	202102
Metsahovi	me013	34	201605	201902							34	201605	201902	34	201605	201902
Metsahovi	me020	260	199408	201609				220	199707	201609	245	199408	201504	245	199408	201504
Metsahovi	me022	26	201701	201902				26	201701	201902						
Metsahovi	me073-1	12	201402	201501				12	201402	201501						
Metsahovi	me073-2	15	201402	201504				13	201402	201504						
Mizusawa	mi007	100	200907	201710				98	200907	201710	100	200907	201710			
Moxa	mo034-1	234	200001	201912				236	200001	201912	240	200001	201912	240	200001	201912
Moxa	mo034-2	237	200001	201912				237	200001	201912	240	200001	201912	240	200001	201912
Ny-Alesund	ny039	149	199909	201201				148	199909	201201	154	199909	201206	154	199909	201206
Onsala	os054	143	200906	202104				127	200906	202003	142	200906	202103	141	200906	202102
Pecny	pe050	164	200705	202101				149	200705	201909	165	200705	202101	165	200705	202101
Potsdam	po018	73	199207	199808	74	199207	199809									
Rochefort	rc019	73	201412	202012												
Rustrel	ru024	56	201510	202104							55	201510	202103	54	201510	202102
Schiltach	bf056-1	138	200910	202103				114	200910	202001	138	200910	202103	137	200910	202102
Schiltach	bf056-2	138	200910	202103				114	200910	202001	138	200910	202103	137	200910	202102
Strasbourg	st005	109	198707	199607							108	198707	199606	108	198707	199606
Strasbourg	st023	62	201602	202103				47	201602	201810	61	201602	202102	51	201602	202004
Strasbourg	st026	262	199702	201811				254	199703	201810	262	199702	201811	262	199702	201811
Sutherland	su037-1	226	200003	202104	98	200003	200412	190	200003	201903	216	200012	202103	215	200012	202102
Sutherland	su037-2	220	200009	202104	52	200009	200412	184	200009	201903	216	200012	202103	215	200012	202102
Sutherland	su052	109	200809	201709				109	200809	201709	109	200809	201709	109	200809	201709
Syowa	sy016	67	199707	200301				56	199707	200301						
Trappes	tr005	94	201302	202102							94	201302	202102	94	201302	202102
Vienna	vi025	114	199707	200612				114	199707	200612	114	199707	200612	114	199707	200612
Wettzell	we006	25	201503	201703				25	201503	201703						
Wettzell	we029-1	212	199811	201803	131	199912	201010	212	199811	201803	212	199811	201803	212	199811	201803
Wettzell	we029-2	212	199811	201803				210	199811	201803	212	199811	201803	212	199811	201803
Wettzell	we030-1	94	201006	201803	71	201006	201604	94	201006	201803	94	201006	201803	94	201006	201803
Wettzell	we030-2	94	201006	201803	71	201006	201604	94	201006	201803	94	201006	201803	94	201006	201803
Wettzell	we103	27	199607	199809				27	199607	199809						
Wuhan	wu004	176	199712	201207	176	199712	201207	100	199712	200905						
Wuhan	wu065	52	201303	201706	52	201303	201706	68	201208	201803	52	201303	201706	52	201303	201706
Yebes	ys064	113	201112	202104				56	201507	202002	110	201112	202103	111	201112	202102
Zugspitze	zu052	31	201809	202103				3	201809	201811	31	201809	202103	30	201809	202002

Table 1: Status of Level-1 (raw gravity and pressure), Level-2 (preprocessed gravity and pressure data) and Level-3 (gravity residuals) data in May 2021.

Data Publication and Citation – DOI

IGETS established the provision of digital object identifiers (DOI) for the data sets of every station. DOIs are unique and persistent identifiers used to reference and link the individual data sets. The advantages are a clear reference to data sets, to link scientific results with associated publications, an improvement of the access to scientific data and an enhancement of the visibility of research data, encouraging new research to be conducted, and foster scientific cooperation.

For Level-1 data, the DOI is assigned for each station, i.e. one for all sensors of a station referencing the station operators. The DOIs of the Level-1 data sets resolve to DOI landing pages with an overview of the station and the data. For data of Level-2 and Level-3, the DOI are assigned for all IGETS stations in total.

Further activities

A web page for IGETS was prepared within the relaunch of the GGOS web site https://ggos.org/item/igets/ which presents the service, illustrates the goals and gives impressions about the stations.
At the IUGG General Assembly in Montreal, a business meeting was held on July, 13 2019 where product updates presented and site reports were given. Next online meeting will occur during the 19th International Symposium on Geodynamics and Earth Tides organized in June 2021 in Wuhan.

References

Barriot, J-P., Ducarme, B. Verschelle, Y (2016). IGETS Analysis Centre Tahiti (ICET): Status of GGP data processing, Poster presentation, 18th International Symposium on Geodynamics and Earth Tides, Trieste.

Boy, J.-P., and Hinderer, J. (2006). Study of the seasonal gravity signal in superconducting gravimeter data, J. Geodyn., 41, 227-233, doi: 10.1016/j.jog.2005.08.035.

Boy, J.-P., and Lyard, F. (2008). High-frequency non-tidal ocean loading effects on surface gravity measurements, Geophys. J. Int., 175, 35-45, doi: 10.1111/j.1365-246X.2008.03895.x.

Boy, J.-P., Barriot, J.-P., Crossley, D., Foerste, C., Hinderer, J., Meurers, B., Palinkas, V., Pagiatakis, S., Sun H.-P., Wziontek, H. (2016). Report of the first year of the International Geodynamics and Earth Tide Service (IGETS), Presentation, 18th International Symposium on Geodynamics and Earth Tides, Trieste.

Boy J-.P., Barriot J.-P., Förste C., Voigt C., Wziontek H. (2020). Achievements of the First 4 Years of the International Geodynamics and Earth Tide Service (IGETS) 2015–2019. In: . International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2020_94.

Gelaro, R. et al. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), J. Clim., 30 (14), 5419–5454, doi: 10.1175/JCLI-D-16-0758.1.

Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N. (2021). FES2014 global ocean tide atlas: design and performance, Ocean Sci., 17, 615–649, doi: 10.5194/os-17-615-2021.

Voigt, C., Förste, C., Wziontek, H., Crossley, D., Meurers, B., Pálinkáš, V., Hinderer, J., Boy, J.-P., Barriot, J.-P., Sun, H. (2016). Report on the Data Base of the International Geodynamics and Earth Tide Service (IGETS), (Scientific Technical Report STR - Data ; 16/08), Potsdam: GFZ German Research Centre for Geosciences.

Voigt, C., Förste, C., Wziontek, H., Crossley, D., Meurers, B., Pálinkáš, V., Hinderer, J., Boy, J.-P., Barriot, J.-P., Sun, H. (2017). The Data Base of the International Geodynamics and Earth Tide Service (IGETS), Geophysical Research Abstracts, Vol. 19, EGU2017-4947, EGU General Assembly 2017.

Bibliography

A list of publications related to IGETS was compiled and is available at the IGETS web page at http://igets.u-strasbg.fr/biblio.php.

International Gravimetric Bureau
(Bureau Gravimétrique International, BGI)

http://bgi.obs-mip.fr

Bureau Gravimétrique International
International Gravimetric Bureau

Director: Sylvain Bonvalot (France)

Structure

The BGI is the scientific service of IAG aimed at ensuring the data inventory and the long term availability of the gravity measurements acquired at the Earth surface. Its main task is the collection, validation and archiving of all gravity measurements (relative or absolute) acquired from land, marine or airborne surveys and the diffusion of the derived data and products to a large variety of users for scientific purposes. The BGI activities are coordinated with those of other IAG gravity services (ISG, IGETS, ICGEM, IDEMS) through the International Gravity Field Service (IGFS).

The BGI has its central bureau in Toulouse (France) and operates with the support of various institutions from France (CNES, CNRS/INSU, IGN, IRD, SHOM, BRGM, IFREMER, Universities of Toulouse, Paris, Strasbourg, Montpellier and Le Mans) and from Germany (BKG). Its directing board includes representative of the supporting institutions and a representative of IAG and of IGFS.

For more information on the BGI structure and membership, see the following references:

- The International Gravimetric Bureau. In: The Geodesist’s Handbook 2020 (Eds. Poutanen, M., Rózsa, S.). Journal of Geodesy. https://doi.org/10.1007/s00190-020-01434-z
- BGI website : http://bgi.obs-mip.fr/

Overview

During the 2019-2021 reporting period, the BGI has continued to support scientific and other users of gravity data. The BGI maintains the 4 global reference databases for relative gravity measurements (from land and marine surveys), for absolute gravity measurements and for reference gravity stations. BGI continues its activity of compilation, validation, archiving and distribution of the surface measurements of the Earth’s gravity field. It also realize and distributes derived products (global or regional grids of gravity anomaly) and gravity processing or analysis software’s. During the 2019-2021 period, also has carried out regional gravity data compilation and validation for international projects related with geoid or gravity anomaly computations (i.e. GEOMED-2, ALP-Array, Vietnam) and has supported the realization of absolute gravity reference networks in several countries. BGI also supports the activities of IAG Sub-commission 2 and participates as co-chair of the IAG Joint Working Group 2.1.1 for the realization of the International Gravity Data Reference System and Frame (IGRS/IGRF). Finally, BGI is also involved in the evaluation of innovative instrumentations for static and dynamic measurements of the Earth gravity such as absolute gravity meters based on cold-atoms technologies. Apart from the above mentioned collaborations, BGI has operated during the reporting period in close collaboration with other IGFS services and with various institutions such as POLIMI Italy, AUTh Greece, DTU Denmark, VÚGTK Czech Republic, NGA USA.

Activities

1. Global gravity databases and products

Most of the databases and services provided are available from the BGI website (http://bgi.obs-mip.fr). It gives access to the 4 global database of gravity observations: 1) Relative measurements from land surveys; 2) Relative measurements from marine surveys; 3) Reference gravity stations related to the former IGSN71 & Potsdam 1930 networks, 4) Absolute measurements.

1.1. Relative gravity database

The most frequent service BGI can provide is the consultation and retrieval of gravity data and information over local or regional areas. Data requests are made through the BGI website at the following links. Few millions of relative data are currently distributed each year to scientific users. For larger areas (regional to global), BGI also propose grids of gravity anomalies (free air, Bouguer, isostatic).

- Land database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Land-Gravity-data
- Marine database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Marine-Gravity-data

1.2. Absolute gravity database

The global database for absolute gravity measurements is jointly operated by BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany). This AGrav database is capable of storing information about stations, instruments, observations and involved institutions. By this, it allows the exchange of meta-data and the provision of contact details of the responsible institutions as well as the storage and long term availability of gravity data and processing details. The database can be accessed from two mirrored sites at BGI and BKG.

- Absolute database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data ; http://agrav.bkg.bund.de/agrav-meta/

A simple exchange format (project files) which includes all relevant information and is known by the majority of users, was selected. In this way the upload of data to the database is possible by any contributor, using a web based upload form. The provided information ranges from meta-data (localization of stations) up to full information on the absolute determination of the gravity field on a given site (raw or processed data, description of measurement sites, etc.).

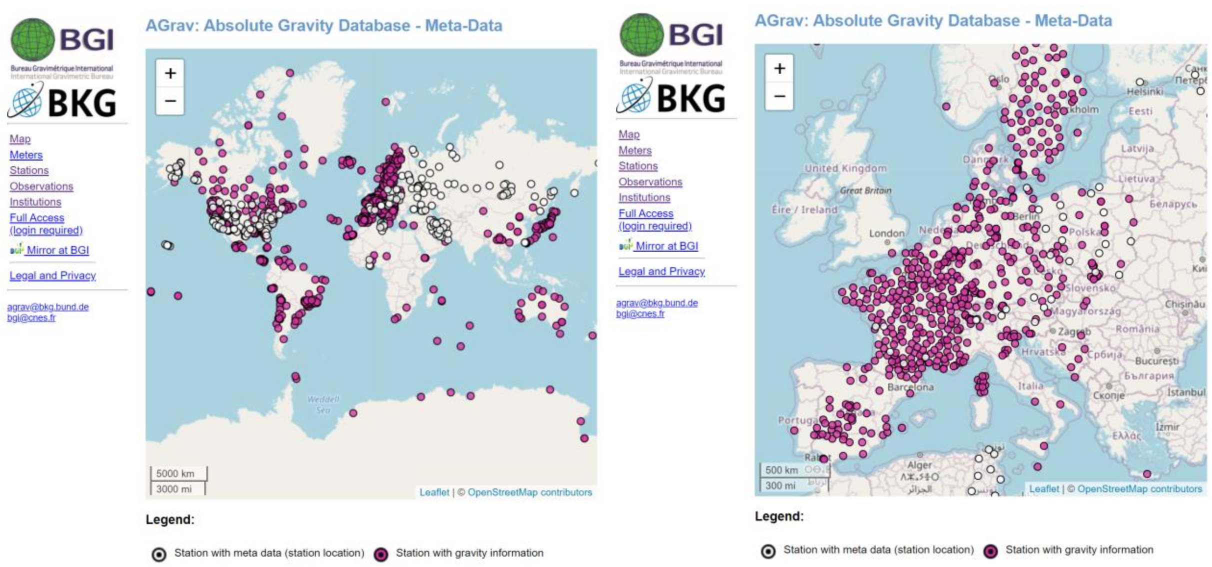


Figure 1: WEB interface of the Absolute Gravity database (BGI-BKG)

Current status (06/2021): 1373 stations / 5146 observations / 78 instruments / 65 institutions

1.3. Regional or global gravity anomaly grids

The BGI continued to provide access or links to high resolution global or regional grids of gravity anomaly such as those derived from the World Gravity Map (Bonvalot et al., *CGMW World Gravity Map*, 2012 ; Balmino et al., *Journal of Geodesy*, 2012) ; EGM2008 (Pavlis et al., *JGR* 2012) or GGMPlus (Hirt et al., *GRL*, 2013) as well as gravity derived crustal thickness model of Antarctica (Llubes et al., 2018)

2. Contribution to regional gravity projects

Regional data compilation & geoid computation

During the reporting period, BGI has contributed to the GEOMED2 project which aims at computing a high resolution geoid in the **Mediterranean area**. It has specially performed gravity data compilation and validation using marine gravity measurements collected over the entire Mediterranean basin. The final release of the GEOMED2 products has been delayed due to the Covid situation. BGI has also supported the realization of gravity data compilation for the **Alp-Array project** (Götze et al., 2019) and for a new geoid model computation for **Vietnam** and surrounding areas (Vu et al., 2019 ; 2020 ; 2021).

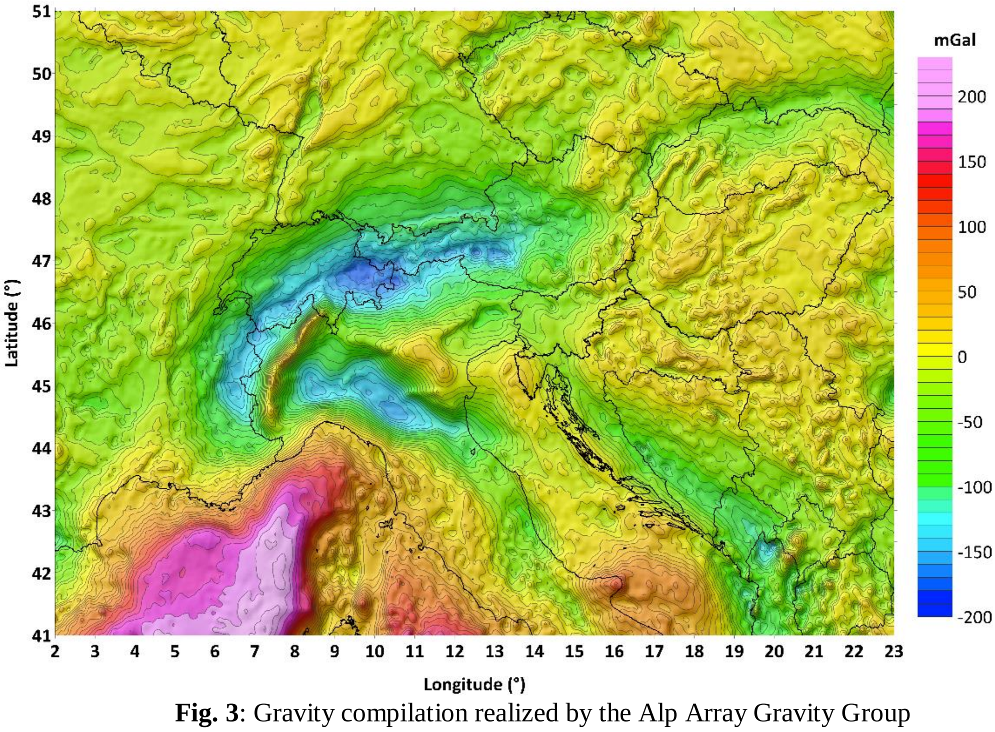


Fig. 3: Gravity compilation realized by the Alp Array Gravity Group The first pan-Alpine surface-gravity database (Zahorec et al., 2021).

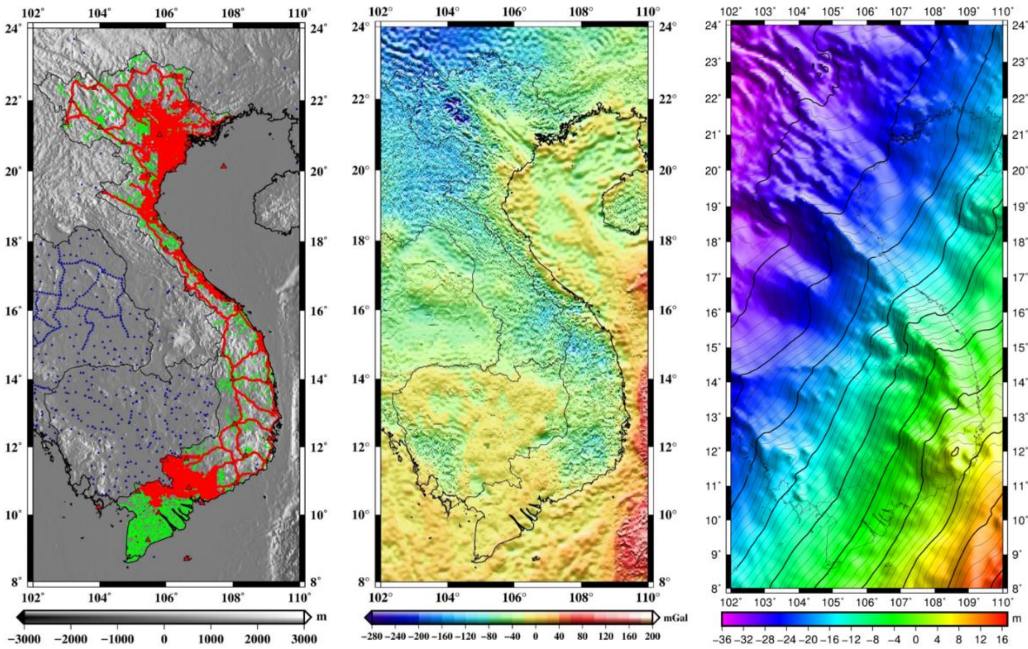


Fig. 4: Gravity data compilation over Vietnam and surrounding areas: a) Data distribution; b) Complete Bouguer anomaly ; c) Quasigeoid. Vu et al. (2019, 2020, 2021).

Establishment of absolute gravity reference networks

BGI contributes with its partners to the realization of absolute gravity networks. For instance, IGN France has renewed its gravity reference networks in France and overseas (French Antillas, Guyana, Mayotte, etc.) by combining absolute and relative gravity surveys (contribution to absolute gravity database). BGI has also supported in the last few years the realization of absolute gravity reference network in South America (Chile, Argentina, Peru).

3. Contribution to the definition of the International Gravity Reference System

BGI coo-chairs the IAG JWG 2.1.1 “Establishment of the International Gravity Reference System & Frame” (Chair: H. Wziontek, Co-Chair: S. Bonvalot). This IGRS aims at fulfilling the following objectives:

- The need for accurate and long term stable reference provided by a primary network of reference stations where gravity is monitored with absolute gravimeters. Such primary network is already a central part of the IAG resolution 2 (2015) and should also contribute to the infrastructure of GGOS Core sites.
- The need for secondary network of gravity stations which ensures accessibility of the system by a global set of sites, compatible with the above defined reference level, to any user. The aim of this secondary network is to identify and make accessible the largest number of absolute gravity values observed worldwide from field surveys of laboratory measurements to provide absolute reference to any purpose (relative gravity surveys, calibration lines, etc.). This network must be considered as the future replacement of the IGSN71 network.

The reference paper for the IGRS/IGRF project can be found in Wziontek et al. (2021)

4. Contribution to cold-atom absolute gravimetry

BGI follows the technical innovations for measuring the Earth gravity field by means of cold-atoms gravity sensors with several research lab in France (Toulouse, Brest, Montpellier and Paris).

A first contribution has been done in the frame of RESIF project (https://www.resif.fr/) with the development of the new Absolute Quantum Gravity (AQG) meter achieved by MUQUANS (https://www.muquans.com). It has led to the evaluation of performances and comparisons with reference gravity meters (MGL FG5 and A10) as well as with the cold-atoms gravity meter (CAG) from LNE-SYRTE. A second contribution is the evaluation of the GIRAFE-2 instrument developed by ONERA France (https://www.onera.fr/fr). This hybrid meter (including accelerometers and a cold atom sensor) has the ability to measure the Earth's gravity continuously on a moving platform. It has been successfully operated along with classical gravity meters and inertial sensors during an airborne survey carried out in 2019 (Collab. BGI, ONERA, DTU, SHOM, CNES, SAFIRE).

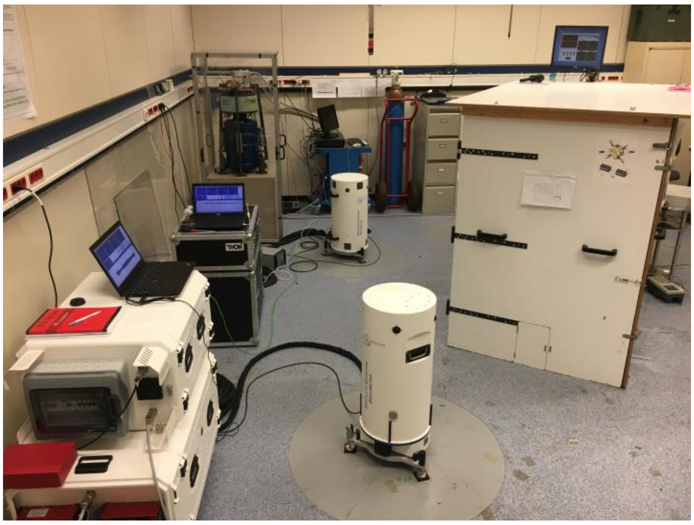


Figure 5a: Inter-comparison of 3 Absolute Quantum Gravimeter (AQG A01, AQG B01 from MUQUANS and CAG) and iGrav at LNE/SYRTE, France.

Figure 5b : GIRAFE-2 cold-atom gravimeter (ONERA) during airborne survey in spring 2019.

Scientific events

International meetings

- 07/2019 : IUGG General Assembly 2019 ; Montreal, CA
- 12/2019 : AGU General Assembly 2019 ; San Francisco, USA
- 04/2020 : EGU General Assembly 2020 ;
- 12/2020 : AGU General Assembly 2020;
- 04/2021 : EGU General Assembly 2021 ;

Participation to IAG structure & working groups

- IAG Sub-commission 2.1: « Land, marine & Airborne gravimetry » (Chair. D. VanWestrum, USA ; P. Dykowski, Poland)
- IAG JWG 2.1.1 : "Establishment of a International Gravity Reference System & Frame (IGRS/IGRF)" (Chair: H. Wziontek, Germany ; Co-Chair: S. Bonvalot, France)
- IAG JWG 2.1.2 : "Unified file formats and processing software for high-precision gravimetry" (Chair: Ilya Oshchepkov, Russia)
- IGFS Advisory Board - http://igfs.topo.auth.gr/structure.html/
- GGOS Consortium - http://www.ggos.org/
- CCM / CIPM (Consultative Committee for Mass and Related Quantities- Working Group "Gravimetry" : https://www.bipm.org/en/committees/cc/wg/ccm-wgg.html

Publications 2019-2021

Bonvalot et al. The International Gravimetric Bureau. In: The Geodesist's Handbook 2020 (Eds. Poutanen, M., Rózsa, S.). Journal of Geodesy (2020). https://doi.org/10.1007/s00190-020-01434-z

Dufrechou G., Martin R., Bonvalot S., Bruinsma S. Insight on the western Mediterranean lithospheric structure from GOCE satellite gravity data. Journal of Geodynamics (2019) - https://doi.org/10.1016/j.jog.2019.01.006

Pallero J.L., Fernandez-Martinez J. L., Fernández-Muñiz Z., Bonvalot S., Gabalda G., Nalpas T. GravPSO2D: A Matlab package for 2D gravity inversion in sedimentary basins using the Particle Swarm Optimization algorithm Computers & Geosciences (2021). https://doi.org/10.1016/j.cageo.2020.104653

Vu D.T., Bonvalot S., Bruinsma S., Bui L.K. A local lithospheric structure model for Vietnam derived from a high-resolution gravimetric geoid. Earth, Planets and Space (2021). https://doi.org/10.1186/s40623-021-01415-2

Vu D.T., Bruinsma S., Bonvalot S., Bui L.K., Balmino G. Determination of the geopotential value on the permanent GNSS stations in Vietnam based on the Geodetic Boundary Value Problem approach. Geophysical Journal International (2021).https://doi.org/10.1093/gji/ggab166

Vu Toan D., Bruinsma S., Bonvalot S. A high resolution gravimetric geoid model for Vietnam Earth, Planets and Space (2019) - https://doi.org/10.1186/s40623-019-1045-3

Vu Toan D., Bruinsma S., Bonvalot S., Vergos G. A quasigeoid derived transformation model accounting for land subsidence in the Mekong Delta towards height system unification in Vietnam. Remote Sensing (2020). https://doi.org/10.3390/rs12050817

Wziontek H., Bonvalot S., Falk R., Gabalda G., Mäkinen J., Palinkas V., Vitushkin L. Status of the Intenational Gravity Reference System and Frame. Journal of Geodesy (2021) 95:7. https://doi.org/10.1007/s00190-020-01438-9

Zahorec et al. The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. Earth System Science Data, 2021. Earth Syst. Sci. Data, 13, 2165–2209, 2021 https://doi.org/10.5194/essd-13-2165-2021

Contacts

Bureau Gravimétrique International
Observatoire Midi-Pyrénées
14, Avenue Edouard Belin 31401 Toulouse Cedex 9, France
Phone: 33-5 61 33 28 90
E-mail: bgi@cnes.fr, sylvain.bonvalot@ird.fr

Contacts for updating BGI databases or obtaining DOI for data, products or software:
bgi@cnes.fr ; agrav@bkg.bund.de

Staff members & experts

S. Bonvalot (Director), France
G. Balmino, France
A. Briais, France
S. Bruinsma, France
G. Gabalda, France
F. Reinquin, France
L. Seoane (deputy Director), France
H. Wziontek, Germany
A. Rulke, Germany
R. Falk, Germany
V. Palinkas, Czech Rep.
G. Vergos, Greece
R. Barzaghi, Italy
S. Merlet, France
M. Diament, France
T. Gattacceca, France
O. Jamet, France
M-F. Lalancette-Lequentrec, France
G. Martelet, France
I. Panet, France
J.-P. Boy, France
J.-D. Bernard, France
N. Le Moigne, France
C. Salaun, France
D. Roussel, France
J. Hinderer, France

International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it/

President: Mirko Reguzzoni (Italy)
Director: Daniela Carrion (Italy)

Structure

The Service is hosted by the Department of Civil and Environmental Engineering at Politecnico di Milano (Italy).

In addition to the president and the director, the ISG staff is composed by other scientists (F. Sansò, R. Barzaghi, G. Sona, A. Albertella, C.I. De Gaetani, L. Rossi, K. Batsukh and J.F. Toro Herrera), as well as a secretary (C. Vajani).

The ISG advisory board is composed by the following scientists with expertise in the field of geoid determination:

- N. Pavlis	(USA)
- M. Sideris	(Canada)
- J. Huang	(Canada)
- R. Forsberg	(Denmark)
- J. Ågren	(Sweden)
- U. Marti	(Switzerland)
- H. Denker	(Germany)
- L. Sánchez	(Germany)
- K. Elger	(Germany)
- I. Tziavos	(Greece)
- D. Blitzkow	(Brazil)
- W. Featherstone	(Australia)
- H. Abd-Elmotaal	(Egypt)
- C. Hwang	(Chinese Taipei)

ISG is currently involved in the Joint Working Groups JWG 2.2.1 of IAG Sub-Commission 2.2 "Error assessment of the 1 cm geoid experiment".

Overview

In the period 2019-2021, most activities have been devoted to standardise the information and increase the offer of services on the available archive of geoid and quasi-geoid models, namely:

- the update of the ISG data format, which is common to all models;
- the establishment of a DOI service, in cooperation with GFZ;
- the establishment of a (preliminary) web-service for height conversion;
- the distribution of the Colorado experiment data and results, through the ISG website.

ISG activities have been disseminated through the participation to international events with oral and poster presentations. A paper on ISG has been published on Earth System Science Data, as well. The traditional activities on school organization and scientific support to researchers on geoid estimation have been suspended due to the advent of the Covid-19 pandemic.

Last but not least, the ISG geoid repository has been continuously updated, significantly increasing the number of collected models. The ISG website has been modified accordingly.

Update of the ISG data format

ISG manages and preserves a repository of regional, national and continental geoid models at a worldwide scale. The repository aims at storing and redistributing geoid models in a standardised data format, providing also ancillary information useful for gravity related analysis. To this aim, the geoids are collected both in the format provided by the owners and in ISG format, a standardised ASCII format with the .isg extension. The first version of the ISG ASCII format was released in 2015 and updated in 2018 (version 1.01). In July 2020, a major new release, version 2.0, was published, mainly introducing more metadata to better characterize the content of the file, and also allowing to store sparse point data. All the new models will be published with version 2.0.

Each individual data file consists of three sections: a) the optional comment section; b) the header section, which contains textual and numerical parameters; c) the data section, which contains the undulation values. To increase data interoperability, section (a) and (b) were designed with the same scheme of the .gfc file, distributed by ICGEM and providing global model coefficients.

In the comment section (a), three paragraphs are strongly recommended, the first one with the licence under which the data are distributed, the second one with the reference to cite when using the data, the third one indicating the data provider and the institution distributing the model.

In ISG format, the header section (b) is composed by structured metadata. It can be conceptually divided into three parts. The first contains textual metadata that are required to characterize the model, such as:

- the name of the model and the year of computation,
- the type of the model (gravimetric, geometric or hybrid),
- the classification between geoid and quasi-geoid,
- the fact that the data are sparse or gridded, and in case the ordering of the gridded data,
- the reference ellipsoid and datum, the reference frame, and the tidal system,
- the fact that the coordinates are geodetic or projected and, in case, the type of projection,
- the units of the undulation data and the coordinate units.

The second part contains numerical metadata that are mainly required to georeferencing the undulation values, such as

- the bounding box of the undulation dataset, i.e. minimum and maximum coordinates,
- the grid step and the number of rows and columns if the data are gridded (the number of rows can be used in sparse data to specify the number of points),
- the no-data value for missing points inside the grid structure.

Finally, the third part contains information about the file, such as the creation date and the format version. Metadata and their keywords depend on the format version. The file format specifications for all the possible versions are available at a dedicated page on the ISG website (https://www.isgeoid.polimi.it/Geoid/format_specs.html).

The data section was originally developed to contain the gridded undulation values, but from the format version 2.0 it is also possible to store sparse data by providing the point coordinates along with the undulation values. In case of gridded data, the point coordinates are defined in the header section and the undulation values are always stored row by row, being the default ordering from North to South, each row going from West to East.

Establishment of a DOI service

Geoid models that are collected by ISG are validated and standardized by converting them into a unique ASCII file format. In order to further improve interoperability and reusability of these models, it is crucial to univocally identify the data file (also by stable links), to assign metadata, to grant proper credit to research authors, and to allow for data citation.

In the framework of the GGOS working group “DOIs for Geodetic Data Sets”, ISG and GFZ are cooperating for developing a DOI minting service for local/regional geoid/quasi-geoid models collected and published via the International Service for the Geoid. The service includes the DOI assignment to the models, the collection and provision of standardised metadata and an additional backup of the models through GFZ Data Services, guaranteeing a persistent data access (the rights for publication of the models have been addressed by ISG and the data are already available for public download via the ISG geoid repository).

Since summer 2020, when the service was activated, the geoid/quasi-geoid distribution has been changed as follows:

• ISG geoid and quasi-geoid models in standardised ISG format (ASCII) can be labelled by DOIs. It is not foreseen to apply DOIs to the models in “original” format (as provided by the authors).
• The models that are labelled by DOIs are published under the Creative Commons Attribution 4-0 International Licence (CC BY 4.0) unless otherwise stated.
• The models that are labelled by DOIs are additionally publicly accessible via machine-readable DOI landing pages and the data catalogue of GFZ Data Services.
• The DOI landing pages have a specific layout for ISG.
• The geoid repository at ISG remains the first access point of ISG geoid models.
• A copy of the models will be archived at GFZ (backup).

Figure 1 provides an overview on the relation between the ISG and the GFZ Data Services for an example of DOI-referenced model. Both the quasi-geoid and geoid solutions, constituting the example model, can be accessed via the dedicated web page in the ISG geoid repository (on the left) and via the DOI landing pages in the GFZ Data Services (on the right). The “File” section of the DOI landing page includes the links to the model file and the corresponding web page in the ISG repository. On the other side, the ISG model web page is enhanced with the recommended citations of the DOI-assigned models and the links to the DOI landing pages at the GFZ Data Services. The arrows show the cross-references between the two web pages.

At the date of 31 May 2021, DOIs were assigned to 20 models stored in the ISG repository, that is about 11% of the total number of open-access models.

In addition to the DOI assignment, the agreement between ISG and Clarivate is still active, thus indexing all ISG geoid and quasi-geoid models in the Data Citation Index and providing the corresponding accession number on the ISG website of the model website

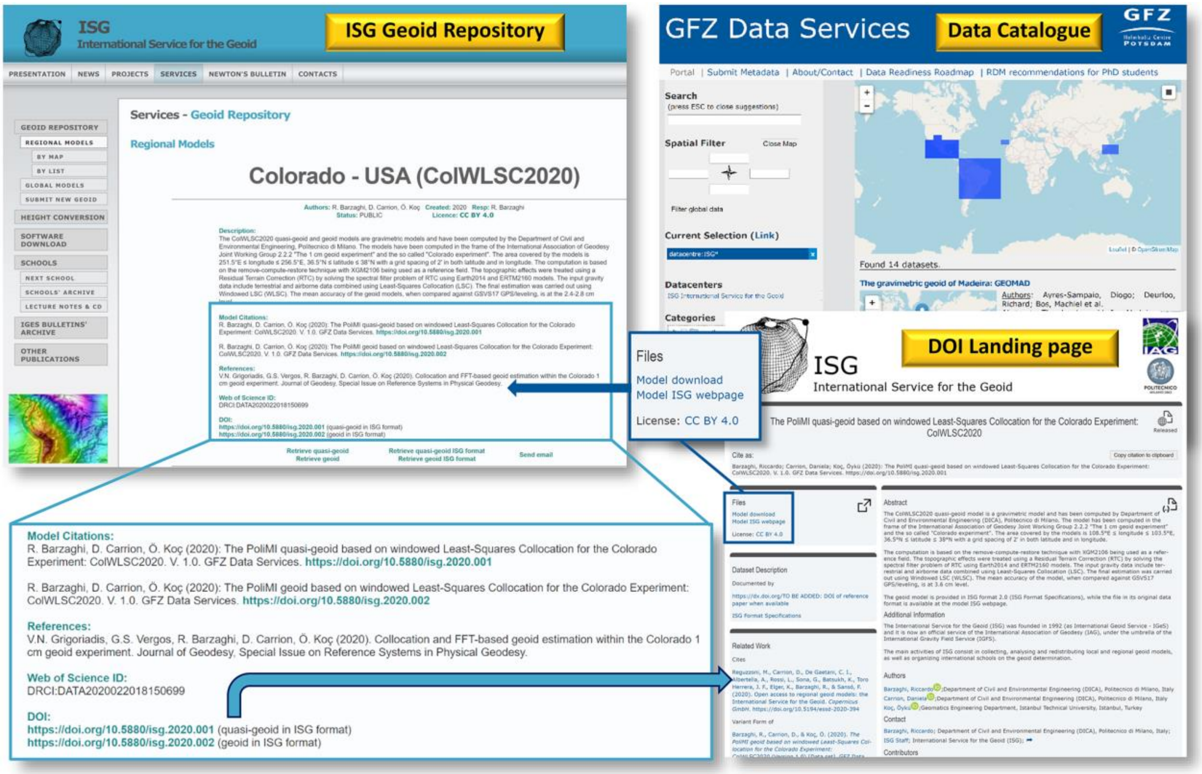


Figure 1: overview on the relation between the ISG and the GFZ Data Services for an example of DOI-referenced model.

Establishment of a web-service for height conversion

In summer 2020, ISG activated a height conversion web-service to the users. They can provide the coordinates of one or more points (in the latter case through a CSV file containing three columns, namely latitude, longitude and height to be converted) and, after selecting the geoid model and the interpolation method, the web-service returns the conversion from ellipsoidal to orthometric height or vice versa. Once the user provides the point coordinates, only the geoid models containing at least one of these points are listed and can be selected by the user for the height conversion. This is possible by exploiting the model bounding box information that is available in the model file header as defined according to the ISG format.

As for the algorithmic point of view, the conversion is based on the formula $H = h - N$, relating the ellipsoidal height h and the orthometric height H through the geoid undulation N. Due to the fact that geoid models used by this service are given on a grid, the currently available interpolation methods are a bilinear interpolation among the four closest grid knots to the input point and the inverse distance weighting interpolation. Other interpolation methods may be made available in the future. The distinction between geoid and quasi-geoid will be performed soon, also mentioning the different reference systems/frame involved in the conversion. In this respect, the implemented web-service has to be considered as a preliminary solution.

As for the software implementation point of view, the web-service is divided into front-end and back-end, the former providing a user interface and the latter performing the calculations. The front-end is the "visible" part of the application (see Figure 2), it is implemented by using an HTML page and JavaScript. The HTML page contains a form with all the needed fields for the height conversion according to the web-service created on the back-end. The interface is designed to change as the user interacts with the application and selects the different options (single or multiple point coordinates). There are also checks on the input file size and format when the user asks for the conversion of more than one point.

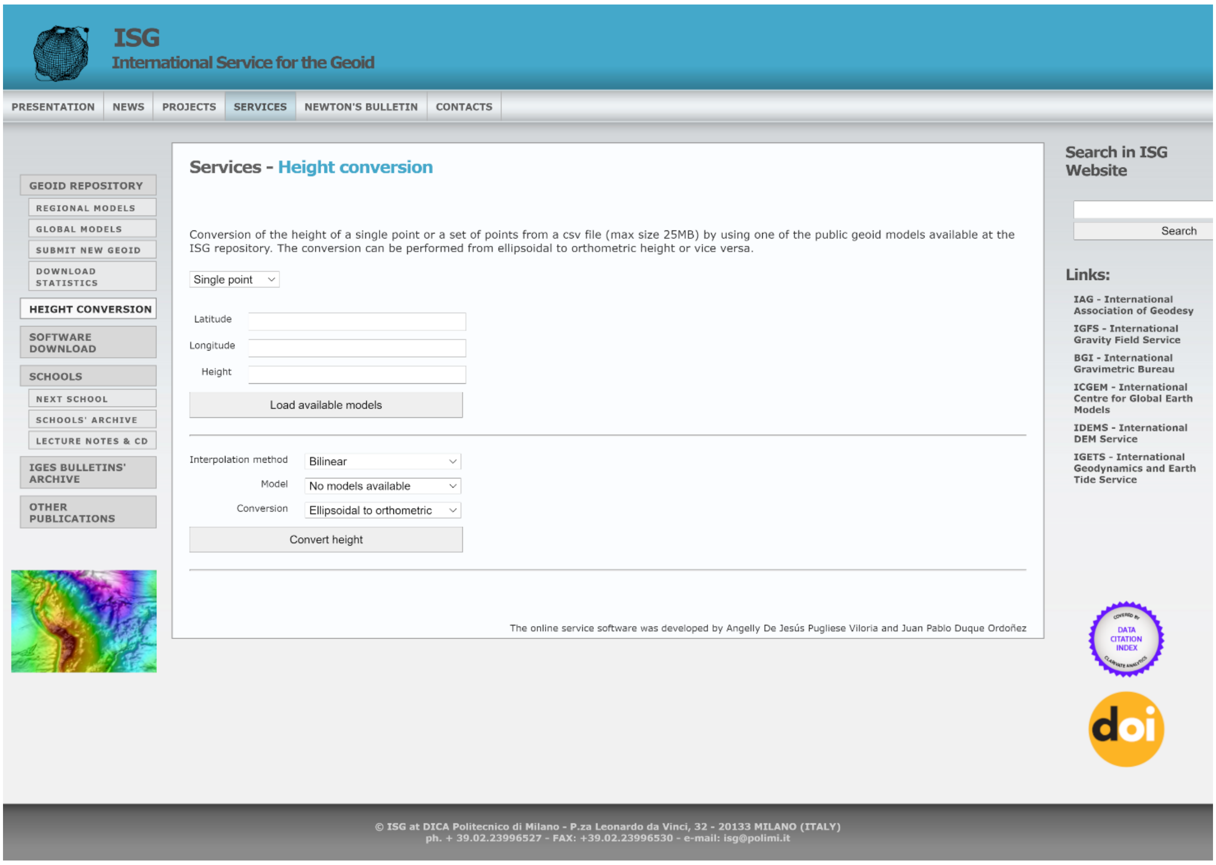


Figure 2: Webpage to access the ISG height conversion web-service.

The back-end is the core of the web-service, performing the required computation without increasing the burden of the front-end. In this way the web-service can be modified or updated without interfering with the front-end. In order to implement the back-end, a REST API (Representational State Transfer Application Programming Interface) was created in Django, a high-level Python web framework that allows performing mathematical calculations using Python with the NumPy library. Four different endpoints were created for the geoid model research and the height conversion, both for a single point and a set of points.
All requests from the front-end to the back-end rely on the HTTP POST method, i.e. enclosing the data in the body of the request messages instead of storing it, while the answers from the back-end are transmitted through a JSON file, which is directly visualized in the HTML page.

Distribution of the Colorado experiment data and results

In the past 4 year period, the 1-cm geoid experiment (also called Colorado experiment) was setup as a joint effort of the Focus Area Unified Height System of the Global Geodetic Observing System (GGOS), the IAG Sub-commission 2.2, IAG Inter-Commission Committee on Theory (ICCT), and many related studies and working groups. The main objective of the experiment was the estimation and comparison of geoid undulations and height anomalies in Colorado using the same input data (provided by the US National Geodetic Survey, NGS) and different methodologies for the gravity field modelling. ISG offered the possibility of publishing both input data and results (in term of geoid and quasi-geoid models) on its website. To this aim, dedicated webpages are now online, one for each solution computed in the frame of the Colorado experiment. A homepage summarizing the project and providing input and validation data is available too. As it is done for any other model in the ISG repository, information about names and institutions of the authors, the publication year of the model, key reference publication(s) and a brief description on the computational method of the model is provided for the Colorado solutions too. Moreover, DOIs can be assigned to these solutions, making it possible to directly cite geoid and quasi-geoid models in scientific publications. Finally, the availability of the input data and possible comparisons with the already existing solutions can foster other researchers to test their own algorithm on this dataset, even if the official experiment is closed. ISG will also publish these additional results.

For the moment, ten solutions have been published on the ISG website, four of them have been already labelled with DOIs (geoid and quasi-geoid models have different DOIs even if they refer to the same solution). This activity has been carried out in the frame of Joint Working Groups JWG 2.2.1 of Sub-Commission 2.2 "Error assessment of the 1 cm geoid experiment".

Participation to conferences and publications

ISG members took part to some international conferences/events, presenting the activities performed by the service. In particular, the following two oral presentations were given:

- "The International Service for the Geoid and its role in South America" at the workshop on the "Implementation of the United Nations' Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America" held in Buenos Aires, Argentina, 16-20 September 2019.
- "The International Service for the Geoid: focus on Asia-Pacific region" at the first Asia Pacific geoid workshop for IAG-Sub-Commission 2.4e, held in Taiwan, 29 October 2020.

Moreover, ISG contributed to the presentation entitled "The IGFS gravity field observations and products contributions to GGOS infrastructure" at EGU General Assembly in 2020. Finally, an abstract entitled "Assigning Digital Object Identifiers to Geoid Models in the ISG Repository" was submitted and accepted as a poster presentation at IAG Scientific Assembly in 2021.

As for the publications, a paper focussing on ISG and mainly on its geoid repository has been recently published, please see M. Reguzzoni, D. Carrion, et al. (2021). Open access to regional geoid models: the International Service for the Geoid. Earth System Science Data, 13, pp. 1653–1666. DOI: 10.5194/essd-13-1653-2021. ISG users are encouraged to cite this paper when using ISG services.

School organization and scientific support to researchers on geoid estimation

One of the main tasks of ISG consists in organizing schools on geoid estimation and related topics. The last international school was held in Mongolia in 2016, at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar. The planning was to organize a new edition in 2020, but the advent of the Covid-19 pandemic led to postpone the school organization when the worldwide health situation will make travelling and hosting safer.

Traditionally, ISG also provides tailored training courses on geoid estimation at Politecnico di Milano. Again, this activity became unfeasible because of the Covid-19 pandemic. However, the possibility of organizing online training activities is being considered.

ISG geoid repository and website update

In the last two years, the ISG archive of local, regional and continental geoid and quasi-geoid models has been continuously updated. Not only the latest release of a model is stored in the archive, but also outdated versions are collected to keep memory of the work done in the past and to allow for comparisons. The full (or almost the full) series of the official geoid models are available for many countries. Three possible policy rules are considered for the model distribution: “public” if it can be freely downloaded from the website, “on demand” in case the authors asked to be informed before distributing the model, and “private” if it is just included in the archive but it cannot be distributed to the users. Therefore, the aim of the “private” policy is to inform users that a model exists without publishing any data through the ISG service. Almost 250 models are currently available in the ISG database, whose composition is reported in Tables 3, 4 and 5 (last update of the statistics was on 31 May 2021). The global coverage of the available gridded geoid models, together with their spatial resolution, is shown in Figure 3.

Europe	81
North America	65
Asia	33
Oceania	22
Africa	19
South America	14
Antarctica	4
Arctic	4
Total	242

Table 3: Number of models per continent in the ISG archive.

< 1991	4
1991 – 1995	15
1996 – 2000	41
2001 – 2005	30
2006 – 2010	56
2011 – 2015	51
2016 – 2020	44
> 2020	1
Total	242

Table 4: Number of models per year in the ISG archive.

Public	181
On-Demand	22
Private	39
Total	242

Table 5: Number of models per policy-rule in the ISG archive.

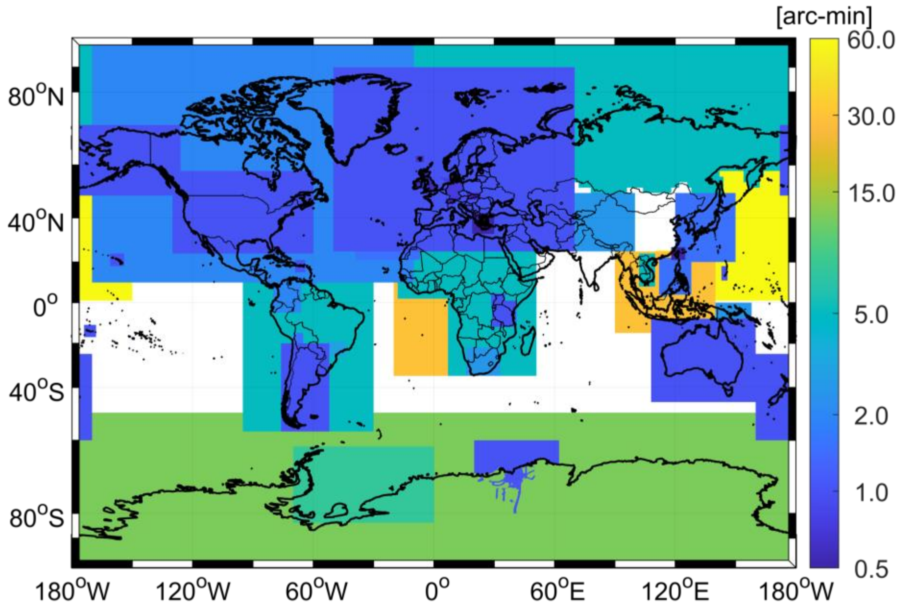


Figure 3: Spatial coverage of the gridded geoid models available at ISG. Colour-bar shows the highest spatial resolution per location (log10 scale, unit: arc-minutes).

The ISG website is updated simultaneously to the ISG archive. For each geoid model that is stored in the archive a dedicated webpage is available on the website, containing information about the model name, year, authors, contact person, type (gravimetric, geometric or hybrid, geoid or quasi-geoid) and policy rule. There is a short description of the model characteristics, at least one bibliographic reference and a model figure. When a DOI is attributed to the model, the corresponding citation is provided, along with the data license (CC BY 4.0), see Figure 4.
If the model is classified as "public", the corresponding data file can be downloaded from the webpage in a unique ASCII format (.isg), whose specifications are provided in the website. After authors' authorization, the "on demand" models can be distributed to users in the same ASCII file format. The webpage of each model can be reached from a complete list of available geoids or by clicking on a geographical map.
Apart from the geoid repository, the website has been updated in the home page and in the section dedicated to the software, adding some Matlab functions to read and write geoid and quasi-geoid models in ISG format. News section has been continuously kept up-to-date. No papers have been submitted to Newton's Bulletin in the last two years. The current home page of the ISG service is shown in Figure 5. Some statistics on the website access are displayed in Figure 6.

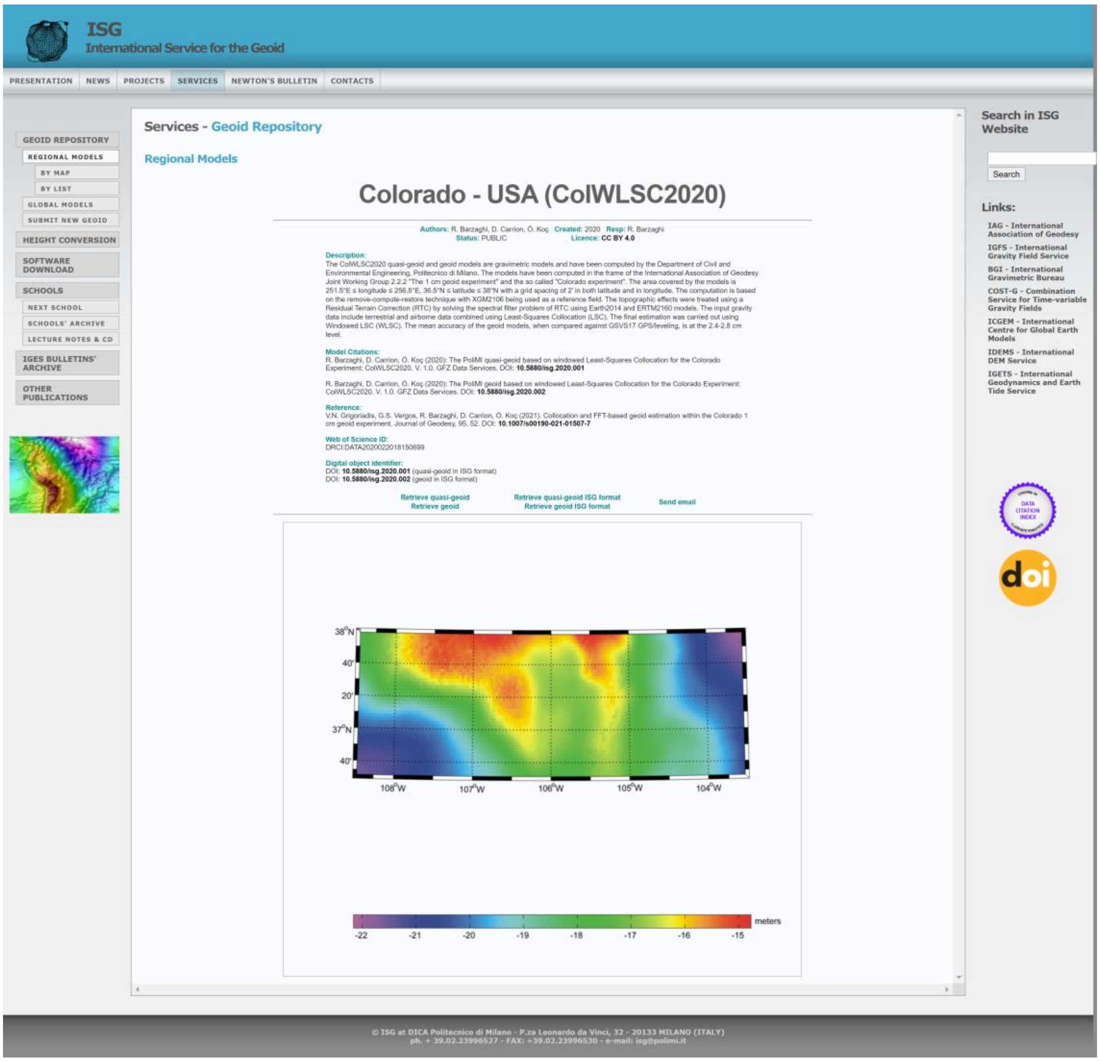


Figure 4: Example of a webpage describing a model stored in the geoid repository (https://www.isgeoid.polimi.it/Geoid/America/USA/Colorado20WLSC_g.html).

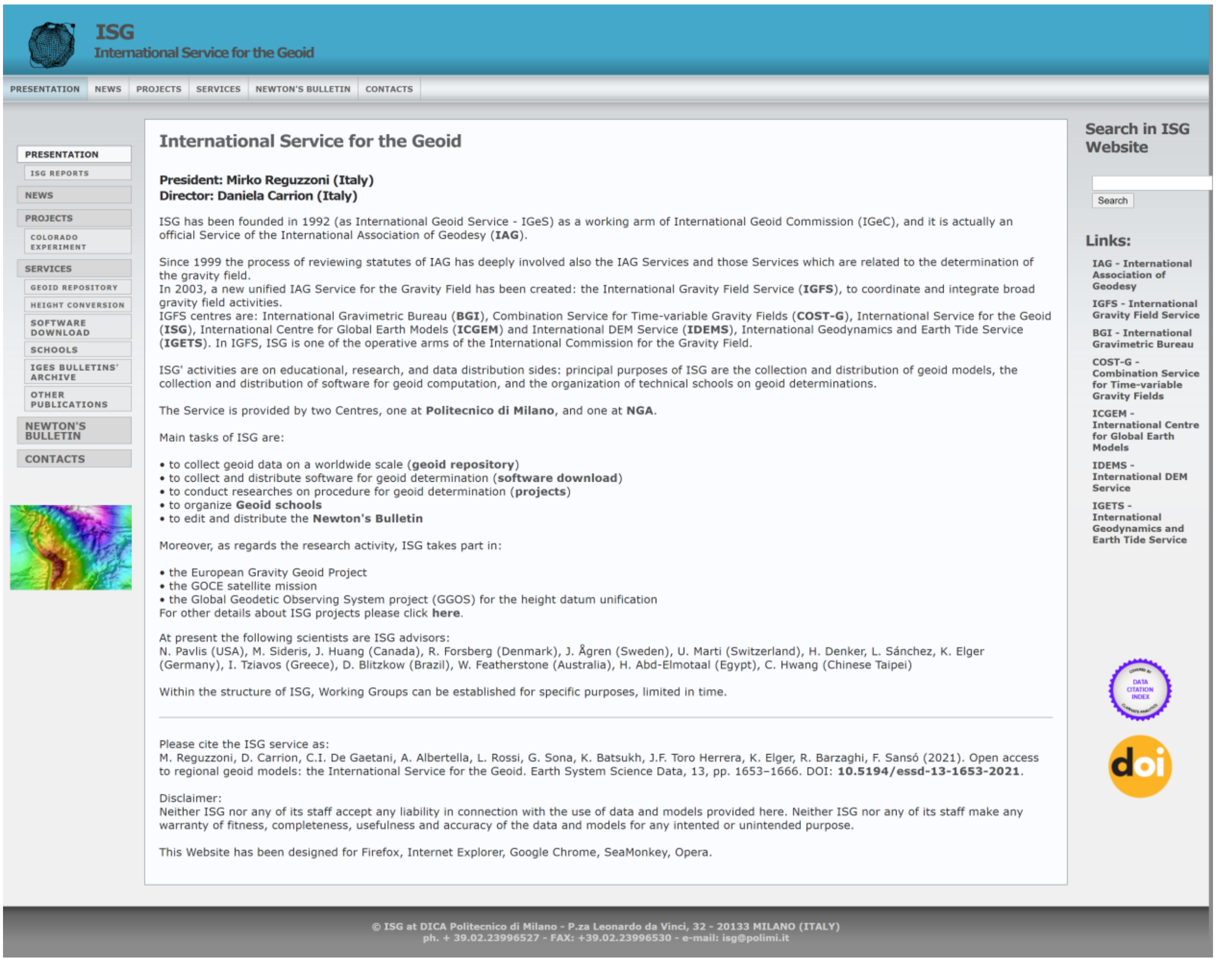


Figure 5: Home page of the ISG website (https://www.isgeoid.polimi.it/).

Figure 6: Statistics on the number of visitors per day (upper panel) and per country (lower panel) for the ISG website from the beginning of 2021 till end of May 2021.

Permanent Service for Mean Sea Level (PSMSL)

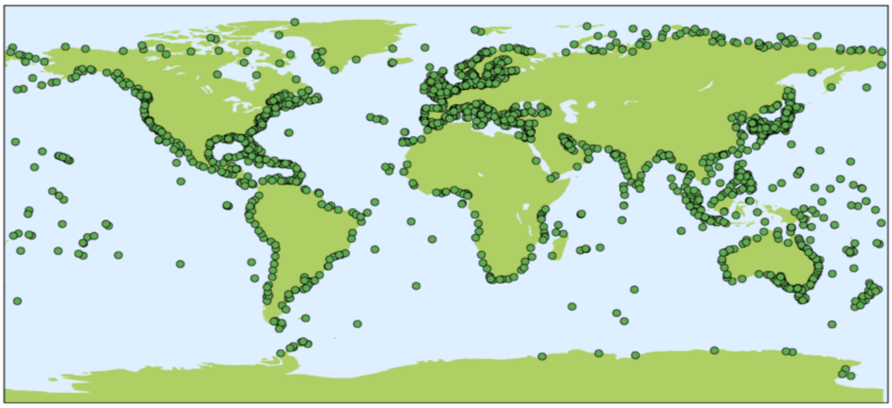
https://www.psmsl.org/

Elizabeth Bradshaw, Kathy Gordon and Andy Matthews
National Oceanography Centre, Liverpool, UK

Introduction

Since 1933, the Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. It is based at the National Oceanography Centre (NOC), which on the 1st November 2019 began operating as an independent self-governing organization – a charitable company limited by guarantee. Funding is provided by the UK Natural Environment Research Council (NERC).

The PSMSL is a service of the International Association of Geodesy (IAG), a Member of the Global Geodetic Observing System (GGOS) Bureau of Networks & Observations, and continues to be one of the main data centres for the International Association for Physical Sciences of the Oceans (IAPSO). The PSMSL operates under the auspices of the International Science Council (ISC) and reports formally to IAPSO's Commission on Mean Sea Level and Tides. The PSMSL is a regular member of the World Data System (WDS) of ISC.

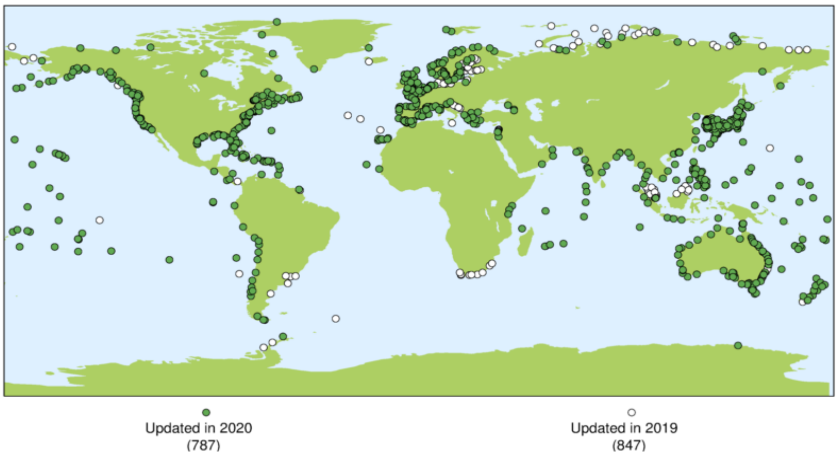


Stations in the PSMSL dataset

Changing sea levels will have a major impact on human life over the next 100 years. We need mean sea level data to study climate change, the impact of human activities on densely populated areas, the economic impacts of sea level rise and to plan coastal engineering. The mission of the PSMSL is to provide the community with a full service for the acquisition, analysis and interpretation of sea level data. Aside from its central role of operation of the global sea level data bank, the PSMSL provides advice to tide gauge operators and analysts. It occupies a central management role in the development of the Global Sea Level Observing System (GLOSS) and hosts important international study groups and meetings on relevant themes.

MSL data received

The database of the PSMSL contains over 72000 station-years of monthly and annual values of mean sea level (MSL) from over 2360 tide gauge stations around the world received from approximately 200 national authorities. On average, approximately 800 stations per year are entered into the database. This database is used extensively throughout the sciences of climate change, oceanography, geodesy and geology, and is the main source of information for international study groups such as the Intergovernmental Panel on Climate Change (IPCC).



Stations updated in 2019 and 2020

The supply of data has remained constant over the last few years, although we have continued to see a decline in data supplied from Arctic gauges. We have also seen a reduction in supply from gauges in Africa, although new instruments have been installed, for example in Ghana.

We are also aware of a lack of delayed mode quality-controlled data being processed from gauges that are reporting in Near Real Time (NRT). This may be due to a lack of resource to process the data, such as funding, time or software required. There have been several new gauges installed in the Caribbean and we have been involved in projects to develop automatic quality control software, to try to process these data. There are also several gauges in South America that report NRT data, but do not process monthly and annual means.

GNSS-IR data processing and delivery

The PSMSL received funding from the European Union Horizon 2020 EuroSea project to create an international archive to preserve and deliver Global Navigation Satellite Systems Interferometric Reflectometry (GNSS-IR) data and to integrate these data with existing sea level observing networks. GNSS-IR sensors provide an alternative method to observe sea level. As well as recording the sea level, these sensors will also provide vertical land movement information from the site.

The GNSS-IR archive will provide delayed mode data from nearly 250 sites, each of which will have a dedicated page containing information about the site and links to the information about the GNSS receiver and nearby tide gauges. The distributed data will include information about the signal used to calculate each data point, allowing users to separate data using particular frequencies, or for example, to separate reflections from inside and outside a harbour. We have also demonstrated that these technologies can be used in near real time, and are working towards delivering this via interoperable ERDDAP servers (https://coastwatch.pfeg.noaa.gov/erddap/index.html).

In 2020, the EuroGOOS tide gauge task team (of which several PSMSL staff are members) reviewed the metadata relating to tide gauges and co-located GNSS receivers on behalf of the European Environment Agency. There has historically been a lack of information regarding the geodetic ties between tide gauges and nearby GNSS receivers, often because they are operated by different organisations. Although this work focused on Europe, we would appreciate help to establish the ellipsoidal height estimation of tide gauge benchmarks globally:
https://eurogoos.eu/download/other_documents/task_teams/SONEL_EuroGOOS_GNSS@TG_metadata_campaign_report.pdf

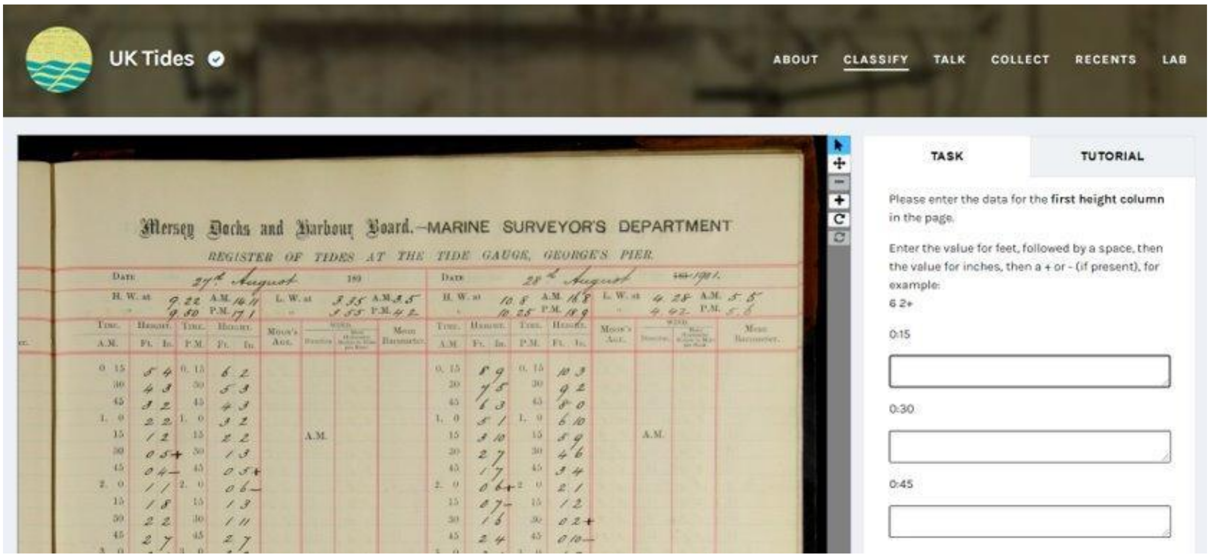
GNSS-IR sea level data portal

Data rescue

The PSMSL continues to play a leading role in sea level data rescue and helped organise the GLOSS/International Hydrographic Organization/International Union of Geodesy and Geophysics/IAPSO Sea Level Data Archaeology Workshop (meeting report - https://unesdoc.unesco.org/ark:/48223/pf0000373327) (Paris, March 2020). The main outcome of the workshop was the recommendation to establish a Data Rescue Working Group.

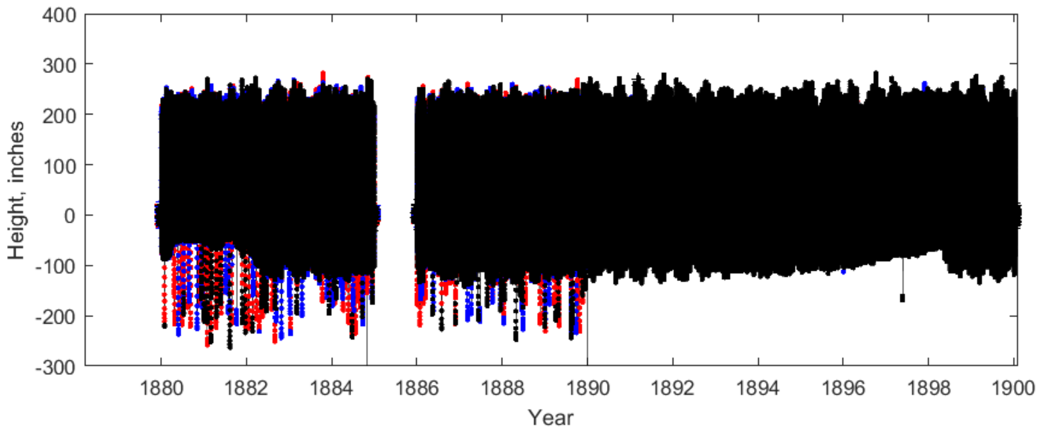
Attendees at the workshop on sea level data archaeology

Another recommendation was to explore a pilot project using the Zooniverse Citizen Science platform (https://www.zooniverse.org/) and we launched the PSMSL project UK Tides (https://www.zooniverse.org/projects/psmsl/uk-tides), built using the using the Zooniverse project builder (www.zooniverse.org/lab) in January 2021.



UK Tides data entry interface

We have had over 2800 registered volunteers digitise ~40 years of 15-minute tide gauge data from two sites in the North West of England.



George's Pier, Liverpool, 1880-1900

The data for George's Pier, Liverpool, shows the gauge drying out at low water from 1896-1898. At the time of writing, data from the 1880s is still being entered by volunteers and quality controlled, and portions in red and blue have yet to be fully completed.

Developing metadata

It is important to the PSMSL that we are able to demonstrate where the data we distribute came from, give credit to those involved in the data lifecycle, and be able to produce a full audit trail. If we have updated records, we need to be able to document why. This information needs to be delivered alongside the data. Currently, it is difficult to uniquely identify tide gauge locations, sensors and suppliers, which can lead to duplicate data on data aggregator websites. It may also be difficult to get a true picture of the status of a network, such as how many gauges are currently operating.

We are working towards developing sea level metadata that will help make the data FAIR (Findable, Accessible, Interoperable and Reusable). Three technical working groups were set up following action items from the EuroGOOS Tide Gauge Task Team Meeting in July 2020. Andy Matthews is a member of the working group on site/station definition, Elizabeth Bradshaw is the lead of the working group on unique ID definition and both joined the working group on minimum metadata and common vocabularies and definition. Recommendations from these working groups formed part of the EuroSea project deliverable D3.3 New Tide Gauge Data Flow Strategy

-https://oceanrep.geomar.de/52175/1/D3.3_New_Tide_Gauge_Data_Flow_Strategy.pdf.

We have also been working with the Global Ocean Observing System (GOOS) Observations Coordination Group (OCG) and OceanOPS to standardise ocean observing system network metadata. PSMSL staff attended the OCG Data Mapping and Metadata workshop in March 2021 and the OCG 12 Workshop: Data & Metadata in May 2021.

Global Extreme Sea Level Analysis (GESLA)-3

GESLA-1 and 2 were global coverage high frequency delayed mode datasets, developed originally for extreme sea level analysis. The current working group is lead by Ivan Haigh (University of Southampton), with support from Marta Marcos (University of the Balearic Islands), Philip Woodworth (National Oceanography Centre, Liverpool), John Hunter (University of Tasmania), Arne Arns (University of Rostock, Germany), Ben Hague (Bureau of Meteorology, Australia) and Stefan Talke (California Polytechnic State University, USA).

In 2019 the working group began the next update of the dataset, GESLA-3. The new dataset will add more stations, station-years and remove duplicates. PSMSL staff have attended working group meetings and provided advice on updating the data format (including adding a netCDF option alongside the previous ASCII data), improving metadata, and considering data policies. We have also had discussions on improving the FAIR data compliance.

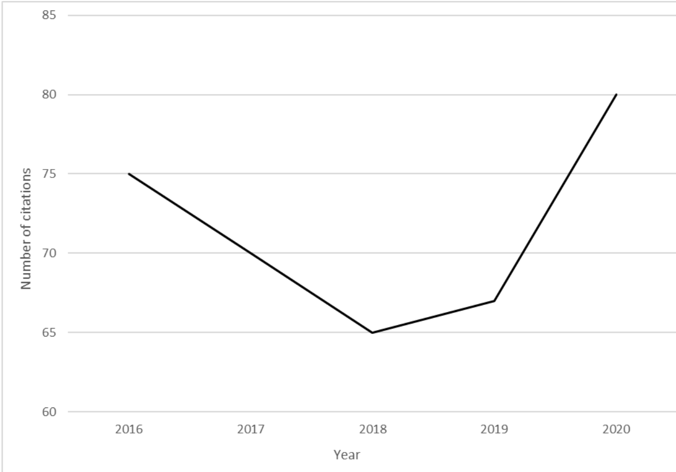
Papers using PSMSL data, 2018-2020

PSMSL collates statistics annually on the number of peer-reviewed published papers that use the PSMSL dataset. We search for papers that have cited Holgate et al (2013) as recommended (https://www.psmsl.org/data/obtaining/reference.php) or Woodworth and Player (2003), using Web of Science, ScienceDirect and Scopus. Several papers don’t use the preferred reference format, so we also use full text searches for the terms “PSMSL” or “Permanent Service”. We then manually filter the results to remove duplicates and papers that don’t actually make use of the dataset, e.g. those that refer to tidal analysis software packages. Currently this method is likely to miss papers that use the PSMSL dataset due to indirect referencing, and our statistics are likely to be biased low.

There were over 200 papers in journals covering a wide variety of subjects, including, technology, data science, paleoscience, climate, hazards, engineering and oceanography (1st January 2018 – 18th December 2020). The top three journals in terms of publications were Journal of Geophysical Research (19, impact factor 2.799), Advances in Space Research (12, impact factor 2.177) and Geophysical Research Letters (8, impact factor 4.58). There were also Nature papers (2, impact factor 42.778), Nature Communications (5, impact factor 12.121) and Proceedings of the National Academy of Sciences of the United States of America papers (2, impact factor 9.412).

In September 2019 the Intergovernmental Panel on Climate Change published the special report, which made use of the PSMSL dataset:

IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E.Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]. In press.



212 papers in 3 years:

2 Nature
5 Nature Communications
2 PNAS
4 Journal of Climate
8 GRL
19 JGR

Papers per year citing the PSMSL dataset

Meetings and media

Andy Matthews attended OceanObs’19 (Hawaii, September 2019) and presented a poster “The Permanent Service for Mean Sea Level (PSMSL): looking ahead”, which focused on plans to incorporate new data resulting from projects such as the European Union funded Horizon 2020 AtlantOS into long term, internationally recognised data banks, and ongoing efforts to ensure distributed data follow the FAIR data management principles (i.e. making data findable, accessible, interoperable, reusable). Highlights of the meeting included discussion sessions on Ocean Best Practices, which stressed the need for best practice documents for quality control and tidal analysis of tide gauge data, and Open Source Software, which highlighted the importance of clear licensing statements on released data and code. Andy also had the opportunity to meet with the Director of the University of Hawaii Sea Level Center to develop plans to distribute sea level data in a common, interoperable NetCDF format.

Elizabeth Bradshaw attended the Unified Analysis Workshop (Paris, October 2019) and gave a presentation “How the Permanent Service for Mean Sea Level is responding to change” as part of the Global Space Geodesy Infrastructure session. She also agreed to represent the PSMSL on the GGOS Working Group on Digital Object Identifiers (DOIs).

Andy Matthews and Elizabeth Bradshaw remotely attended the GGOS Days 2019 (November 2019) and participated in the discussions on the future of Focus Area 3 (Sea Level) and the Bureau of Networks and Observations open meeting. There was interest from the other services in the GNSS-IR at tide gauges.

Andy Matthews attended the Atmospheric Circulation Reconstructions over the Earth (ACRE) British Isles workshop (Reading, UK, February 2020) and gave a presentation on incorporating rescued data into the PSMSL dataset entitled "Recovered historical sea level data: what happens next?".

PSMSL staff organised and attended several sessions at the virtual European Geosciences Union (EGU) Assembly in May 2020. Svetlana Jevrejeva convened a session on sea level rise and Joanne Williams convened a session on tides. Andy Matthews discussed his presentation, “An International Data Centre for GNSS Interferometric Reflectometry Data for Observing Sea Level Change” (https://meetingorganizer.copernicus.org/EGU2020/EGU2020-9706.html) in the Sea level rise: past, present and future session. Elizabeth Bradshaw discussed her presentation “Sea level in the Global Geodetic Observing System”

(https://meetingorganizer.copernicus.org/EGU2020/EGU2020-3054.html) in the Global Geodetic Observing System: Improving infrastructure for future science session.

After the GGOS EGU session, Elizabeth Bradshaw joined the GGOS DOI working group in May 2020 and has attended the monthly meetings of the group, to contribute from a PSMSL perspective.

Both Elizabeth Bradshaw and Andy Matthews attended the eighth EuroGOOS Tide Gauge Task Team meeting by videoconference in July 2020. Andy Matthews gave a presentation on the PSMSL’s role as a GLOSS data centre, discussing data flow, products and web tools for users.

Elizabeth Bradshaw and Andy Matthews attended the World Data System Members’ Forum in September 2020. Elizabeth Bradshaw gave a presentation entitled “The Permanent Service for Mean Sea Level - Navigating the digital ocean”, focussing on the main goals and challenges for PSMSL over the coming five years.

Andy Matthews attended the World Meteorological Organization theme 1 preparatory workshop "Changing landscape of weather, climate and water data" in September 2020.

PSMSL staff were involved in a number of posters and presentations at the AGU fall meeting in December 2020. Andy Matthews gave a presentation entitled, “Extending Sea Level Records by Rescuing Historical Data using a Citizen Science Platform” and gave an eLightning presentation on “Updating the Permanent Service for Mean Sea Level Archive for the TRUST Era”. Elizabeth Bradshaw contributed to the GGOS presentation “GGOS Bureau of Networks and Observations: Network Infrastructure and Related Activities”.

Andy Matthews, Elizabeth Bradshaw and Angela Hibbert were on the organising committee of the 1st EuroSea Tide Gauge Network Workshop, held in January 2021. Andy Matthews gave a presentation on the Citizen Science data rescue work and Elizabeth Bradshaw talked about “Global sea level data - moving towards a free and FAIR flow”.

In January Elizabeth Bradshaw appeared on BBC local radio to discuss the UK tides Citizen Science project. Andy Matthews was interviewed by NPR radio about the same project, and the interview appeared in March on NPR morning edition.

In March the UK Met Office hosted a Climate Data Challenge virtual hackathon. Elizabeth Bradshaw attended on behalf of PSMSL as a sea level data expert, and Andy Matthews participated in the event, working on a project that used webcams and machine learning to look at wave overtopping.

In April, Andy Matthews attended the International Conference on Marine Data and Information Systems 2021 and presented “Using citizen science to rescue tide gauge data”.

Andy Matthews attended the EGU General Assembly 2021 on behalf of PSMSL and gave a presentation on “Rescuing historical sea level data using a citizen science platform”. Elizabeth Bradshaw also contributed to the presentation “The use of ERDDAP in a self-monitoring and nowcast hazard alerting coastal flood system” and the presentation given by the GGOS DOI Working Group, “News from the GGOS DOI Working Group”. Joanne Williams convened a session on tides and Svetlana Jevrejeva convened a session on sea level rise.

Training and visitors

Unfortunately, during the period covered by this report, we have been unable to host as many visitors or training courses as we would typically have done. However, we did have visitors to the National Oceanography Centre, Liverpool in October 2019 who met with the sea level group. We also demonstrated the Doodson-Légé tidal prediction machine.

Angela Hibbert hosted one-to-one sea level and MATLAB training in Mozambique in February 2020. Angela then ran two virtual training courses to Madagascar, one on tides in December 2020, and one on sea level and extremes in January 2021.

Staff and advisory group

In 2019 Elizabeth Bradshaw replaced Lesley Rickards as head of PSMSL, with Lesley continuing to provide support as a technical advisor. We are grateful to Lesley for leaving PSMSL on a solid footing, with a clear remit. At the time of writing, three members of staff work for PSMSL and we are supported by the NOC Sea Level sub-group. The sub-group provides technical and scientific advice and represents PSMSL at meetings and workshops.

- Elizabeth Bradshaw (PSMSL Head)
- Kathy Gordon (PSMSL quality assurance and communications)
- Angela Hibbert (NOC Sea Level group, Capacity building & network development)
- Chris Hughes (NOC Sea Level group, Scientific Advisor)
- Svetlana Jevrejeva (PSMSL Scientific Advisor)
- Andy Matthews (PSMSL Technical lead)
- Lesley Rickards (former Director, Technical Advisor)
- Joanne Williams (NOC Sea Level group, Software development, data rescue & storm surges)
- Simon Williams (NOC Sea Level group, Vertical Land Movement & GNSS-IR)
- Chris Wilson (NOC Sea Level group, Scientific Advisor)
- Philip Woodworth (NOC Sea Level group, Scientific Advisor)

The PSMSL reports formally to the IAPSO Commission on Mean Sea Level and Tides (President Dr. G.T. Mitchum, USA). It is also served by an Advisory Group which is currently under review and membership will be updated in 2021.

Summary

Despite the challenges of the previous year, the PSMSL has continued to be productive. We have been able to attend more conferences and meetings, due to not having to travel, and have focussed on initiating the Citizen Science pilot study. We have seen an increase in the papers published using the PSMSL dataset, which may be due to a decrease in the ability of users to collect new data, and encouraging reuse of existing data. The three IPCC working groups' contributions to the Sixth Assessment Report are due in the second half of 2021, and will make use of the PSMSL dataset. Future plans include:

- Improving our delivery of GNSS-IR data

  The development of GNSS-Interferometric Reflectometry (GNSS-IR) and the use of low cost GNSS sensors to measure sea level may help fill in gaps in the current global tide gauge network. Installing GNSS-IR for sea level at a site would also enable the monitoring of vertical land motion, and help measure and maintain geodetic ties between tide gauges and GNSS receivers. We are developing a mechanism to deliver NRT GNSS-IR data through ERDDAP.

- Improving our metadata in the context of FAIR, TRUST and CARE principles

  We are working towards FAIR (Findable, Accessible, Interoperable, and Reusable), TRUST (Transparency, Responsibility, User Focus, Sustainability and Technology) and CARE (Collective benefit, Authority to control, Responsibility, and Ethics) principles. The GLOSS 2012 implementation plan emphasised the need for an open data policy with timely, unrestricted access for all. Clarity over the source and provenance of data can be helped by developing unique identifiers for sites and instruments, and by the exchange of data via well-described data services using controlled vocabularies.

  We will continue to improve ocean observation metadata and will work with the Observations Coordination Group and OceanOPS on the metadata harmonisation working group. We are working with the EuroGOOS tide gauge task team to improve lineage metadata. PSMSL staff lead or sit on the technical working groups for site/station definition, unique ID definition and minimum metadata definition.

- Sea level data rescue

  We will report to the upcoming GLOSS meeting the results of the UK Tides Citizen Science pilot project. We will also issue the Zooniverse data with a DOI and publish a data rescue paper. We are currently exploring other techniques to digitise tide gauge charts, which may require the use of machine reading and learning techniques so data can be recovered algorithmically.

- Improving the PSMSL website

  We will continue to update and improve the PSMSL website and are working towards distributing our data in netCDF format via our ERDDAP server. We will make available automatic quality control software in MATLAB and Python to encourage the quality control of sea level data and improve the data flow of monthly and annual mean sea level data. We are working on improving links with other services e.g., we will link to the GGOS IDS web service to show DORIS beacons at tide gauges.

Annex 1: Selected publications

Smythe-Wright, D., Gould, W. J., McDougall, T. J., Sparnocchia, S., & **Woodworth, P. L.** (2019). IAPSO: tales from the ocean frontier. *History of Geo-and Space Sciences*, 10(1), 137-150.

Ponte, Rui M., et al. (2019). Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level. *Frontiers in Marine Science*, 6, 437.

Benveniste, J., et al. (2019). Requirements for a coastal hazards observing system. *Frontiers in Marine Science*, 6, 348.

Little, C. M., Hu, A., **Hughes, C. W.**, McCarthy, G. D., Piecuch, C. G., Ponte, R. M., & Thomas, M. D. (2019). The relationship between US east coast sea level and the Atlantic meridional overturning circulation: A review. *Journal of Geophysical Research: Oceans*, 124(9), 6435-6458.

Unnikrishnan, A. S., **Matthews, A**., Gravelle, M., Testut, L., Aarup, T., **Woodworth, P. L.**, Kumar, B. A. (2019) Tide gauges. In: Beal, Lisa M.; Vialard, Jérôme; Roxy, Mathew K., (eds.) Full Report. *IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR/IOC-GOOS Indian Ocean Region Panel (IORP)*, 31-34.

Filmer, M. S., **Williams, S. D. P.**, **Hughes, C. W.**, Wöppelmann, G., Featherstone, W. E., **Woodworth, P. L.**, & Parker, A. L. (2020). An experiment to test satellite radar interferometry-observed geodetic ties to remotely monitor vertical land motion at tide gauges. *Global and Planetary Change*, 185, 103084.

Arns, A., Wahl, T., Wolff, C., Vafeidis, A. T., Haigh, I. D., **Woodworth, P.**, Niehueser, S. & Jensen, J. (2020). Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts. Nature communications, 11(1), 1-9.

Bruneau, N., Polton, J., **Williams, J.**, & Holt, J. (2020). Estimation of global coastal sea level extremes using neural networks. *Environmental Research Letters*, 15(7), 074030.

Pérez Gomez, B., Aarup, T., **Bradshaw, E.**, Illigner, J., **Matthews, A.**, Mitchell, B., **Rickards, L.**, Stone, P. and Widlansky, M. and **Williams, J.**, (2020). *Quality Control of in situ Sea Level Observations: a Review and Progress towards Automated Quality Control, Vol. 1*.

Bradshaw, E., Ferret, Y., Pons, F., Testut, L., & **Woodworth, P.** (2020). *Workshop on sea level data archaeology*, Paris, 10-12 March 2020.

Kendon, M., McCarthy, M., **Jevrejeva, S.**, **Matthews, A.**, Sparks, T., & Garforth, J. (2020). State of the UK Climate 2019. *International Journal of Climatology*, 40, 1-69.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., **Hogarth, P.**, Zanna, L., Cheng, L. and Wu, Y.H., (2020). The causes of sea-level rise since 1900. *Nature*, 584(7821), 393-397.

Jevrejeva, S., Bricheno, L., Brown, J., Byrne, D., De Dominicis, M., **Matthews, A.**, Rynders, S., Palanisamy, H. and Wolf, J. (2020). Quantifying processes contributing to marine hazards to inform coastal climate resilience assessments, demonstrated for the Caribbean Sea. *Natural Hazards and Earth System Sciences*, 20(10), 2609-2626.

Hogarth, P., **Hughes, C. W.**, **Williams, S. D. P.**, & **Wilson, C.** (2020). Improved and extended tide gauge records for the British Isles leading to more consistent estimates of sea level rise and acceleration since 1958. *Progress in Oceanography*, 184, 102333.

Woodworth, P. L. (2020). Celebrating 100 years of tidal science on Merseyside. *Ocean Challenge*, 24(1), 10-11.

Woodworth, P. L. (2020). Tide prediction machines at the Liverpool Tidal Institute. *History of Geo-and Space Sciences*, 11(1), 15-29.

Larson, K. M., Lay, T., Yamazaki, Y., Cheung, K. F., Ye, L., **Williams, S. D. P.**, & Davis, J. L. (2021). Dynamic sea level variation from GNSS: 2020 Shumagin earthquake tsunami resonance and Hurricane Laura. *Geophysical Research Letters*, 48(4), e2020GL091378.

Hogarth, P., **Pugh, D. T.**, **Hughes, C. W.**, & **Williams, S. D. P.** (2021). Changes in mean sea level around Great Britain over the past 200 years. *Progress in Oceanography*, 192, 102521.

Woodworth, P. L., Hunter, J. R., Marcos, M., & **Hughes, C. W.** (2021). Towards reliable global allowances for sea level rise. *Global and Planetary Change*, 103522.

Annex 2: Stations received by country, 2019-2020

American Samoa	1	Maldives	3
Antarctica	4	Malta	1
Argentina	4	Marshall Islands	3
Australia	74	Martinique	1
Bahamas	1	Mauritius	2
Bangladesh	1	Mayotte	1
Belgium	3	Micronesia, Federated States of	3
Bermuda	1	Monaco	1
Canada	47	Myanmar	2
Cape Verde	1	Nauru	1
Chile	15	Netherlands	11
China	6	New Caledonia	5
Cocos (Keeling) Islands	1	New Zealand	13
Colombia	1	Northern Mariana Islands	1
Cook Islands	2	Norway	23
Costa Rica	2	Oman	3
Croatia	5	Palau	1
Cuba	11	Panama	1
Curaçao	1	Papua New Guinea	1
Dominican Republic	2	Peru	2
Ecuador	3	Philippines	22
El Salvador	1	Portugal	5
Fiji	3	Puerto Rico	7
Finland	13	Réunion	2
France	36	Russian Federation	44
French Guiana	2	Saint Pierre and Miquelon	1
French Polynesia	6	Samoa	1
Georgia	2	Senegal	1
Germany	8	Seychelles	1
Greece	18	Singapore	10
Greenland	3	Solomon Islands	1
Grenada	1	South Africa	9
Guadeloupe	1	South Georgia & South Sandwich Is.	1
Guam	2	Spain	49
Haiti	1	Svalbard and Jan Mayen	3
Hong Kong	6	Sweden	27
Iceland	1	Tanzania, United Republic of	1
India	11	Thailand	5
Indonesia	8	Tonga	1
Isle of Man	1	Tuvalu	1
Israel	7	United Kingdom	34
Italy	3	United States	127
Japan	99	United States Minor Outlying Islands	3
Jersey	1	Uruguay	2
Kenya	2	Vanuatu	1
Kiribati	3	Viet Nam	2

Korea, Republic of	46
Lithuania	1
Malaysia	18

Virgin Islands, U.S.	4
Wallis and Futuna	2
Åland Islands	1

Annex 3: Data suppliers, 2019-2020 (number of stations)

Servicio de Hidrografia Naval, Argentina	Argentina	3
Manly Hydraulics Laboratory	Australia	11
National Tidal Centre	Australia	78
Agency for Maritime and Coastal Services	Belgium	3
Canadian Hydrographic Service	Canada	47
Servicio Hidrografico y Oceanografico de la Armada	Chile	16
National Marine Data and Information Service	China	6
Hidrografski Institut, Split	Croatia	5
Cuban National Tidal Service	Cuba	11
Danish National Space Center	Denmark	3
Finnish Meteorological Institute	Finland	14
Institut Geographique National, France	France	1
Service Hyd. et Ocean. de la Marine	France	55
Dept. of Oceanology and Meteorology, Georgia	Georgia	2
Bundesamt fur Seeschifffahrt und Hydrographie Hamburg	Germany	8
Hellenic Navy Hydrographic Service	Greece	18
Hong Kong Observatory	Hong Kong	6
Icelandic Coast Guard - Hydrographic Dept.	Iceland	1
Survey of India	India	11
Israel Oceanographic and Limnological Res. ltd.	Israel	1
Survey of Israel	Israel	6
ARPAE	Italy	1
Instituto Talassografico di Trieste	Italy	2
Geographical Survey Institute	Japan	25
Japan Meteorological Agency	Japan	54
Japan Oceanographic Data Centre, M.S.A.	Japan	20
Korea Hydrographic and Oceanographic Agency	Korea, Republic of	46
Geodetic Institute, Vilnius Gediminas Technical University	Lithuania	1
Department of Survey and Mapping	Malaysia	18
Malta Maritime Authority	Malta	1
Meteo – France	Martinique	1
Meteorological Services, Mauritius	Mauritius	2
Rijkswaterstaat	Netherlands	11
Land Information New Zealand	New Zealand	12
Norwegian Mapping Authority	Norway	24
National Mapping and Resource Information Authority	Philippines	22
Hydrographic Institute	Portugal	5
Arctic and Antarctic Research Institute	Russian Federation	40
World Data Center B1	Russian Federation	6
Maritime Port Authority of Singapore	Singapore	10
Directorate of Hydrography, S.A.	South Africa	9
Dr. Josep Pascual Massaguer	Spain	1

Geolab	Spain	1
Instituto Espanol de Oceanografia	Spain	11
Puertos del Estado	Spain	36
Swedish Met. and Hyd. Institute	Sweden	27
Oceanographic Division, Hydrographic Dept.	Thailand	5
National Oceanography Centre / Environment Agency	United Kingdom	38
NOAA / NOS	United States	143
Panama Canal Commission	United States	1
University of Hawaii Sea Level Centre	United States	56

Annex 4: Acronyms

ACRE Atmospheric Circulation Reconstructions over the Earth
DOI Digital Object Identifier
EGU European Geosciences Union
EuroGOOS European Global Ocean Observing System
GESLA Global Extreme Sea Level Analysis
GGOS Global Geodetic Observing System
GLOSS Global Sea Level Observing System
GNSS-IR Global Navigation Satellite Systems Interferometric Reflectometry
GOOS Global Ocean Observing System
GRL Geophysical Research Letters
IAG International Association of Geodesy
IAPSO International Association for Physical Sciences of the Oceans
IHO International Hydrographic Organization
IPCC Intergovernmental Panel on Climate Change
ISC International Science Council
IUGG International Union of Geodesy and Geophysics
JGR Journal of Geophysical Research
NERC Natural Environment Research Council
NOAA National Oceanic and Atmospheric Administration
NOC National Oceanography Centre
NOS National Ocean Service
NRT Near Real Time
MSL Mean Sea Level
OCG Observations Coordination Group
PNAS Proceedings of the National Academy of Sciences of the United States of America
PSMSL Permanent Service for Mean Sea Level
WDS World Data System

Journal of Geodesy

http://link.springer.com/journal/190

Editor-in-Chief: Jürgen Kusche (Germany)
Assistant-Editor-in-Chief: Peiliang Xu (Japan)

Activity Report

Journal of Geodesy (JoG) is an international journal concerned with the science of geodesy and related inter-disciplinary sciences. JoG is the official scientific journal of the IAG and it publishes monthly research articles, review papers, and short notes. Its publishing company, based on an agreement with IAG, is Springer Heidelberg.

The Editor-in-Chief (EiC) is responsible for the scientific content of the journal. He, and since 2021 the Assistant-Editor-in-Chief (AEiC), make the final decision on whether a manuscript is accepted for publication, advised by an Editorial Board (EB). The 2019-2023 EB comprises currently 25 members (associate editors) from 16 countries:

T. Balz (China), J. Benveniste (Italy), S. Bettadpur (USA), T. v. Dam (Luxemburg), Y. Gao (Canada), S.-C. Han (Australia), B. Gunter (USA), T. Hobiger (Germany), C. Huang (China), U. Hugentobler (Germany), A. Jäggi (Switzerland), A. Klos (Poland), H.-J. Kutterer (Germany), F. Lemoine (USA), Z. Malkin (Russia), V. Michel (Germany), F.G. Nievinski (Brazil), N. Penna (UK), R. Riva (The Netherlands), M. Schindelegger (Germany), Y. Shen (China), I. Tziavos (Greece), M. Vermeer (Finland), P. Wielgosz (Poland), Y. Yuan (China).

JoG uses the Editorial Manager (EM), a web-based peer review system, which allows easy manuscript submission, provides author information and e-mail updates, and helps reducing the turnaround time. In recent years, EM has added automated workflows e.g. for plagiarism checking and authorship change requests.

JoG publishes special issues on topics of general interest to the geodetic community, where all contributions must be of highest standards. The most recently published special issue (Volume 93, issue 11, November 2019) was dedicated to “Satellite Laser Ranging”, and two other Special Issues (“Reference Systems in Phsical Geodesy” and “CONT17”) are currently in preparation.

Indeed, JoG would like to encourage authors to (1) submit review papers and (2) initiate special issues related to topics of high interest to the geodetic community. JoG publishes also short notes once in a while, when topics are timely and of interest to a broad readership.

Impact Factor

The Impact Factor (IF) of JoG has shown some variability over the last years; the current (2019) Impact Factor is 4.806, based on Thomson Reuters JCR (Journal Citation Report). Measured by the IF, JoG is 2019 among the top 10 journals within Springer's topical journal collections: rank 7 out of 30 in Remote Sensing journals, and rank 8 out of 85 in Geochemistry and Geophysics journals. For the last years JoG has seen the following evolution of the IF (the 2020 IF will likely be published in July 2021):

Table 1: JoG Impact Factor for 2015-2019

Year	Impact Factor
2015	2.486
2016	2.949
2017	4.633
2018	4.528
2019	4.806

Submissions and acceptance

The number of submissions has steadily increased with on average about 10% additional submissions each year. The top 10 countries with the highest number of submissions are China, Germany, US, France, Australia, Canada, Iran, Italy, Netherlands, and the UK.

Table 2: JoG submitted and accepted manuscripts (per calendar year) for 2015-2020

Year	submitted	accepted
2015	247	77
2016	271	97
2017	260	97
2018	307	103
2019	364	101
2020	389	114

The acceptance rate has slightly gone down to around 29% now.

Review statistics and turnaround time

The JoG knows a nominal review period of 28 days. Table 3 shows some statistics of the review process. Indeed, the average number of days to complete a review is nearly stable at about 32 – 35. However, as it is obvious from the table, in order to obtain three reviews (which is nominal) the associate editors have to invite, on average, five to six potential reviewers. The other observation is that turnaround time measured in days from submission to first decision had increased in 2019; this can be largely explained by the increased editorial load from receiving more submissions but it appears to be brought back in 2020.

Table 3: JoG number of review invitations and completed reviews and average turnaround time (submission to first decision in days) for 2015-2020

Year	Review invitations	Completed reviews	Average Turnaround time
2015	953	596	56.1
2016	1297	787	59.9
2017	1212	761	70.4
2018	1446	829	70.1
2019	1717	849	92.4
2020	1796	953	70.9

Editorial policy

The journal's editorial policy is continuously developed through discussions among the EB, with Springer and with the IAG EC, and based on author and reviewer communications. A summary of the most important editorial policies and recent updates with respect to workflows is provided in Kusche and Xu (2021).

IAG Young Authors Award

This award is to draw attention to important contributions by young scientists in the Journal of Geodesy and to foster excellence in scientific writing. On the basis of suggestions made by the EB, the EiC provides a shortlist of award candidates to the IAG EC every two years.

Kusche J. and P. Xu (2021): Journal of Geodesy: editorial policies in view of increased new paper submissions, *J. Geodesy* 95:61

IAG Symposia Series

Editor-in-Chief: Jeff Freymueller, USA
Assistant Editor-in-Chief: Laura Sánchez, Germany

Editor-in-Chief Jeff Freymueller moved from the University of Alaska Fairbanks to Michigan State University in late 2018. That move caused a great deal of disruption for 2018 through 2019, but Assistant Editor-in-Chief Laura Sánchez increased her workload in response. Her strong contributions are very much appreciated!

Transition to Electronic Books and Open Access

A key decision was made for the series during the 2015-2019 period, which was to complete the transition from paper books to electronic books, and for the papers/volumes to be Open Access. These decisions came into effect starting with the Montreal volume for papers presented at the 2019 IUGG meeting. A new contract is now in place with Springer, and this makes small volumes much more affordable than in the past. IAG pays for the open access fees for the volumes for the General Assemblies and Scientific Assemblies, and depending on meeting size may need to contribute to the cost for other symposia. The new policies are:

- All IAG sponsored Symposia are expected to publish a Proceedings volume in the series
- Symposia organizers will include $50 in their registration fees for the cost of the Proceedings

Completion of older volumes

The publishing of two older volumes was completed in 2019-2021:

- Volume 150. Fiducial Reference Measurements for Altimetry: Proceedings of the International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications
- Volume 151. Proceedings of the IX Hotine-Marussi Symposium

Recently completed and ongoing volumes

The COVID-19 pandemic caused delay or cancellation of a number of planned symposia, so only two symposia have been held that have volumes in the series:

- Volume 152. Beyond 100: The Next Century in Geodesy *[Montreal IUGG, in final steps of publication, with all papers completed]*
- Volume 153. 5th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements *[editorial work in late stages, working on final papers]*

Restricting papers to those presented at IAG Symposia

There was an awkward situation that arose with the Hotine-Marussi volume. One paper was submitted that had not been presented at the symposium, although the author attended. The paper was peer reviewed through the regular process, handled by one of the symposium organizers as AE, and then accepted based on that review. The paper happened to be critical of some ideas presented by one of the presentations made at the meeting, and this was a cause of unhappiness on the part of those who had been criticized (and whose own paper was not published). To my knowledge, this is the first time that we have had a paper submitted that was not presented at the symposium; the usual case is that people present at the meeting but do not submit a paper.

After discussion with the IAG EC, we decided that papers in the series needed to be based on presentations that were made at the symposium in question. There were pros and cons discussed by the EC, and there will be judgement calls needed given that sometimes work is improved between the meeting and the paper submission, and we do not wish to discourage this. We are asking Springer if they can add a question to their website submission form to identify the presentation at the meeting that the paper is based upon.

Other Notable Points and Future Outlook

- Communication with Springer has not always been simple, as it was not always clear who should be the point of contact for different things. This has been clarified, and Annett Büttner is the primary point of contact there for the series, for issues that go above the purely technical (such as handling of papers in EM). This is working more smoothly than in the past.
- In consultation with the EC, we decided to increase the maximum paper length for IAG Symposia series papers from 6 pages to 8 pages, or 10 pages for invited papers. The editors may extend these limits further for individual papers, if needed. Because of the way the Springer contract scales this is unlikely to increase costs for IAG (it is unlikely but possible that it would bump a volume up to the next price tier).
- IAG should plan for a changeover in the Editorship for the 2023-2027 period. The structure of an Editor-in-Chief and Assistant Editor-in-Chief has worked well, and communication and coordination can be facilitated well using a shared Google email account and Google Docs.