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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 online 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 41 contains the reports of all IAG components for the period 2015 to 2019 and is presented at the IUGG-IAG General Assembly in Montreal, Canada, July 8 to 18, 2019.

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://iag.dgfi.tum.de). Printed versions are available on request. As the term of the IAG Secretary General ends according to the IAG Bylaws after three periods at the latest, the position is handed over to Markku Poutanen at the end of July 2019, and the IAG Office is moving to the Finnish Geospatial Research Institute (FGI), National Land Survey of Finland, e-mail: iag.office@nls.fi.

Hermann Drewes
IAG Secretary General 2007-2019

Franz Kuglitsch
Assistant Secretary

Commission 1 – Reference Frames

http://iag.geo.tuwien.ac.at/c1/

President: Geoffrey Blewitt (USA)
Vice President: Johannes Böhm (Austria)

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Overview

Commission 1 activities have been dealing with the theoretical aspects of how best to define reference systems, and how such reference systems can be used for practical and scientific applications. The reader is referred to the Geodesists Handbook 2016 for further details on the objectives of Commission 1 and its components. Commission 1 has been closely interacting with other IAG components including Commissions, ICCT, Services, and GGOS, where reference system aspects are of concern. Many of these interactions are facilitated by Joint Study Groups and Joint Working Groups of Commission 1. This report summarizes the work performed during 2015-2019 by the various components of Commission 1, including the Sub-commissions and their Working Groups, and Joint Working Groups who have their primary affiliation with Commission 1.

In addition to the work performed by the components of Commission 1, the following summarizes activities in 2015-2019 that were performed on behalf of the entire Commission:

- A web site for Commission 1 was established at http://iag.geo.tuwien.ac.at/c1/.
- The terms of reference and structure of Commission 1, and membership/descriptions of its components were detailed in our contribution to the Geodesists Handbook 2016.
- The Steering Committee of Commission 1 has met annually, in accordance with the IAG bylaws:
    1. Vienna, Austria, April 2016;
    2. Kobe, Japan, August 2017;
    3. Pasadena, USA, July 2018; and
    4. Montreal, Canada, July 2019.
- Commission 1 leadership convened four IAG Symposia:
    1. at the IAG-IASPEI Joint Assembly in Kobe, Japan, July-August 2017;
    2. "Reference Frames for Applications in Geosciences" (REFAG) at the COSPAR 42nd Assembly in Pasadena, California, USA, July 2018;
    3. at the IUGG General Assembly in Montreal, Canada, July 2019, with 5 oral sessions and one poster session scheduled; and
    4. at the COSPAR 43rd Assembly in Sydney, Australia, in August 2020, which will be chaired by Heike Peter (Germany), Chair of the Technical Panel on Satellite Dynamics (PSD).
- Considering that Commission 1 is defined to be identical with Sub-commission B2 of COSPAR, symposium 2 and symposium 4 listed above serve to reinvigorate the connection between IAG and COSPAR.
- Commission 1 was represented at all the IAG Executive Committee Meetings, at which progress reports were presented:
    1. San Francisco, USA (2015);
    2. Potsdam, Germany (2016);
    3. Vienna, Austria (2017), and
    4. Washington DC, USA (2019), and
    5. Montreal, Canada (2019)
- Commission 1 was represented at the IAG Strategic Planning Meeting in Potsdam, Germany, 2016.

The following pages now provide 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 focusses 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.

The GGOS Working Group "Performance Simulations and Architectural Trade-Offs (PLATO)" was installed in 2013. In the IAG structure 2015-2019 PLATO acts as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. In 2016 PLATO was converted into a "Standing Committee" in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups.

In addition to a large variety of SLR, LLR and VLBI simulations covering different aspects related to the design of ground- and space-based architecture of measurement systems, to improved analysis methods, and to observation scenarios and their impact on TRF accuracy and stability, PLATO members contributed important simulation results for the proposal for the EGRASP/Eratosthenes mission proposal in reply of ESA's Earth Exploror-9 call prepared under the lead of Richard Biancale.

Working Group 1.1.1 on co-location using clocks and new sensors was set up. A position paper was prepared focusing on the relevance of precise time and frequency distribution at fundamental stations and corresponding closure measurements as a method to monitor local ties. A meeting is planned addressing the next generation geodetic stations and metrology concept. Activities of the ESA Topical Team on Geodesy, Clocks and Time Transfer exploit synergies with the IAG WG 1.1.1.

Terms of Reference

Space techniques play a fundamental role for the realization and dissemination of highly accurate and long-term stable terrestrial and celestial reference frames as well as for accurate monitoring of the Earth orientation parameters linking the two fundamental frames. The current space geodetic techniques contributing to ITRF and ICRF, i.e., Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) have particular strengths and technique-specific weaknesses.

Strengths of the techniques are exploited by combining them making use of fundamental sites co-locating more than one technique. Sub-commission 1.1 focusses 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 of stations and satellites, troposphere parameters, and clock parameters.

Working Groups of Sub-commission 1.1:

WG 1.1.1: Co-location using Clocks and New Sensors

Chair: *Ulrich Schreiber (Germany)*

Members
- *Sten Bergstrand (Sweden)*
- *Srinivas Bettadpur (USA)*
- *Rüdiger Haas (Sweden)*
- *Younghee Kwak (Germany)*
- *David McCormick (USA)*
- *Markku Poutanen (Finnland)*
- *Ivan Prochazka (Czech Republic)*

Activities and publications during the period 2015-2019

The establishment of accurate local ties of different space geodetic techniques at fundamental geodetic observatories poses a long-standing problem. While geometric ties can be determined at sub-millimeter-level, the relation to physical phase centers of the instruments and temporal stability of such offsets are usually known with significantly lower precision. This working group evaluates novel ways for inter-technique cross-calibration at geodetic sites using existing and new sensors and technologies, such as highly accurate time and frequency transfer, ultra-stable clocks, and co-location targets. The activities of the working group are closely related to IAG JWG 2.1 on Relativistic Geodesy. A corresponding coordination meeting took place in Hannover, Germany, on April 12, 2017.

1. Position Paper

A position paper addressing the main topics of the working group was formulated stimulating the discussions among the WG members. The position paper addresses the issue of local ties at geodetic observatories and highlights a concept allowing to access the physical phase center of SLR as well as VLBI and other space geodetic instruments through closure measurements of travel times. The concept involves precise time distribution of timing signals between the instruments and a common calibration target through compensated optical fibers.

Figure 1.1.1 shows the concept of a demonstrator that is developed at the Geodetic Observatory in Wettzell allowing to cross-calibrate the reference points of several VLBI telescopes. A precisely time-tagged signal is broadcast by a reference target and received by the radio telescopes through standard receive channels. The signal is registered with respect to a reference signal (p-cal and formatter) with precisely known time relation to the broadcast signal. The concept thus allows to precisely relate the geometric free space travel distance from the reference target to instrument reference point through time closure measurements.

The highlighted concept is currently built up at the Geodetic Observatory Wettzell in the framework of the research unit FOR 1503 funded by the German Sciene Foundation (DFG). Similar concepts and performance and implementation issues for the other space geodetic techniques are discussed in the context of the working group.

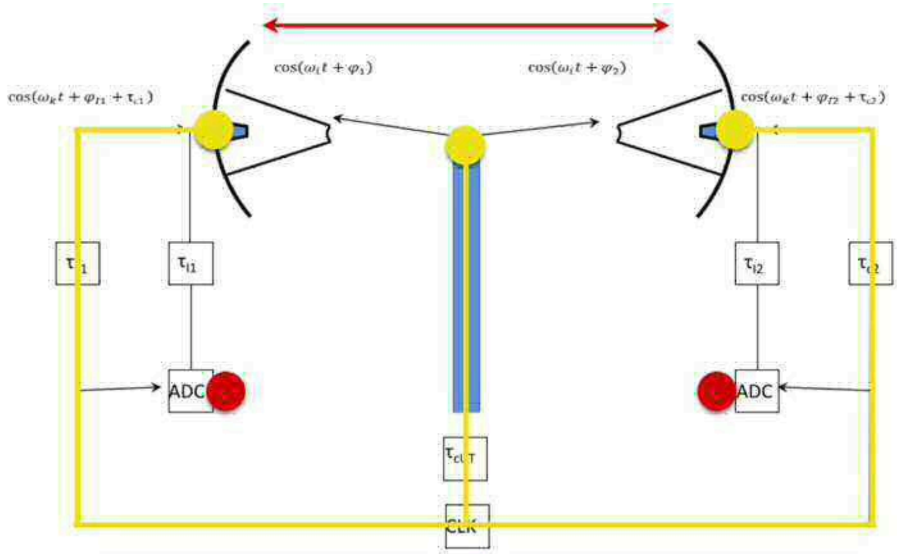

Fig 1.1.1. Concept for precise cross-calibration of the reference points of VLBI telescopes through time closure measurements.

2. Meeting on Next Generation Geodetic Stations and Metrology

A workshop on Next Generation Geodetic Stations and Metrology is planned by Srinivas Bettadpur at Center for Space Research at University of Texas at Austin for late summer 2017. Background is the operation of the McDonald Geodetic Observatory as a multi-technique geodetic observatory within the NSAS's Next Generation Space Geodesy Network. The goal of the workshop is to develop a list of areas of attention and research that bear the potential for leading to an idealized geodetic observatory supporting the needs of a future terrestrial reference frame.

The effort attempts to reassess the available knowledge from the viewpoint of metrology science and its implementation with the needs defined by the next generation reference frame. Topics of discussion are in particular the contribution of distribution of precise time and frequency between the different systems at an observatory, concepts of inter-system survey ties at ppm-level, contribution of gravity measurements, and requirements for characterization of the environment.

3. ESA Topical Team on Geodesy, Clocks and Time Transfer

In the framework of the ESA Topical Team on Geodesy, Clocks and Time Transfer a workshop is in planning focussing on distribution of precise time between geodetic observatories using space techniques. The topical team is chaired by Ulli Schreiber and receives funding from ESA for the organization of workshops. It consists of an international group of experts and coordinates the activities of different research groups working on topics related to clocks and time transfer for geodetic applications, activities that are relevant in the context of the tasks of IAG WG 1.1.1. The topical team identifies scientific problems and relevant new technologies and organizes topical workshops. A main focus is the exploitation of the Atomic Clock Ensemble in Space (ACES) that will be launched in 2020 to the International Space Station.

JWG 1.1.2: Performance Simulations and Architectural Trade-Offs (PLATO)

Chair: *Daniela Thaller (Germany)*
Vice Chair: *Benjamin Männel (Germany)*

Members

- *AIUB (Astronomical Institute, University of Bern, Switzerland)*
- *BKG (Bundesamt für Kartographie und Geodäsie, Germany)*
- *CNES (Center National d'Etudes Spatiales, France)*
- *DGFI-TUM (Deutsches Geodätisches Forschungsinstitut, TU München, Germany)*
- *ETH Zürich, Switzerland*
- *GFZ (GeoForschungsZentrum Potsdam, Germany)*
- *GRGS (Group de Recherche de Géodésie Spatial, France)*
- *GSFC (Goddard Space Flight Center, USA)*
- *IfE (Institut für Erdmessung, University of Hannover, Germany)*
- *IGN (Institut National de l'Information Géographique en Forestièr, France)*
- *JCET (Joint Center for Earth Systems Technology, USA)*
- *JPL (Jet Propulsion Laboratory, USA)*
- *NMA (Norwegian Mapping Authority)*
- *TU Berlin, Germany*
- *TU München, Germany*
- *TU Wien, Austria*

Activities and publications during the period 2015-2019

The terrestrial reference frame (TRF) is the foundation for virtually all space-based and ground-based Earth observations. Positions of objects are determined within an underlying TRF and the accuracy with which objects can be positioned ultimately depends on the accuracy of the reference frame. In order to meet the anticipated future needs of science and society GGOS has determined that the accuracy and stability of the ITRF needs to be better than 1mm and 0.1mm/y, respectively. The current ITRF is at least an order of magnitude less accurate and stable than these goals. Further improvements of the ITRF are thought to be achieved by:

- Developing next generation space-geodetic stations with improved technology and system performance;
- Improving the ground network configuration in view of global coverage and co-locations;
- Improving the number and accuracy of surveys between co-located stations;
- Deploying, improving and optimizing space-based co-locations.

This joint working group aids these activities and helps to evaluate the impact on the accuracy and stability of future ITRFs. To this purpose a variety of aspects related to design of ground- and space-based architectures of measurement systems and their impact on TRF accuracy and stability are investigated. WG members develop improved analysis methods using all existing data and co-locations and carry out extensive simulations for future improvements and optimization of ground network, space segment and observation scenarios.

Organization

On the meeting of the GGOS Bureau of Networks and Observations during EGU in April 2016 it was decided that PLATO will be a “Standing Committee” in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups. In the IAG structure 2015-2019 PLATO acts also as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. This report overlaps with the corresponding Traveaux report for the GGOS Bureau of Networks and Observations.

In June 2016 Richard Gross (JPL) who co-chaired PLATO since 2013 handed over the co-chair to Benjamin Männel (GFZ).

Members of PLATO are informed about ongoing and planned activities with a newsletter.

1. Meetings

In regular meetings in conjunction with the EGU, Vienna (annually in April), WG members report about the progress of the work related to PLATO including performed and planned studies, results from simulations and analysis of real data and the results of the groups have been compared.

2. Achievements

Several members were successful in acquiring funding for simulation studies (DGFI-TUM, AIUB, TU Vienna, GFZ). Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn). The following sections give information on achievements related to specific areas.

SLR Simulations

Simulations for improved global SLR station network were carried out. Simulations for an SLR station in Antarctica (Syowa, co-located with VLBI) showed the benefit for geocenter parameter determination. Simulations for improved SLR tracking of GNSS satellites started.

LLR Simulations

Simulations related to more LLR data assuming millimeter ranging accuracies (up to three future single-prism reflectors on the moon and two additional LLR sites on the southern hemisphere) were carried out. The effect on the lunar reflector coordinates, the mass of the Earth-Moon system and two relativistic parameters (temporal variation of the gravitational constant and equivalence principle) was studied. Especially, the measurements to the new type of reflectors would lead to an improved accuracy of the estimated parameters up to a factor of 6 over a decade of new measurements.

VLBI Simulations

Simulations (and analysis of data as far as available) for new VGOS telescopes employing next generation broadband VLBI technology, showed that the GGOS requirements of 1 mm accuracy and 0.1 mm/year stability will likely be fulfilled for the reference frame. Simulations and analysis of VLBI tracking data of GNSS satellites and the Chinese APOD cube-satellite (i.e. using co-locations in space) were carried out using the Australian VLBI antennas for several sessions during 2016.

Local Ties

The impact of the Local ties 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. It was shown that the LT standard deviations of 1 mm or better lead to the best datum realization of an SLR+VLBI-TRF. Simulating wrong LT indicate Wettzell, Badary and AGGO as important LT sites in the SLR and VLBI combination.

E-GRASP/Eratosthenes

PLATO members were actively participating on the preparation E-GRASP/Eratosthenes proposal lead by Richard Biancale. The proposal was submitted in 2016 in response of the ESA Earth Explorer-9 call. After good scientific assessment by ESA a revised version of the proposal was submitted 2017 EE9 call. The satellite mission proposed co-locates all fundamental space-based geodetic instruments, including GNSS and DORIS receivers, laser retro-reflectors, and a VLBI transmitter on the same satellite platform on a highly eccentric orbit with particular attention on the time and space metrology on board.

A variety of simulations were performed by PLATO members both for discriminating the best orbital scenario according to many geometric/technical/physical criteria and for assessing the expected performances on the TRF according to GGOS goals.

3. Recommended Future Work

It is recommended that future work include the examination of trade-off options for station deployment and closure, technology upgrades, impact of site ties, etc. Simulation studies related to ground infrastructure are planned to assess impact on reference frame products of network configuration, system performance, technique and technology mix, co-location conditions, site ties while simulation studies related to space infrastructure are planned to assess impact on reference frame products of: co-location in space, space ties, available satellites.

Work to project future network capability over the next 5- and 10-year periods using projected network configuration in new system implementation is recommended. Improved analysis methods for reference frame products by including all existing data and available co-locations should be developed and analysis campaign with exchanged simulated observations.

4. Conferences

PLATO is present at the main geodetic. Presentation were given at the IGS Workshop in Sydney in Feb. 2017, IVS General Meeting in Johannesburg in March 2016, the EGU General Assembly in Vienna in April 2015 and April 2016, the IUGG General Assembly in July 2015, the ILRS Worhshop in Potsdam in October 2016, at the AGU Fall Metting in San Francisco in December 2016. A presentation was given at the IAG Scientific Assembly July, 30 - August 4, 2017 in Kobe, Japan with title "The GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)" highlighting results of ongoing studies and giving first recommendations.

5. Publications

Ampatzidis D, König R, Glaser S, Schuh H (2016), The Assessment of the Temporal Evolution of Space Geodetic Terrestrial Reference Frames, IAG Symposia Series, DOI 10.1007/1345_2016_251

Glaser S, Ampatzidis D, König R, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2016), Simulation of VLBI Observations to Determine a Global TRF for GGOS, IAG Symposia Series, DOI 10.1007/1345_2016_256

Glaser S, König R, Ampatzidis D, Nilsson T, Heinkelmann R, Flechner F, Schuh H (2017), A Global Terrestrial Reference Frame from simulated VLBI and SLR data in view of GGOS, Journal of Geodesy, DOI 10.1007/s00190-017-1021-2

Plank L, Hellerschmied A, McCallum J, Böhm J, Lovell J (2017), VLBI observations of GNSS satellites: from scheduling to analysis. J Geod, Springer, doi:10.1007/s00190-016-0992-8

Schuh H, König R, Ampatzidis D, Glaser S, Flechtner F, Heinkelmann R, Nilsson T (2016), GGOS-SIM – Simulation of the Reference Frame for the Global Geodetic Observing System, IAG Symposia Series, DOI 10.1007/1345_2015_217

Sub-commission 1.2: Global Reference Frames

Chair: *X. Collilieux (France)*

Overview

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). Since 2016, it includes the link to world height system (WHS). It studies fundamental questions and more practical aspects that can improve current terrestrial reference frame (TRF) determinations.

Numerous activities are actually realized in other IAG-related structures, namely:
• Sub-commission 1.3 on "Regional reference frames", including EUREF, SIRGAS…
• International Earth Rotation and Reference Systems Service (IERS)
• Other relevant IAG services (IGS, ILRS, IVS, IDS)
• IAG Global Geodetic Observing System (GGOS)
• Inter-Commission Committee on Theory.
We therefore encourage the reader to refer to their individual reports.

At first, this report highlights recent works with respect to the relativistic modelling of reference frames. Thus, it presents the ITRF2014, the latest realization of the International Terrestrial Reference System (ITRS), which is published by the International Earth Rotation and Reference Systems Service (IERS). It provides the coordinates of a set of points at the Earth and delivered in a self-consistent Terrestrial Reference Frame with their variance-covariance information. Those are computed for more than 35 years of observations from the four space geodetic techniques, namely: DORIS, GNSS, SLR and VLBI. The report also presents the work of the IERS combination centers which conduct researches on Terrestrial Reference Frame determination. Whereas vertical coordinate reference system was up to now realized at the continental scale, work is underway to realize a world height system. This activity is summarized in this report. Such a realization should be interoperable and consistent with the current geometric determination of the Terrestrial Reference System. Recent Researches on local ties and space ties are then summarized. Finally, undergoing work on ISO standardization and conventions is summarized.

Summary of the Sub-commission's activities during the period 2015-2019

Contributors to this report:

- *Z. Altamimi*
- *R. Biancale*
- *C. Boucher*
- *X. Collilieux (president)*
- *P. Delva*
- *R. Gross*
- *L. Sanchez*
- *M. Seitz*
- *N. Stamatakos*
- *D. Thaller*
- *S. Williams*

Relativistic modelling

Relativistic reference frames are based on a network of clocks in space linked with time transfer technologies. Such realized frames are entirely decoupled from ground fixed stations and could be used to reference any point on the Earth's surface.

Recent work by Kostić et al. (2015) is worth reporting here. They have presented a new method for implementing a relativistic positioning system with a GNSS. The spacetime metric is described with a perturbed Schwarzschild metric, while the dynamics is completely solved using a first order perturbation approach, including perturbations due to Earth multipoles (up to the 6th), the Moon, the Sun, Venus, Jupiter, solid tide, ocean tide, and Kerr rotation effect. The authors find that positioning in this perturbed spacetime is highly accurate and time efficient already with standard numerical procedures and laptop.

Within IAG, relativistic modelling is investigated in JWG 2.1 "Relativistic Geodesy: First Steps Towards a New Geodetic Technique". See the Commission 2 report for more details.

ITRS center and ITRF2014

Overview

The main activities of the ITRS Center during the period 2015-2019 include the maintenance of the ITRF network, database and website. The full report is available in the report of the ITRS center in the IERS section of the travaux. Main points are summarized in the following.

Activities and publications

A) The main activities of the ITRS Center related to research analysis during this period include:

- The ITRS Product Center collects all new surveys operated by either Institut national de l'information géographique et forestière (IGN) or the hosting agencies of ITRF co-location sites. At the occasion of the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Center. These new survey results were made available via the ITRF website after the release of the ITRF2014.
- The operational entity of the ITRS Center at the IGN Survey department has prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not used with mm precision.

B) Publication of ITRF2014:

- During the preparation of ITRF2014, various tests and combined coordinate sets have been processed by IERS combination centers (see below).
- The final ITRF2014 solution was published in January 2016, with a dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.
- A full ITRF2014 article was published in Journal of Geophysical Research (Altamimi et al., 2016).
- the ITRF2014 is available for download at the dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.

The ITRF2014 is an improved realization of the International Terrestrial Reference System (ITRS) and is demonstrated to be of higher quality than the past ITRF versions. It involves two main innovations dealing with the modelling of station non-linear motions, namely seasonal (annual and semi-annual) signals present in the time series of station positions and post-seismic deformations for 124 sites that were subject to major earthquakes. In order to illustrate the performance of the modelling of the non-linear station motions, figure 1.2.1 shows, as an example, the trajectory of Tsukuba (Japan) site after the Tohoku earthquake, where GNSS and VLBI instruments are co-located. The Post-Seismic Deformation parametric model fitted to the GPS data was then applied to the VLBI time series. Figure The de-trended residuals of both stations are also shown, after removing the linear velocity and annual and semi-annual signals.

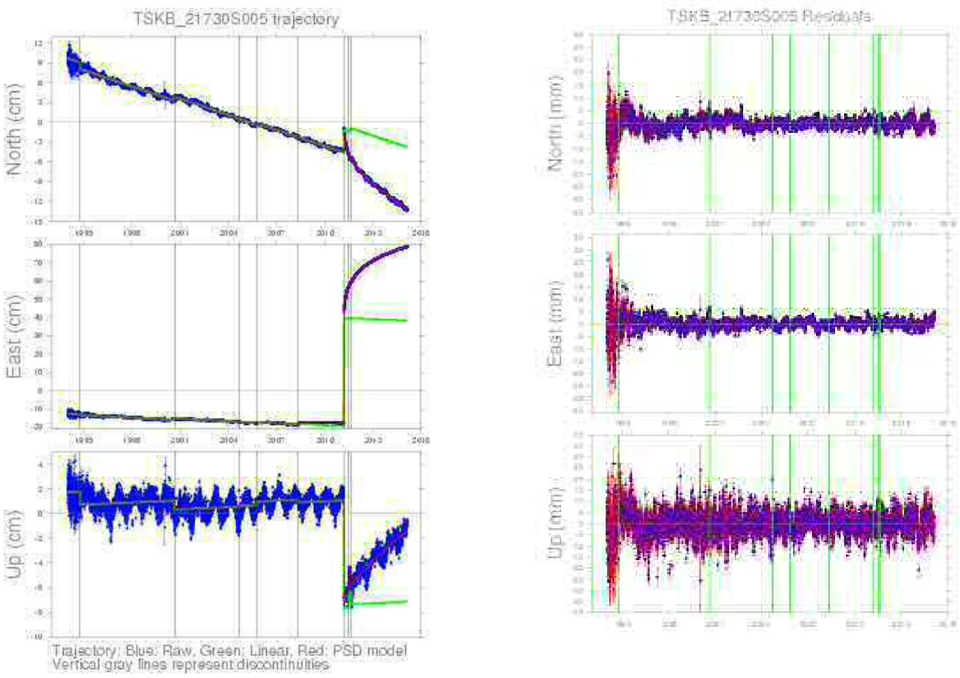

Fig. 1.2.1. Left) Site trajectory of Tsukuba (Japon), GNSS. Right) De-trended residuals of Tsukuba (Japon), GNSS

IERS Combination center

Report of the IERS components can be found in the IAG report. Relevant components of the report are summarized in this document since they are related to Terrestrial Reference Frame computation strategy that is a field of research.

IERS Combination center: DGFI

Deutsches Geodätisches Forschungsinstitut - Technische Universität München (DGFI-TUM) is acting as one of the ITRS Combination Centers within the IERS since 2001.

DGFI-TUM's latest realization of the ITRS is the DTRF2014. The DTRF2014 is an independent realization of the ITRS based on the same input data as the realizations ITRF2014 and JTRF2014 (see section IERS combination center: JPL). While the ITRF2014 is based on the combination of solutions, the DTRF2014 is computed by the combination of normal equations. DTRF2014 is the first ITRS realization corrected for non-tidal atmospheric and hydrological loading. However, all information to reconstruct the real station positions at each observation epoch is delivered. DTRF2014 is available for download at <http://www.dgfi.tum.de/en/science-data-products/dtrf2014/>. In addition to this work, the impact of the joint station coordinates and EOP combination on the ICRS realization was object of new research.

IERS Combination center: IGN

The members of the IGN Combination Center, 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. Main contributions are report below:

- Specific new developments were achieved and validated in preparation for the ITRF2014: CATREF software was enhanced and upgraded to include periodic terms of the station position time series, such as in particular annual, semi-annual terms for all techniques and draconitic signals for satellite techniques, especially GNSS.
- Other developments were also finalized and validated, such as modelling of post-seismic deformations for sites affected by major Earthquakes, as well as an improved strategy for the detection of discontinuities in the technique station position time series.
- First and early results of the ITRF2014 input data analysis were presented at various conferences in 2015.
- A preliminary ITRF2014 solution called ITRF2014P was generated and submitted on September 09, 2015 to the Technique Centers of the four techniques for evaluation. A certain number of feedbacks were then received and all concerns were answered and taken into account for the final ITRF2014 solution.

IERS Combination center: JPL

The Jet Propulsion Laboratory (JPL) is developing a sequential estimation approach to determining combined, multi-technique terrestrial reference frames. An approach based on a Kalman filter/smoother was initially taken. Kalman filters are commonly used to estimate the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used as constraints to tie the technique-specific measurements to each other. JPL’s Kalman filter and smoother for reference frame determination (KALREF) combines these measurements to determine ITRF-like reference frames subject to constraints imposed on the allowed evolution of the station positions. KALREF includes options to model the station motion as linear, linear and annual, or linear, annual, and semiannual. Through the use of stochastic models for the process noise, the station positions can be constrained to exactly follow these models of the station motion (by setting the process noise to zero), to recover the observed station positions (by setting the process noise to a large value), or to follow a smoothed path (by setting the process noise to some intermediate value). KALREF was used to determine JTRF2014, JPL’s realization of a terrestrial reference frame using the ITRF2014 input data sets.

Based upon the lessons learned in using KALREF to determine JTRF2014, JPL has decided to move from a Kalman filter/smoother-based approach to sequentially estimating TRFs to one based on a square-root information filter. Square-root information filters are numerically superior to Kalman filters and can more naturally account for degeneracies in the system of equations being solved. Unlike KALREF which had a 1-week fixed time step, the square-root reference frame filter (SREF) now being developed will have a variable time step, allowing measurements to be assimilated at the epoch of their observation. SREF will also include both dynamic and stochastic models of the EOPs to improve their prediction and will include a model for postseismic station displacements to improve the predictions of the motions of stations affected by large earthquakes. And SREF will be able to optionally assimilate VLBI-observed radio source positions to jointly determine terrestrial and celestial reference frames. SREF is currently being validated and is expected to be used to determine JTRF2020.

Link to gravity

The JWG 0.1.2 “Strategy for the Realization of the International Height Reference System (IHRS)” is working on specifying the International Height Reference System realization process, namely the determination of the International Height Reference Frame (IHRF). The working group has first determined the selection criteria of the IHRF stations. Among them, reference stations should be co-located with current ITRF multi-technique network, regional reference frame stations, national levelling benchmarks and tide gauges. About 170 stations distributed worldwide have been proposed. The estimation process of the gravitational potential values at those sites and their accuracy has been studied. Three comparison campaigns have been carried out by the working group: a first campaign based on common points but different input data; a second campaign based on a common set of input data and a minimum set of standards; a third campaign as a reprocessing of the second one. More details, discussions of the results and references can be found in the JWG 0.1.2 report.

Local ties

At co-location sites where several technique instruments are operating, the relative positions of the instrument reference points need to be known. They are called local tie vectors. Those are indispensable datasets for deriving and validating a Terrestrial Reference Frame. It is fundamental to support research for local tie determination to reach a 1-mm accuracy monitoring of the local tie vectors. Communication on the best practices for determining local tie vectors is also of the outmost importance since the determination a local tie vector is an expensive task. As mentioned above in the ITRS center report, a new IERS technical note has being published to report the procedures that have been defined at IGN France for surveying co-location sites (Poyard et al., 2017).

The research activity related to the derivation of local tie vectors is summarized in the JWG 1.1 Joint Working Group on “Site Survey and co-location” report.

Space ties

Up to now, Terrestrial Reference Frames are computed from separate technique coordinate sets and terrestrial local ties. However, the position of satellites that carry several positioning sensors (laser reflectors, GNSS antenna, DORIS antenna) can be determining by a simultaneous computation using all available data. In this case, the relative positions of the instruments on board of the satellites (determined using measurement or known a priori) plays the role of a space tie in a Terrestrial Reference Frame processing at the observation level.

This issue is discussed in the JWG 1.1.3 named “Performance Simulations and Architectural Trade-Offs (PLATO)”. During the two first years, the working group has conducted several studies based on simulated data to show the impact of including VLBI measurements on satellites, the effect for an improved SLR tracking to GNSS satellites and the interest of improving the SLR tracking network configuration. Please report to the report of the working group for more details and references.

ISO standardization

The standardization activity related to Terrestrial Reference Frames is studied in the GGOS Working Group "ITRS Standards for ISO TC 211", see the report of GGOS “Bureau of Products and Standards”. The group is presently working on a draft of the ISO TC211/19161-1 standard.

Link to conventions

The IERS conventions chapter 4, version 1.3.0, has been updated on 01 April 2019 for ITRF2014 release. All the versions of the IERS conventions, including the most recent are available at the IERS convention center web sites:
<http://iers-conventions.obspm.fr/conventions_versions.php> or
<http://maia.usno.navy.mil/conventions_versions.php>.

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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".

This final report gathers the contributions of the above regional sub-commissions and WG for the period 2015-2019. 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 common key 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 (international GNSS network) 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 with a special consideration of gravity and other data;
- 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 initiatives of the GGRF (Global Geodetic Reference Frame) WG of the UN-GGIM (United Nations Initiative on Global Geospatial Information Management).

The reports of the individual Sub-commissions and the WG are presented hereafter.

Sub-commission 1.3a: Europe (EUREF)

Chair: Markku Poutanen (Finland)

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 geo-referencing 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 focus 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 IGS;
- Improvement of the European Vertical Reference System;
- 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 Technical Working Group (TWG), since 2017 EUREF Governing Board (GB), which take place three times a year, and at the annual EUREF Symposia. The symposia that place every year since 1990, with an attendance of about 100-120 participants coming from more than 30 European countries and other continents, representing Universities, Research Centres and NMAs (National Mapping Agencies). The organization of the EUREF Symposia is supported by EuroGeographics, the consortium of the European National Mapping and Cadastre Agencies (NMCAs), reflecting the importance of EUREF for practical purposes.

The latest EUREF symposia took place in San Sebastian, Spain (2016), Wroclaw, Poland (2017), Amsterdam, The Netherlands (2018), and Tallinn, Estonia (2019).

GB members

Elmar Brockmann (Switzerland)
Carine Bruyninx (Belgium)
Rolf Dach (Switzerland)
Jan Dousa (Czech Republic)
Rui Fernandes (Portugal)
Ambrus Kenyeres (Hungary, GB chair)
Juliette Legrand (Belgium)
Martin Lidberg (Sweden)
Tomasz Liwosz (Poland)
Martin Poutanen (Finland, EUREF chair, ex-officio)

Rosa Pacione (Italy)
Martina Sacher (Germany)
Wolfgang Söhne (Germany, EUREF secretary, ex-officio)
Christof Völksen (Germany)

Zuheir Altamimi (France), Alessandro Caporali (Italy), and João Torres (Portugal) are regularly participating to the GB meetings as honorary members.
Andrzej Araszkiewicz (Poland) is regularly participating to the GB meetings as invited guest

Activities and publications during the period 2015-2019

EPN – Tracking Network, Network Coordination, EPN Central Bureau

Over the last four years, the number of permanent GNSS tracking stations in Europe belonging to the European Permanent Network was growing from 265 by mid-2015 to 336 by mid-2019. The number of sites recording GLONASS data simultaneously to GPS data was significantly increasing from 70 % by mid-2015 to 94 % by mid-2019.

One focus was on the upgrade of the EPN towards a multi-GNSS network. By mid-2019, 210 stations (63 %) are recording Galileo data. Moreover, 169 stations are recording the BeiDou constellation, and 22 stations are recording the regional QZSS.

In Nov. 2016, the EPN Central Bureau (CB) launched a completely revised version of the web portal (http://www.epncb.oma.be). The navigation was re-arranged, and the portfolio was streamlined to remove old and no longer used items. Moreover, the access was made more flexible to be used also with modern equipment like, e.g., smartphones and tablets. In 2017, new multi-GNSS data quality checks were implemented, including the re-analysis of all historical RINEX 2 and 3 EPN data. Finally, the new "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^3G, available from https://gnss-metadata.eu), developed by the EPN CB, has reached in 2018 the level of maturity required for operational use in EUREF and consequently all EPN and EPN densification metadata were migrated to M^3G.

The EUREF Regional Data Centre (RDC) and the Analysis Centre (AC) in Graz, Austria was closed in 2017. Therefore, in 2016 the Austrian colleagues started to build up a new RDC and a new AC at the Bundesamt für Eich- und Vermessungswesen (BEV) in parallel to the existing structure and took over full functionalities in 2017.

Most of the activities covering EPN are reported on an annual basis in the Technical Reports of the IGS. In addition to the overview and summary given here, see Bruyninx et al. (2015), Bruyninx et al. (2016), Bruyninx et al. (2017), and Bruyninx et al. (2018) for more details.

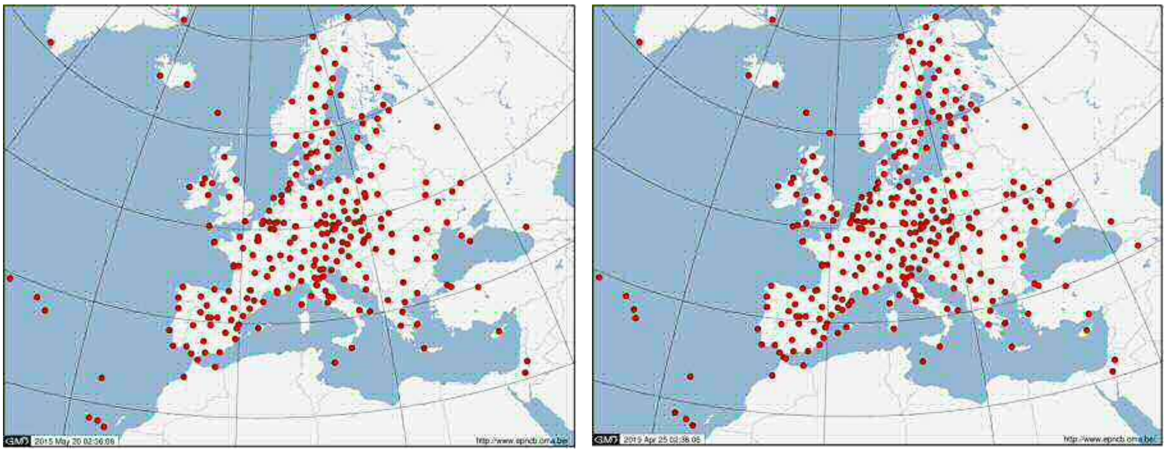

Figure 1.3a.1. EUREF Permanent GNSS Network (http://www.epncb.oma.be/networkdata/stationmaps.php), status May 2015 (left) and April 2019 (right).

During the reporting period, the first EPN stations started providing real-time data in RTCM 3.2 and 3.3 format. In addition to GPS and GLONASS, most of the streams contain Galileo, BeiDou, QZSS and SBAS. The monitoring of the three EUREF broadcasters at the EPN CB was extended. In addition to the RTCM 2 and 3.1 format, also the RTCM 3.2 and 3.3 data stream contents are now verified against the proposed content of the sourcetable.

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EPN – Analysis Centre Coordinator, Troposphere Coordinator, Reference Frame Coordinator

The EPN Analysis Centre Coordinator (ACC) combines GNSS coordinate solutions provided by 16 EPN Analysis Centres into official EPN solutions.

In 2016, the ACC worked in the Working Group “EPN Reprocessing”. In the beginning of 2016, the EPN-Repro2 reprocessing wasfinalized. The ACC combined daily solutions computed by five EPN ACs (ASI, GOP, IGE, LPT and MUT) for the period 1996-2013; the results have proven high homogeneity of the individual AC solutions.

At the end of 2016, a methodology for creating weekly combined EPN solutions was changed (EPN LAC mail 2134). Up to and including week 1924, the weekly combined solutions were created directly from the AC weekly solutions. Since week 1925 (Nov. 27, 2016), the daily AC solutions have been used for that purpose; at first the daily AC solutions are combined for each day of the week, and then the seven daily combined solutions are stacked into a weekly solution. It was verified that the new approach allows to handle more consistently daily position outliers (for both AC and combined solutions), and helps to mitigate possible inconsistencies between AC solutions which could be observed when combining on a weekly level. Due to the change in the combination strategy, the EPN ACC website (http://www.epnacc.wat.edu.pl) has been updated. The website now contains graphs and maps presenting coordinate consistency of AC daily solutions with respect to the daily combined solutions for each station and day of the last combined week.

To be consistent with IGS products, since January 29, 2017 (GPS week 1934) the EPN ACs started to use the IGS14/epn_14.atx framework during GNSS data analysis. Since week 1934, also EPN combined coordinate solutions have been aligned to the IGS14 reference frame (Liwosz and Araszkiewicz, 2017).

Since week 1980 (Dec. 17, 2017) the troposphere modelling has been harmonized among EPN ACs, i.e., all ACs started to use the VMF1/ECMWF approach (before week 1980 9 ACs used VMF1/ECMWF, and 7 used the GMF/GPT approach). After week 1980 better consistency between AC coordinate solutions was observed for some stations. Also, the scale differences between the combined solution and solutions provided by three ACs (BKG, IGE and ROB), which used the GMF/GPT approach before week 1980, were noticeably decreased (Liwosz and Araszkiewicz, 2018).

At the EUREF symposium 2018 held in Amsterdam, the EUREF plenary adopted a resolution encouraging the ACs to build up the capabilities for processing Galileo observations and asking the EUREF community, GSA, ESA and the GNSS industry to provide the missing receiver antenna calibrations for Galileo signals. Following this resolution, some ACs started creating GNSS processing solutions including Galileo observations in addition to GPS and GLONASS, in parallel to the operational GPS+GLONASS solutions, and making them available to the Analysis Centres Coordinator and the Troposphere Coordinator, so that the impact of Galileo observations on the combination products could be analyzed.

In 2018, the ACC analyzed the impact of including Galileo observations in EPN AC products on combined EPN station positions. In the test phase (EPN LAC Mail no. 2344), eight ACs (BEK, BKG, IGE, ROB, UPA, NKG, SUT, WUT) provided solutions including Galileo observations (in addition to the operational solutions). In comparison with the operational combined solutions, mean position differences (over 33 weeks) for the majority of stations did not exceed 1 mm in the horizontal components, and 3 mm in the vertical component. For the troposphere, the differences in the total zenith delays were below 1 mm.

Since the impact of adding Galileo observations on combined positions was small, it was decided that starting with week 2044 (March 10, 2019) these observations may be included in the EPN operational products (EPN LAC Mail no. 2407).

Besides station coordinates, the 16 EPN ACs also submit Zenith Total Delay (ZTD) parameters and horizontal gradients on a routine basis in the legacy SINEX_TRO format that are used by the TC to deliver the EPN official tropospheric product. The EPN official tropospheric product is based on a combination of the contributing solutions using a generalized least square method (Pacione et al., 2011). Starting from GPS week 2034, in addition to the legacy format, the EPN tropospheric combined solution release in SINEX_TRO v2.0 format (Pacione and Dousa, 2017). The ZTDs and horizontal gradients are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. At the EPN Analysis Centres Workshop in Brussels in 2017, the harmonization of the troposphere modelling among the EPN ACs was proposed in order to increase the consistency between AC solutions. It was agreed that from GPS week 1980 onwards it would be mandatory to model the tropospheric delay using the VMF1 mapping function together with a priori hydrostatic delays from VMF1 grids (based on atmospheric pressure data from ECMWF).

The mean bias and standard deviation of the AC individual ZTD contributions with respect to the combined ZTD solution, http://epncb.eu/_productsservices/sitezenithpathdelays/, allow for monitoring of the agreement of the AC solutions versus the combination. Twice per year, the EPN multi-year tropospheric solution is updated and it is announced by means of a EUREF mail. Last update done in March 2019 and covering the period 1996-2018 (see EUREF mail 09770).

For each EPN station ZTD time series, ZTD monthly mean and comparison with radiosonde data (if collocated) plots are updated and available at the EPN Central Bureau http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/.

In 2016, the TC worked in the Working Group "EPN Reprocessing" in close cooperation with the WG3 of the COST Action ES1206 'GNSS4SWEC' (REF) being the availability of 20+ years of GNSS data is a valuable data set for the development of a climate data record of GNSS tropospheric products. The EPN-Repro2 tropospheric data set (Pacione et al., 2017; Pacione, 2016) is open to the user community and, on a European scale, it has been established as a reference data set for monitoring trend and variability in atmospheric water vapor.

Starting with the release of IGS14 in January 2017, the EPN multi-year position and velocity solution was replaced by a new version based on the daily EPN-repro2 solutions (from GPS week 834 to GPS week 1772) and the daily EPN routine solutions (from GPS weeks 1773 up to present). The solution is computed with the CATREF software (Altamimi et. al., 2007). It has a revised discontinuity list and incorporates the ITRF2014 post-seismic deformation models (ftp://itrf.ign.fr/pub/itrf/itrf2014/ITRF2014-psd-gnss.dat) for five stations belonging to the EPN: ANKR00TUR, BUCU00ROU, ISTA00TUR, REYK00ISL, TUBI00TUR. It is consistent with the epn_14.atx ground antenna calibrations and aligned to the IGS14 reference frame. In order to insure the consistency of the daily solutions with the IGS14/epn_14.atx, the positions prior to GPS week 1934 were corrected (using the latitude-dependent models from IGS, IGSMAIL-7399) for the position changes caused by the change from epn_08.atx to epn_14.atx. The EPN multi-year solution is updated each 15 weeks at EPN CB website. To guarantee the quality and reliability of the solution, several checks are performed at each release. The position time series are screened in order to look for outliers and discontinuities.

The agreement of the EPN solution w.r.t. IGS14 and the weekly updates of the IGS multi-year solution IGSYYPWW is monitored. Hector software (Bos et al., 2013) is used to derive realistic error estimates and assess the quality and the reliability of the stations. In addition to the time series of the multi-year solution, extended time series are updated daily by adding the EPN daily combined solutions (operational and rapid) not yet included in the final combined EPN solution. Together with the RINEX data quality check monitoring performed by EPN CB, these quick updates allow to monitor the behaviour of the EPN stations and to react promptly in case of degradations at a station.

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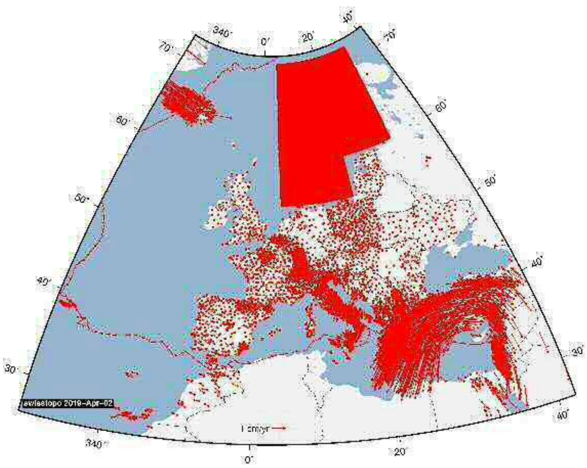
Working Groups – Multi-GNSS WG, Reprocessing WG, WG on European Dense Velocities, EPN Densification WG, Deformation Modelling WG

Thanks to the effort of the Multi-GNSS WG and the EPN CB, the number of stations submitting RINEX 3 files to the EPN increased significantly to 222 stations. In addition, the use of long RINEX filenames increased significantly to 199 stations. In 2016, the first EPN Analysis Centre (LPT, swisstopo) started processing Galileo and BeiDou data in addition to GPS and GLONASS on a routine basis. As of mid-2019, several other Analysis Centres included Galileo in their processing, at least in a parallel test-processing environment.

The second reprocessing of the EPN, Repro-2, was finalized in 2016. Covering the period 1996 to 2014, five analysis centres (ACs) were contributing. Three ACs processed the complete EPN using three different software packages (BSW 5.2, GAMIT 10.5 and GIPSY 6.2), two ACs processed large subnetworks with BSW5.2. The combinations were carried out by the Analysis Centre and the Troposphere Coordinators, respectively. The combination results for coordinates as well as for troposphere parameters are the basis for the new accumulated EPN solutions.

The WG on European Dense Velocities is collecting velocity results from many European countries and institutions. The inputs with detailed statistics, the combination results and the residuals of the individual contributions against the combined solution are regularly updated and presented on a dedicated web page (http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html). More than 53000 individual values are stored in the database (status end of March 2019).

The EPN densification project is combining weekly SINEX solutions provided by European countries for their dense national active GNSS networks with the weekly EPN SINEX solutions, resulting in a cumulative position and velocity solution for more than 3300 stations (http://www.epncb.oma.be/_densification/).



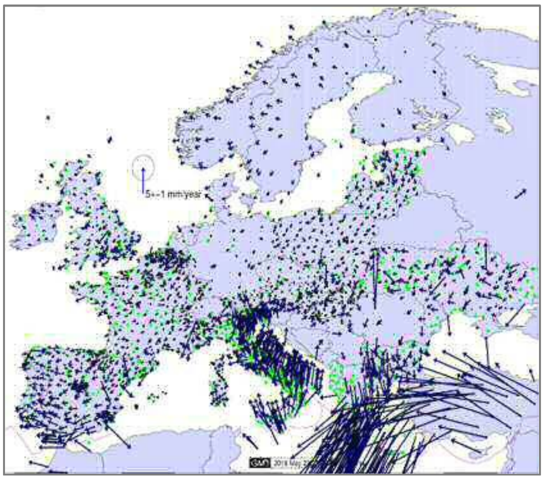


Figure 1.3a.2. combined horizontal velocities from the WG on European Dense Velocities (left, http://pnac.swisstopo.admin.ch/divers/dens_vel/combvel_eu_all_cmb_basic_dh.jpg) and ETRF2000 velocities from WG on EPN Densification (http://www.epncb.oma.be/densification/coordinates/posvel_map.php).

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European Terrestrial Reference System 89 (ETRS89)

The ETRS89 is intimately linked to the ITRS through a similarity transformation of 14 parameters. Consequently, for each ITRS realization (ITRFyy) a corresponding ETRS89 frame (ETRFyy) can be defined. The ITRF2014 was the occasion to propose an ETRF2014 where its origin coincides with that of ITRF2014, and therefore the seven transformation parameters are all zeros at epoch 1989.0, while their temporal rates are zeros, except the three rotation rates. The latter actually represent the three components of the Eurasian plate rotation pole in ITRF2014 (Altamimi, 2018).

The release of ITRF2014 imposed the question to the EUREF GB how to deal with the corresponding ETRS89 realization. The EUREF GB discussed three different options and solutions: a) to introduce an updated ETRS89 realization, called ETRF2014, b) to introduce ETRF2014 with an origin coinciding with the ITRF2014 origin, or c) to keep the ETRF2000 as it is. To get in advance a feedback from the user community, in 2016 EUREF Resolution No. 3 was approved to launch a questionnaire and to distribute it to the EUREF community, namely the NMAs. The feedback given by 35 replies from 29 countries to the questionnaire showed that the majority of the NMAs was in favor of keeping ETRF2000 but many countries explained reasons, which would justify an updated ETRS89 realization, e.g. crustal movement, land uplift, or inhomogeneous velocity field (Söhne et al., 2017).

The 2017 EUREF Resolution No. 1 recognizes the diverse requirements regarding national implementations of ETRS89, and respects the different countries' decisions on adopting their preferred ETRS89 realizations (http://www.euref.eu/symposia/2017Wroclaw/06-01-Resolutions-EUREF2017.pdf).

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European Vertical Reference System (EVRS)

The last realization of the European Vertical Reference System (EVRS) has been released in 2008 under the name EVRF2007. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was approved proposing to the European Commission the adoption of the EVRF2007 as the mandatory vertical reference for pan-European geo-information. EVRF2007 is based on the measurements of the Unified European Leveling Network (UELN). The datum is realized by 13 datum points distributed evenly over the stable part of Europe. The measurements have been reduced to the common epoch 2000 by applying corrections for the glacial isostatic adjustment (land uplift) in Fenno-Scandinavia, which are provided by the Nordic Geodetic Commission (NKG) under the name NKG2005LU.

In the meantime, UELN is continuously enhanced using additional or updated leveling data submitted by different countries (Fig. 1.3a.2). Since 2015, the network parts of Germany and Switzerland have been replaced by new measured leveling data. Also in 2015, the French scientific zero-order leveling network NIREF has been integrated in the UELN. NIREF was observed between 1983 and 2014 and is much more precise than IGN69 data, but not dense enough to replace completely these old data in UELN. Therefore, both networks were combined. Because of a known bias in the North-South direction the data of IGN69 were introduced with lower weights than NIREF data. The including of NIREF data in UELN allowed the first time to integrate the height difference between France and UK that had been measured through the Channel tunnel in 1994. Using the NIREF data and the tunnel measurement the computed UELN height in Dover (UK) changed by 140 mm.

In 2016, Estonia delivered new leveling data in a very high precision.

In 2017, UELN has been expanded by Belarus, which provided 1st order leveling data at the first time.

In 2018, Belgium, Italy and Slovenia delivered new measured leveling data of their countries. Furthermore, parts of the network of Czech Republic have been replaced by new measured leveling data. Moreover, the UELN could be enlarged by the leveling network of Ukraine.
Furthermore, between 2016 and 2018 some supplements or corrections were delivered by the Netherlands, Norway and Slovakia.

At the EUREF symposium in Tallinn 2019, a new realization of the EVRS was adopted. According to the EVRS definition, the EVRF2019 is in the level of Normaal Amsterdams Peil (NAP). The heights are normal heights in the zero-tide system. Unlike EVRF2007, the heights of EVRF2019 are additionally provided in the mean-tide system, in order to support users that need conformity of heights with the mean sea level, especially in the field of oceanography.

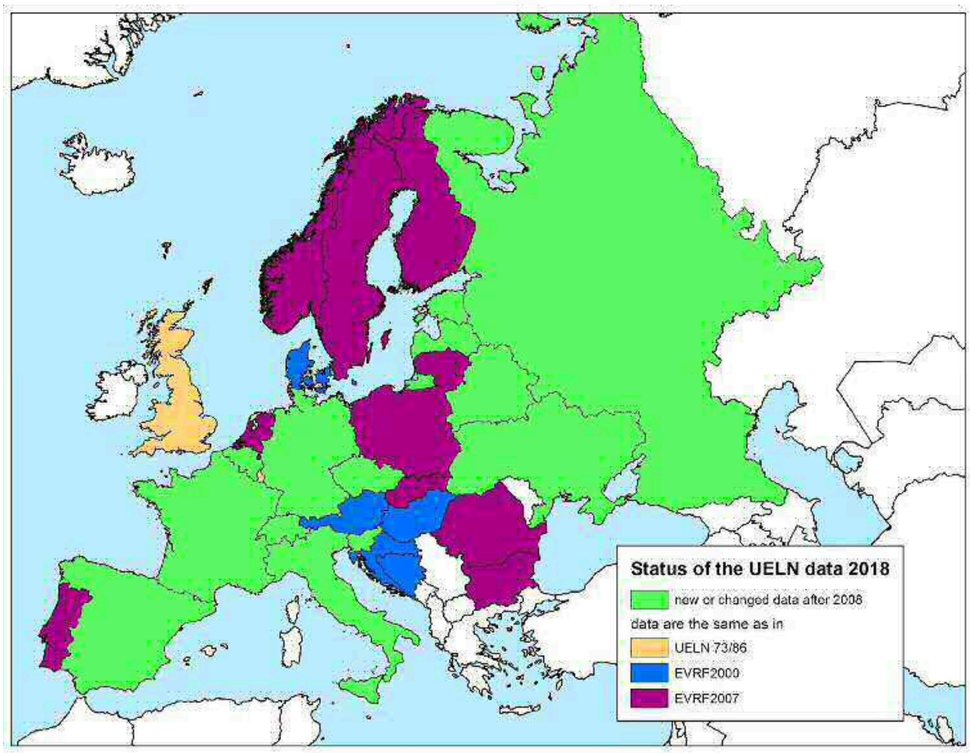

Figure 1.3a.3. Status of the United European Leveling Network (UELN)

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Revision of EUREF Terms of References

During 2015 and 2016, the EUREF Terms of References (ToR) have been updated, discussed in EUREF 2015 and 2016 symposia as well as during the TWG meetings. The ToR were adopted in the EUREF 2017 symposium in Wroclaw. One visible change was the renaming of the Technical Working Group into Governing Board.

Cooperation with other organizations and international integration

GB members Z. Altamimi, C. Bruyninx, and M. Poutanen are participating to the work on the United Nations (UN) Global Geodetic Reference Frame (GGRF) and the permanent UN Sub-committee on Geodesy (SoG) within UN Committee of Experts on Management Global Geospatial Information (UN-GGIM). The implementation plan, based on the roadmap accepted in 2016, and the UN General Assembly resolution in 2015 on sustainable global geodetic reference frame, is presently under development.

M. Poutanen is chairing the UN-GGIM: Europe special expert group "GRF-Europe". He also gave reports on EUREF activities at the meetings of the UN International Committee on Global Navigation Satellite Systems (ICG) in Boulder, USA (ICG10, 2015), Sochi, Russia (ICG11, 2016), Kyoto, Japan (ICG12, 2017) and Xi'an, China (ICG13, 2018).

The European Plate Observing System (EPOS) gathers input from geodesy, geology, seismology, volcanology, or geomagnetism to understand the complex dynamic Earth system. EPOS is approaching the end of its implementation Phase. EUREF's activities, e.g. the EPN and its combined solutions will contribute to EPOS "GNSS Data and Products" services and, therefore, EUREF has been engaged in the preparation of the Operational Phase of EPOS, which should start in 2019-2020.

The cooperation between EUREF and the Central European GNSS Research Network (CEGRN) involves 33 Central European Countries and measurement campaigns every two years since 1996. The cooperation results in a strong support to the EUREF WGs on Densification, Dense Velocity Field and Deformation Modelling and joint publications in peer reviewed journals.

EUREF has been invited to participate to the Pan-European Ground Motion Service (EU-GMS) which is going to be established as a service using Copernicus, in particular Interferometric Synthetic Aperture Radar (InSAR) data of the Sentinel satellites of the Copernicus programme of the European Space Agency (ESA). EUREF's contribution to the service would be to serve as a reference.

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Outreach and capacity building

A dedicated EUREF-related session 2.3 "Applications and future of European references frames – (more than) 30 years of EUREF" was organized at the 2019 General Assembly of the European Geosciences Union (EGU) in Vienna. 20 presentations were given with 7 oral presentations and 13 posters

https://meetingorganizer.copernicus.org/EGU2019/sessionprogramme#G2

EUREF Governing Board resp. Technical Working Group meetings:

- Oct., 13, 2015, in Bern, Switzerland, hosted by AIUB (Astronomical Institute of the University of Bern)
- Feb, 29 - March, 1, 2016, in Lisbon, Portugal, hosted by IPMA (Instituto Português do Mar e Atmosfera)
- May, 23, 2016, in San Sebastian, Spain, hosted by ARANZADI (Sociedad de Ciencias Aranzadi)
- Oct., 20-21, 2016, in Vienna, Austria, hosted by BEV (Bundesamt für Eich- und Vermessungswesen)
- February, 16, 2017 in Matera, Italy, hosted by ASI/e-geos (Space Geodesy Centre)
- May, 28-29, 2018 in Amsterdam, The Netherlands, hosted by Kadaster (Nederlands Kadaster)
- Oct., 24, 2018 in Brussels, Belgium, hosted by ROB (Royal Observatory of Belgium)
- February, 12-13, 2019, in Budapest, Hungary, hosted by FÖMI (BFKH FTFF Satellite Geodetic Observatory)
- May, 20-21, 2019, in Tallinn, Estonia, hosted by MAA-AMET (Estonian Land Board)

EUREF Annual Symposia:

- May, 25-27, 2016, in San Sebastian, Spain (approx. 95 participants from 28 countries)
- May, 15-17, 2017, in Wroclaw, Poland (approx. 106 participants from 28 countries)
- May, 30-June, 01, 2018 in Amsterdam, The Netherlands (approx. 110 participants from 31 countries)
- May, 22-24, 2019 in Tallinn, Estonia

Figure 1.3a.4. Participants of EUREF annual symposium in San Sebastian (2016, top) and in Wroclaw (2017)

EUREF Analysis Workshops:

- Oct., 14-15, 2015, in Bern, Switzerland, AIUB (Astronomical Institute of the University of Bern)
- Oct., 25-26, 2017, in Brussels, Belgium, ROB (Royal Observatory of Belgium)

EUREF Tutorials:

- May, 24, 2016, "Terrestrial Reference Systems in Practice", San Sebastian, Spain (approx. 60 participants)
- May, 16, 2017, "(Open) Real-time Infrastructure and Applications in Europe (and Beyond) ", Wroclaw, Poland (approx. 45 participants)
- May, 29, 2018, "InSAR-Geodesy and Geodetic Infrastructure", Amsterdam, The Netherlands (approx. 50 participants)
- May, 21, 2019, "Transformations using PROJ", Tallinn, Estonia

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Sub-Commission 1.3b: South and Central America (SIRGAS)

Chair: William Martinez (Colombia)
Vice-chair: Virginia Mackern (Argentina)

Introduction and structure

SIRGAS is the Geocentric Reference System for the Americas. Its definition corresponds to the International Terrestrial Reference System (ITRS) and it is realized by a regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes the definition and realization 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 administrative issues are managed by an Executive Committee, which depends on the Directing Council, main body of the organization. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed by 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 scientific and technical activities are coordinated by the Working Groups in close cooperation with the Scientific Council and the representatives of IAG and PAIGH.

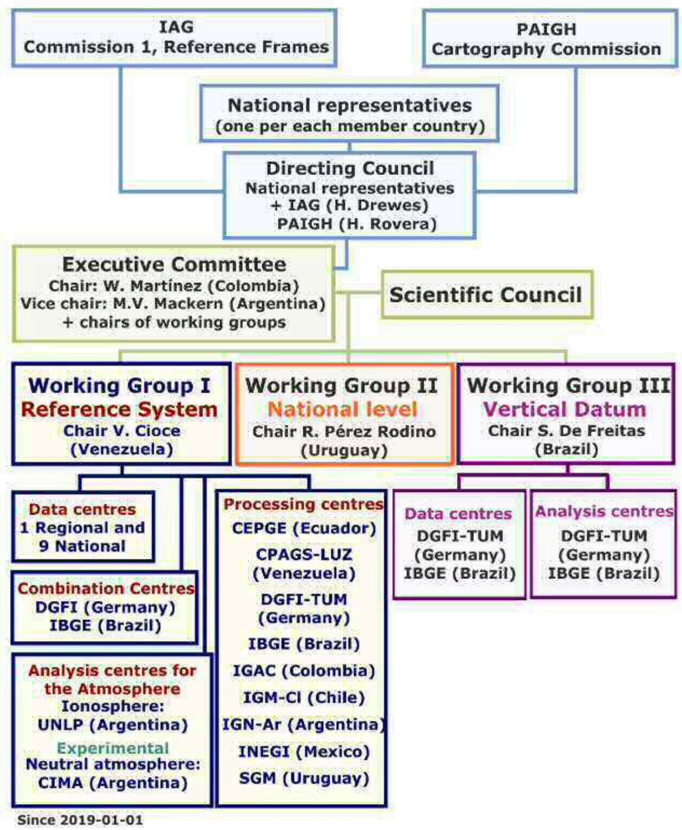

Figure 1.3b.1. SIRGAS structure

Members

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Activities during the period 2015-2019

SIRGAS-CON GNSS network

The number of continuously operating GNSS stations included in the SIRGAS-CON network (see Figure 1.3b.2) is 395 (322 active and 73 inactive) of which 59 belong to the global International GNSS network (IGS), 339 have GPS+GLONASS capability, 79 measure on GPS+GLONASS+Galileo and 43 GPS+GLONASS+Galileo+BeiDou (see Figure 1.3b.3). For historic works, 138 removed stations may also be considered.

Nine SIRGAS Local Processing Centers compute loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. All Analysis Centers follow unified standards for the computation of the loosely constrained solutions.

The support of the countries interested on adopting SIRGAS as official referenc frame continued. At this moment, 19 countries in the region have already adopted SIRGAS as the official reference frame for Geodesy and Cartography. More than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership.

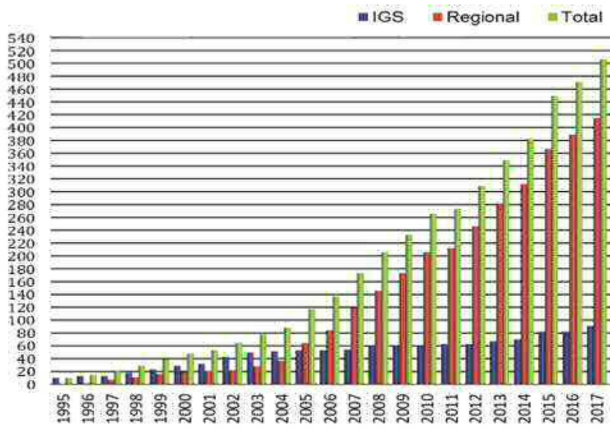

Figure 1.3b.2. Number of GNSS SIRGAS-CON stations

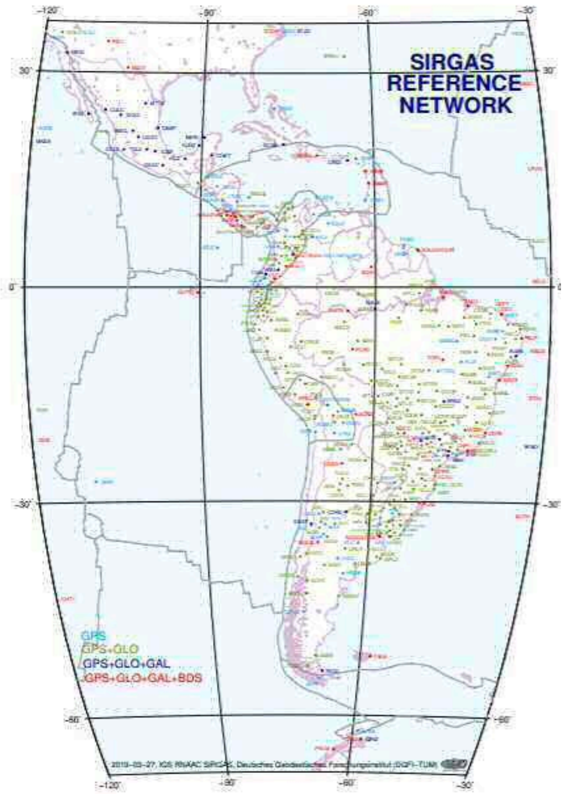

Figure 1.3b.3. Distribution of GNSS SIRGAS-CON stations

Figure 1.3b.4. Distribution of GNSS SIRGAS-CON RT stations

SIRGAS continues its consolidation as the continental reference frame and as the basic layer of spatial data infrastructures national and regional levels.

The SIRGAS-Real Time project advances successfully: Its objectives were achieved and its support to the countries is integrated into the WGII (SIRGAS at the national level). Figure 1.3b.4 shows the SIRGAS stations that transmit data in real time in the region. These data are available from the IGS-RT caster and from national casters (Table 1.3b.1). WGI and WGII recognize the need to adjust the measurement intervals of the permanent stations to 1 second in order to provide more appropriate data for seismological and atmospheric phenomena.

Caster	IP: Port	Web link
SIRGAS Experimental	200.3.123.65:2101	http://www.fceia.unr.edu.ar/gps/mapatr/
REGNA-SGM (Uy)	201.217.132.178:2101	http://www.sgm.gub.uy/
RAMSAC-NTRIP (Ar)	ntrip.ign.gob.ar:2101	http://www.ign.gob.ar/NuestrasActividades/Geodesia/RamsacNtrip/
IBGE - IP (Br)	gps-ntrip.ibge.gov.br:2101	http://www.ibge.gov.br/home/geociencias/geodesia/rbmc/ntrip/
IGS-RT	www.igs-ip.net:2101	http://register.rtcm-ntrip.org/cgi-bin/registration.cgi

Table 1.3b.1. RT Casters

An effort has been made by the countries to increase the usage of SIRGAS products and the maintenance of its geodetic infrastructure. Work has been done in the context of the MONOLIN group (NO Lineal Movements) studying the different earthquakes that occurred in Latin America and their influence on the coordinates, thanks to the measurements at the SIRGAS_CON stations. This has allowed studying the seismic activity of the region. Particularly the work related to, or based on, the monitoring of the post-seismic deformations, lead to national frame updates and the development of the last two velocity models VEMOS2015 (Sanchez and Drewes 2016a, 2016b) and VEMOS2017 (Drewes and Sanchez 2017a, 2017b) (see Figure 1.3b.5).

SIRGAS_CON a densification of the ITRF in Latin America

To keep the SIRGAS objective of densifying the ITRF in Latin America, the weekly and multi-year solutions have been adjusted to the corresponding ITRF according to the specified standards. Therefore, the weekly SIRGAS realizations refer:

- To the IGS05 (ITRF2005) from Nov. 4, 2006 to April 16, 2011
- To the IGS08/IGb08 (ITRF2008) from April 17, 2011 to January 28, 2017
- To the IGS14 (ITRF2014) since January 29, 2017.

The artificial coordinates changes caused by the frame changes are show in Figure 1.3b.5 (ITRF2005 to ITRF2008) and Figure 1.3b.6 (ITRF2008 to ITRF2014).

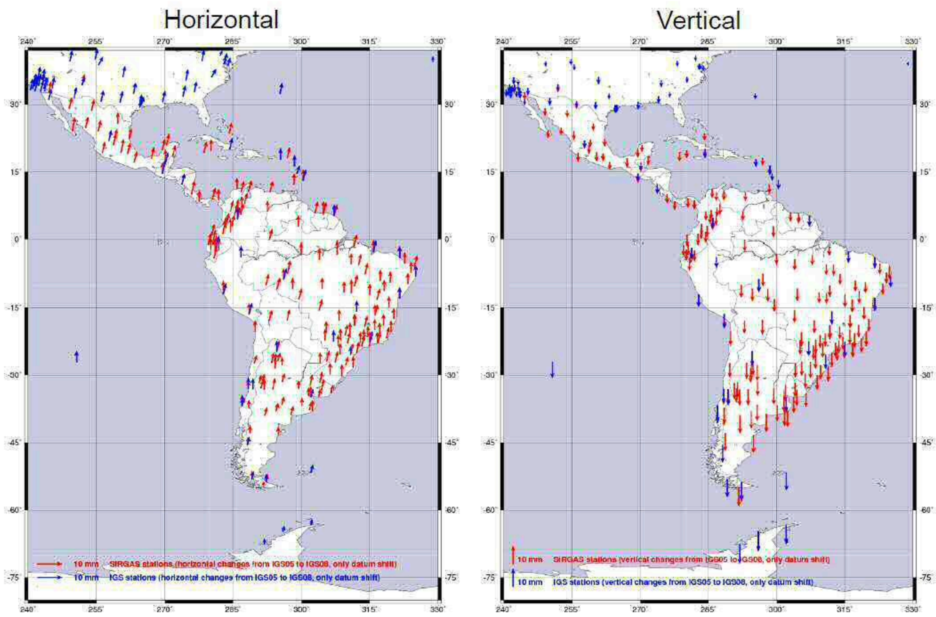

Figure 1.3b.5. Jumps caused by the change of ITRF2005 to ITRF2008, in Horizontal coordinates (left) and in Vertical coordinates (right) (Sánchez, 2018), taken from www.sirgas.org.

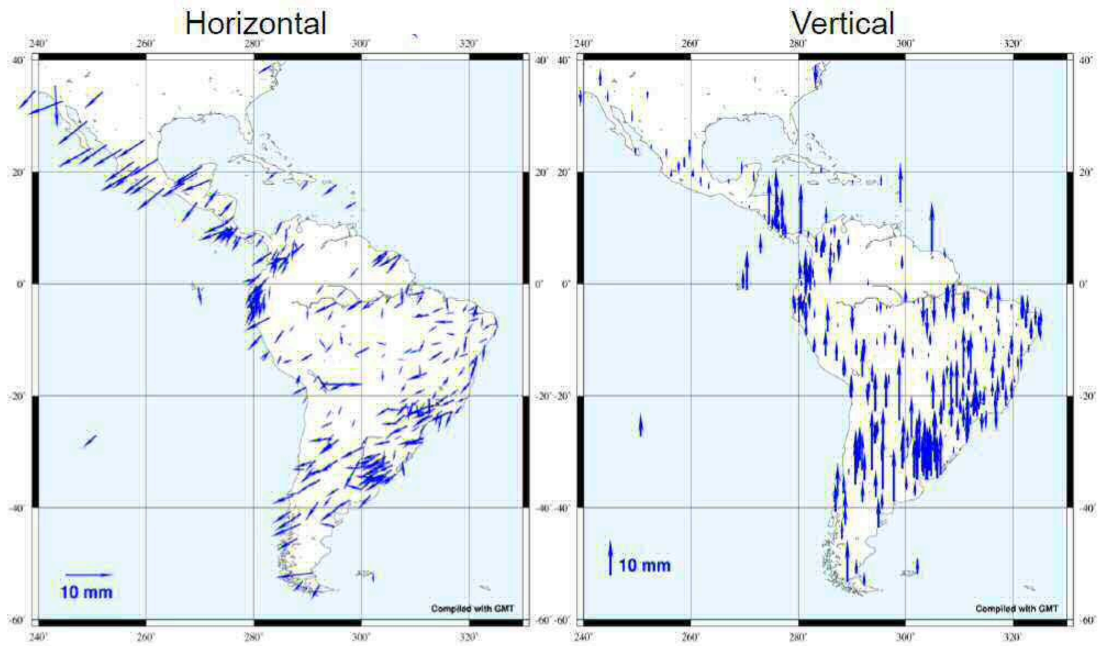

Figure 1.3b.6. Jumps caused by the change of ITRF2008 to ITRF2014, in Horizontal coordinates (left) and in Vertical coordinates (right) (Sánchez 2018), taken from www.sirgas.org.

Two SIRGAS multi-year solution, SIR15P01 and SIR17P01, have been computed.

- SIR15P01 includes positions and velocities of 303 SIRGAS reference stations and 153 additional stations. SIR15P01 refers to the IGb08 frame, epoch 2013.0. It covered a five years period from March 14, 2010 to April 11, 2015. The normal equations between 2010-03-14 and 2011-04-17 were reprocessed using the IGS products generated during the second reprocessing of the global IGS network and applying the absolute corrections to the variations of the phase centers referred to the IGS08. The averaged RMS precision for the station positions at the reference epoch is ± 0.7 mm in the north-south component, ± 0.9 mm in the east-west component, and ± 3.5 mm in the height. The averaged RMS precision for the station velocities is ±0.5mm/a in the north-south component, ±0.8mm/a in the east-west component, and±1.6mm/a in the vertical component. (Sánchez and Drewes, 2016c).

- SIR17P01 includes only weekly solutions referring to the IGS08/IGb08 and covers the time span from 2011-04-17 to 2017-01-28. SIR17P01 contains 345 stations with 504 occupations; it refers to the IGS14, epoch 2015.0 and its precision is about ±1,2 mm (horizontal) and ±2,5 mm (vertical) for the station positions and ±0,7 mm/a (horizontal) and ±1,1 mm/a (vertical) for the constant velocities. The main objective of this solution is the computation of an updated deformation model for Latin America (VEMOS). Therefore, 150 additional stations were processed and linear station motions from 2014-01-06 to 2017-01-28 were computed. This "extended" solution, called VMS17P01 (Figure 1.3.b.7), was the input for VEMOS2017 (Drewes and Sánchez, 2018).

Figure 1.3b.7. SIR17P01 velocities (left) and VMS17P01 velocities (right) (Sánchez 2018), taken from www.sirgas.org.

SIRGAS Vertical Reference System (SVRS)

SIRGAS continues promoting the activities related to the unified vertical datum (WGIII). Four workshops were organized to promote the development of the SIRGAS Vertical Reference System (SVRS), see section on Outreach. The coordination of these activities begun to achieve some results. Three countries adjusted their Vertical Reference Frame (VRF) in terms of geopotential numbers: Argentina, Brazil and Uruguay. Their networks represent more than 60% of first order spirit leveling points (Argentine, 18000 points; Brazil, 70000 points and Uruguay, 1500 points) in the region. However, several problems remain to be resolved. Among these: the lack of international connections among countries to form consistent loops for simultaneous adjustment; the unavailability of original leveling data in some countries; and the situation of that each VRN had been linked to a different local Vertical Datum.

Since the creation of the IAG/GGOS 0.1.2. Working Group on Strategy for the Realization of the International Height Reference System (IHRS) in 2016, SIRGAS WG III is inserted in its activities. In this context, once again, SIRGAS is involved into the most important activities of geodesy through the selection of key national stations and in the future complementary measurements for the materialization of the IHRS in the region, which has been entrusted to the National Representatives and Institutions. The main current protocols of SIRGAS regarding the SIRGAS Vertical Reference System (SVRS) are:

- It is performed by appropriate physical heights (involving gravity by geopotential numbers) [HP = f (CP)];
- Connected to the geometric component of SIRGAS;
- Integration of vertical networks of member countries;
- Referred to a global reference level W0 of the IHRS / IAG;
- Associated with a specific reference period; i.e., you should consider the temporal variations of the coordinates and the network.
- Linked with a profile of GGRF stations consistent with the ITRF.

In the beginning of 2017, SIRGAS proposed a set of 22 IHRF stations distributed in the South America, Central America and Caribbean regions (Figure 1.3.b.8). Since then, SIRGAS WG III is involved in the testing of approaches for facing the realization of such stations.

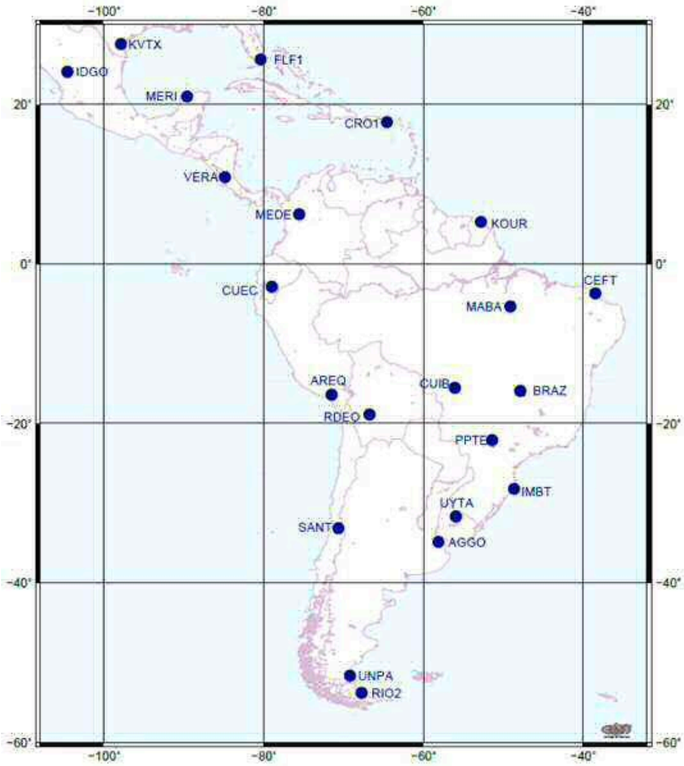

Figure 1.3b.8. Proposed IHRF stations in SIRGAS (Freitas et al., 2018), taken from www.sirgas.org.

Two initiatives merit emphasis: The link of Ecuadorian Vertical Datum to IHRS accomplished in 2017 linked to two experimental approaches (Carrión, 2017; Carrión et al. 2018), and the insertion of two South American research groups linked to SIRGAS in the Colorado Experiment organized by the IAG/GGOS 0.1.2. Working Group. This experiment is related to the development of the strategies for the realization of IHRS stations. The experiment considered the Molodensky approach for solving the Geodetic Boundary Value Problem (GBVP, De Freitas et al, 2018). Some provisional results related to the six Brazilian IHRF stations are now available.

Updated velocity models in Latin America

Two SIRGAS Velocity Models were developed:

VEMOS2015 (Sánchez and Drewes, 2016; Figure 1.3.b.9) was inferred from GNSS (GPS+GLONASS) measurements gained after the strong earthquakes occurred in 2010 in Chile and Mexico (Sánchez et al., 2013; 2016). It is based on a multi-year velocity solution for a network of 456 continuously operating GNSS stations comprising a five years period from March 14, 2010 to April 11, 2015. VEMOS2015 was computed using the least square collocation (LSC) approach with empirically determined covariance functions. It covers the region from 55°S, 110°W to 32°N, 35°W with a spatial resolution of 1°x1°. The average prediction uncertainty is ±0.6 mm/a in the north-south direction and ±1.2 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone (Chile) while the minimum values of about ±0.1 mm/a, occur in the stable eastern part of the South American plate.

The main purpose of VEMOS2015 is to allow the translation of station positions through time. However, this model is only valid for the time period 2010-2015. For the translation of station positions before the 2010 earthquakes, the model VEMOS2009 (Drewes and Heidbach, 2012) should be used and April 11, 2015, the model VEMOS2017 (Drewes and Sanchez, 2017) should be used. Although VEMOS2015 includes GNSS observations over five years, some regions were affected by further earthquakes and their effects are not included in VEMOS2015. VEMOS2015 is available at:

https://doi.pangaea.de/10.1594/PANGAEA.863132.

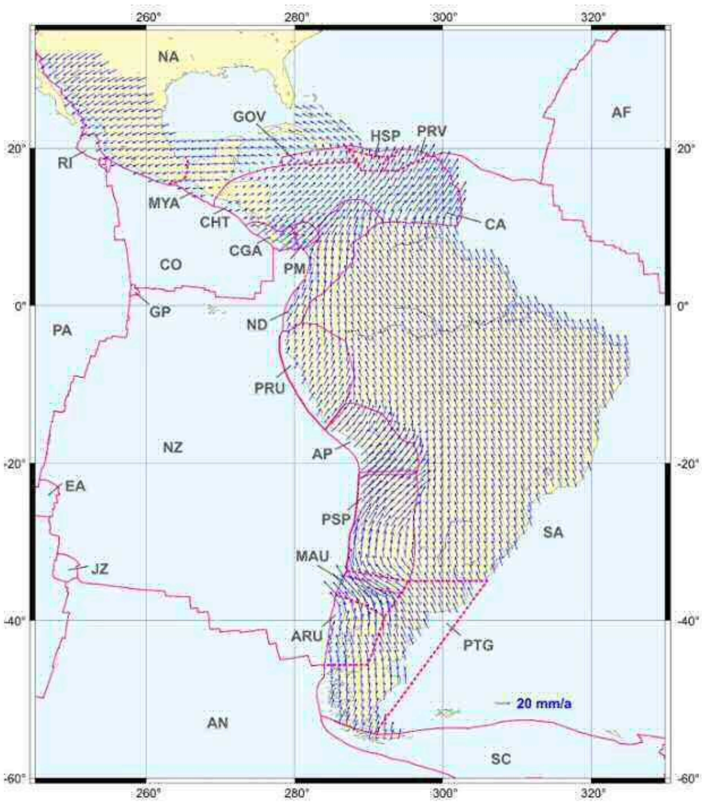

Figure 1.3b.9. Surface kinematics VEMOS2015 (Sánchez and Drewes , 2016)

VEMOS2017 (Drewes and Sánchez, 2017; see Figure 1.3.b.10) was inferred from GNSS (GPS+GLONASS). It is based on a multi-year velocity solution for a network of 495 continuously operating GNSS stations comprising a five years period from April 17, 2011 to January 28, 2017. VEMOS2017 was computed using LSC. The average prediction uncertainty is ±0.7 mm/a (horizontal) and ±1,1 mm/a (vertical) (Drewes and Sánchez, 2018).

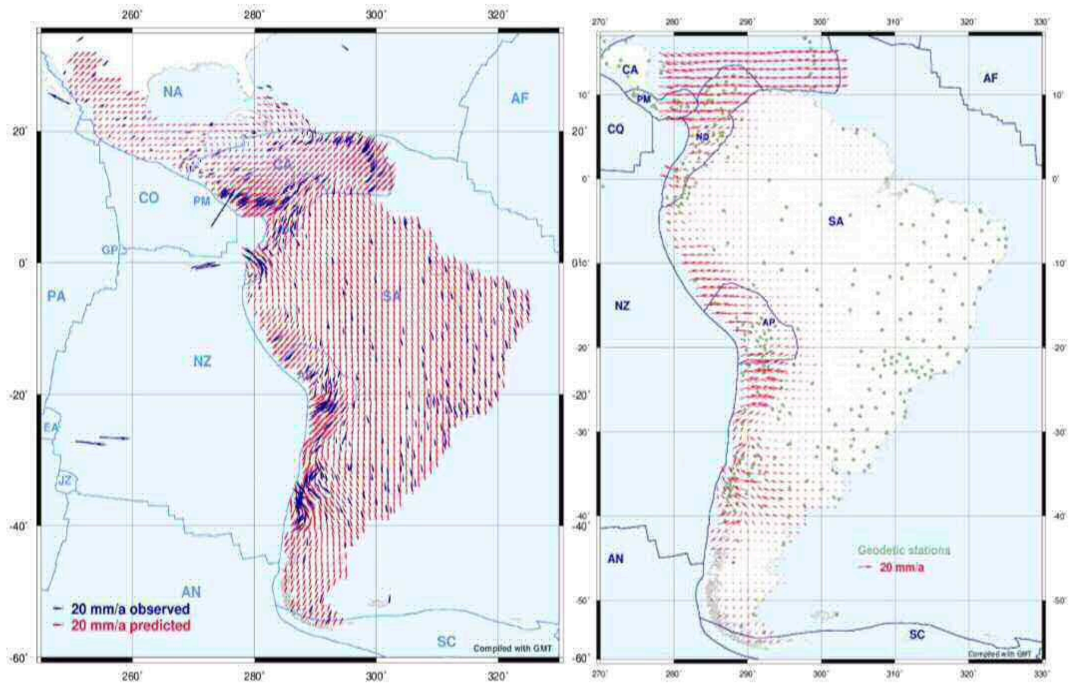

Figure 1.3b.10. Surface kinematics and deformation model VEMOS2017 (1-2014 to 1-2017) (Drewes, 2017)

(Drewes, 2017) made an exhaustive analysis of the varying surface kinematics in Latin America: VEMOS 2009, 2015, and 2017 (Figure 1.3.b.11 and Figure 1.3.b.12) and showed that it is necessary to update this model regularly. In forthcoming activities, we shall improve the distribution of the continuously operating GNSS stations, especially along the boundaries between the different tectonic plates. In the analysis of the station position time series, we want to consider possible surface loading and local effects to improve the reliability of the estimated velocities. There are perform detailed studies about the temporal-spatial evolution of the deformation field in the SIRGAS region.

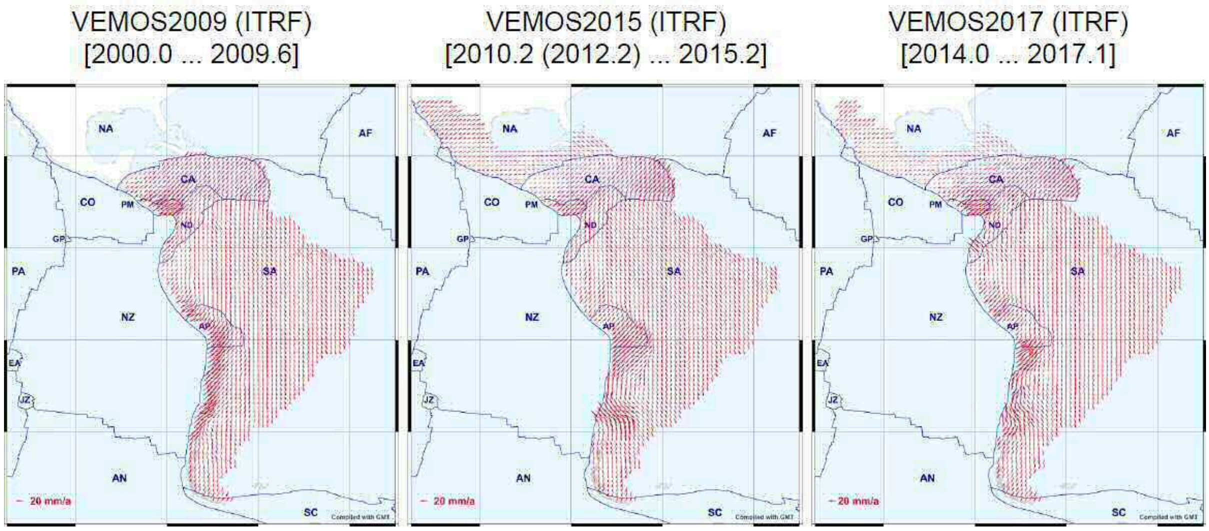

Figure 1.3.b.11. VEMOS2009 (left) referred to the ITRF2005, VEMOS2015 (centre) referred to Igb08 and VEMOS2017 (right) referred to IGS14, (Drewes, 2017)

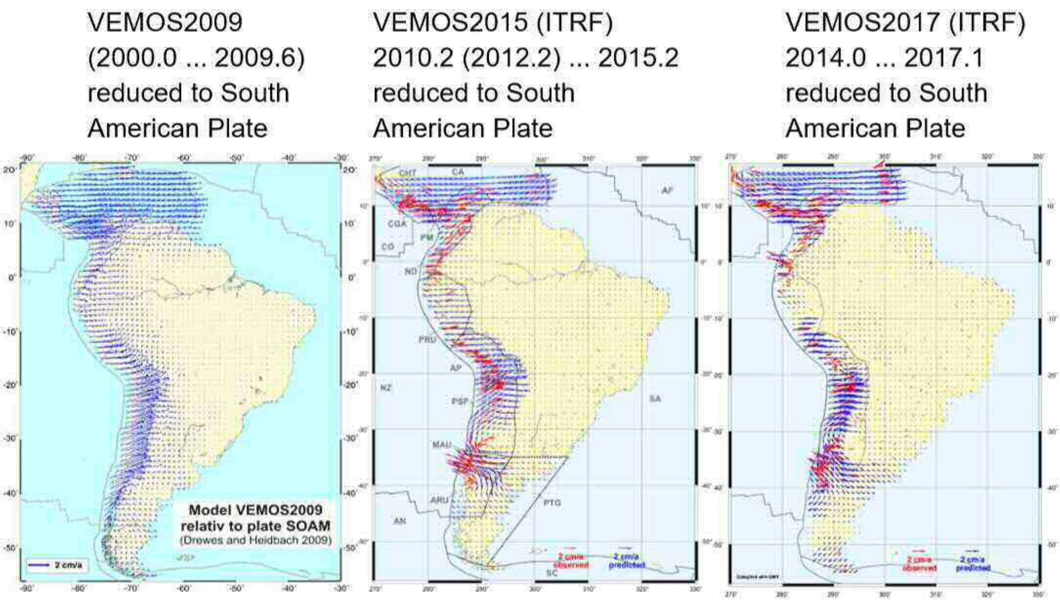

Figure 1.3b.12. Kinematic velocities (from VEMOS) with respect to South American Plate velocities, (Drewes, 2017)

Atmospheric monitoring

The integrated water vapor (IWV) was retrieved from the ZTD in each SIRGAS-CON station. From the tropospheric zenith delays obtained in the processing of the SIRGAS-CON network, the integrated tropospheric water vapor was calculated applying the strategy described by Calori (2016) in the 400 GNSS stations of SIRGAS. The time series of this variable have been generated for the period 2014 to 2018, and IWV average (Figure 1.3.b.13), maximum and minimum values for each station have been calculated (Camisay et al, 2018, Mateo et al, 2018 and Granados et al, 2018). The process of mapping this variable is being developed. These were estimated from the Analysis Centre for the Neutral atmosphere, CIMA (Centro de Ingenieria Mendoza Argentina)

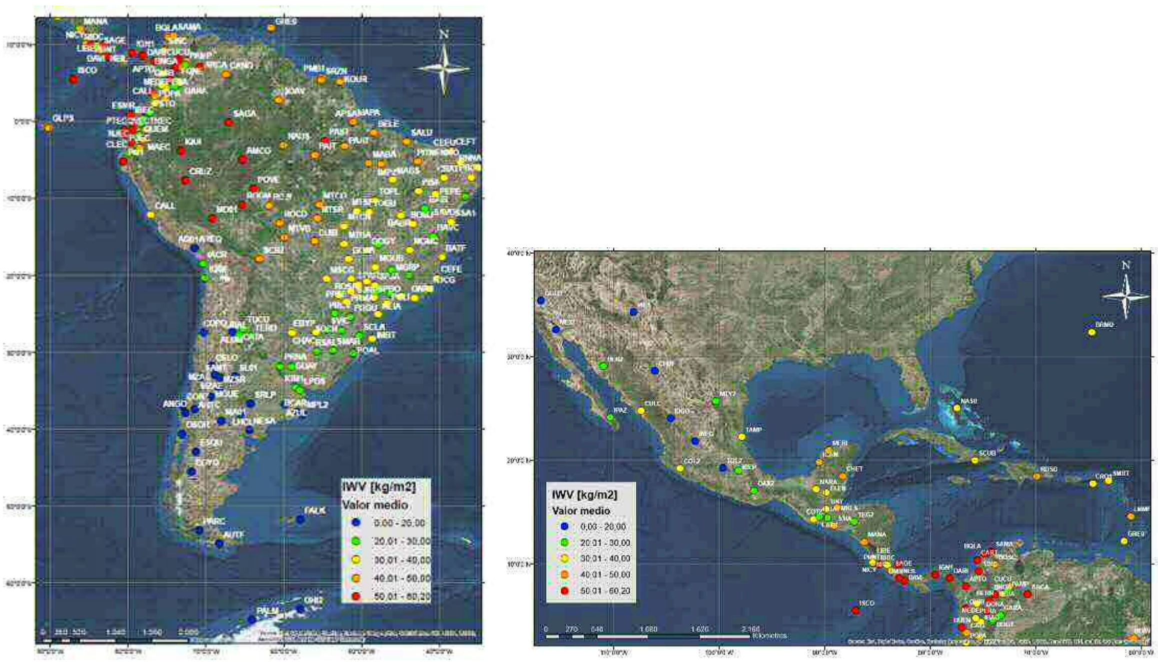

Figure 1.3b.13. IWV averaged value from SIRGAS stations in South America (right) and in Central America and Caribbean (left).

25 years of SIRGAS

In 2018, the geodetic community of Latin America has celebrated together with SIRGAS, the 25 years since that important Asunción meeting of 1993 (Figure 1.3b.14). During this session, an account was made of the main achievements of SIRGAS in these 25 years and a tribute was celebrated to the referring geodesists that have accompanied SIRGAS during its trajectory (Figure 1.3b.15).

Figure 1.3b.14. Conference International for the Geocentric Datum definition in South America, Asunción 1993.

Figure 1.3b.15. SIRGAS tribute to the referring geodesists that have accompanied SIRGAS during its trajectory, Aguascalientes, Mexico, 2018

On this context, during the meeting of the Directing Council, held on Oct. 11 2018, by Resolution, SIRGAS granted the distinction of Honorary President of SIRGAS to Prof. Dr. Hermann Drewes as public proof of admiration, respect and gratitude for being the Father Founder of SIRGAS and for his 25 years of uninterrupted support (Figure 1.3b.16)

Figure 1.3b.16. SIRGAS granted the distinction of Honorary President of SIRGAS to Prof. Dr. Hermann Drewes, Oct., 2018 (left). Coordination of the First GPS SIRGAS Campaign, La Plata, Argentina 1994 (right)

Cooperation with other organizations and international integration

SIRGAS is a member of Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and also corresponds to a Working Group of the Cartography Commission of the PAIGH. SIRGAS has remained active in the United Nations (UN) GGRF Sub-Committee and will continue participating in the corresponding working groups. Representatives of the executive committee of SIRGAS have participated in the UN-GGIM Americas events and have endorsed the appointment of referents of the region in the Subcommittee of the World Reference Geodetic Framework of the (GGRF - UN-GGIM). In the SIRGAS events, particular emphasis has been placed on the implementation of the Join Action Plan signed with PAIGH, UN-GGIM: Americas and GEoSUR for the advance of the regional spatial data infrastructure.

Outreach and capacity building

During the period 2015-2019, SIRGAS organized the following meetings:

SIRGAS symposiums:

Four annual SIRGAS symposiums were organized with the support of the IAG and the PAIGH. The principal topics presented were: SIRGAS advances and new challenges; maintenance and new perspectives for the continental reference frame; detection and evaluation of geodynamic effects on the reference frame; reports of the analysis and combination centers; progress in the implementation and maintenance of national frameworks; SIRGAS in real time; aspects of the practical application of SIRGAS products; geodetic estimation of geophysical parameters; advances in SIRGAS Unified Vertical Reference System; gravimetry and geoid; geodetic analysis of the Earth's crust deformation; atmosphere studies based on the SIRGAS infrastructure; other geodetic techniques in SIRGAS and various working group reports. Presentations in: http://www.sirgas.org/en/sirgas-symposia/

- SIRGAS2015, Nov. 18 to 20, 2015, Santo Domingo, Dominican Republic: 148 participants (Figure 1.3.b.17) from 19 countries; 54 oral presentations and 15 posters.

  Prior to the Symposium (Nov. 16 and 17), a new edition of the SIRGAS School on Reference Systems was held. Both events were hosted by the Universidad Nacional Pedro Henríquez Ureña (UNPHU). They were also supported by the project "Monitoring crustal deformation and the ionosphere by GPS in the Caribbean" granted by the IUGG in agreement with the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the International Association of Geomagnetism and Aeronomy (IAGA).

Figure 1.3b.17. Symposium SIRGAS2015

- SIRGAS2016, Nov. 16-18, 2016, Quito, Ecuador: 217 participants (Figure 1.3b.18), from 14 countries; 56 oral presentations and 12 posters; hosted by the Instituto Geográfico Militar of Ecuador.

Figure 1.3b.18. Symposium SIRGAS2016

- SIRGAS2017, Nov. 27-30, 2017, Mendoza, Argentina: 128 participants (Figure 1.3b.19) from 16 countries; 51 oral presentations and 18 posters; organized by the Universidad Nacional de Cuyo and the Universidad Juan Agustín Maza.
- Five invited conferences: "Current activities of the IAG" (H. Drewes), "Some applications of ionospheric and geodetic models supported by real-time GNSS measurements" (M. Hernández-Pajares), "SLR – An Overview and General Aspects" (D. Thaller), "SLR and the Gravity Field" (D. Thaller), and "SLR and the Global Terrestrial Reference Frame" (D. Thaller).
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Figure 1.3b.19. Symposium SIRGAS2017, Mendoza, Argentina, 2017

- SIRGAS2018, Oct. 9-12, 2018, Aguascalientes, Mexico: 97 participants (Figure 1.3b.20) from 21 countries; 43 oral presentations and 13 posters; organized by the Instituto Nacional de Estadistica y Geografía (INEGI) of Mexico.

  The symposium included a session "Tribute for the 25 years of SIRGAS" and five invited presentations: "Challenges to be faced by Geodesy in the coming years from the perspective of the IAG" (H. Drewes), "Strategy for the establishment of the IHRS" (L. Sanchez), "The development of SIRGAS over 25 years and prospective challenges of science and humanity" (H. Drewes), and "Participation and geodetic development of Latin American countries during the 25 years of the SIRGAS project and SIRGAS in future time" (M. Hoyer).

  In the frame of this symposium, two additional activities were programmed: A "Conversation SIRGAS in practice" on Oct. 7 (5 presentations) and a workshop about Vertical Datum from Oct. 15 to 17, 2018.

Figure 1.3b.20. Symposium SIRGAS2018, INEGI, Aguascalientes, Mexico.

Training events:

- The SIRGAS School 2015, Nov. 18-19, 2015, Santo Domingo, Dominican Republic: 60 participants from 19 countries.
  The subject of the school concentrated on strengthening the basic concepts needed for the appropriate generation and use of fundamental geodetic and geophysical data in the Caribbean Region, especially for studying, understanding and modelling deformations of the Earth's surface and features of the ionosphere, and its influence on navigation systems used for civil aviation.
- Four Workshops in Vertical Reference SIRGAS System focussed on the unification of the National Vertical Networks in the region of SIRGAS in order to realize a continental adjustment by means of processing and adjustment of geopotential numbers. The processing and adjustment of gravimetric and leveling data corresponding to the national vertical networks were also considered. Sílvio R.C. de Freitas (Brasil), Chair of SIRGAS WG III, coordinated the Workshops. The basis of data processing was a software package developed by H. Drewes and L. Sánchez. Preliminary analyses of the consistency of national networks was done by using a software package developed by R. Teixeira Luz (Brazil). All of them acted as instructors in some Workshops.
  - 3rd WGIII Workshop 2015, May 18-22, 2015, Curitiba, Brazil: 29 participants (Figure 1.3.b.21) from 10 countries. The workshop included five nine-hour sessions with theoretical classes and practical exercises.

Figure 1.3b.21. 3rd WGIII Workshop, Curitiba, Brazil 2015

- 4th WGIII Workshop 2016, Nov. 21-25, 2016,Quito, Ecuador: 45 participants (Figure 1.3.b.22) from 10 countries

Figure 1.3b.22. 4th SIRGAS Workshop 2016

- 5th WGIII Workshop 2017, Nov. 6-10, 2017, Heredia, Costa Rica: 33 participants (Figure 1.3.b.23) from 5 countries

Figure 1.3b.23. 5th SIRGAS Workshop 2017, Heredia, Costa Rica.

- 6th WGIII Workshop 2018, Oct. 15-17, 2018, Aguascalientes, Mexico: 33 participants (Figure 1.3b.24) from 12 countries. On this occasion, issues related to the unification of the vertical datum for the SIRGAS member countries were developed again, such as the guidelines and actions for the materialization of the IHRS. Classes were taught with theoretical foundations and practical tasks were developed with data provided by the countries attending the workshop.

Figure 1.3b.24. 6th SIRGAS Workshop 2018, INEGI, Aguascalientes, Mexico.

- The SIRGAS Workshop on Real Time GNSS positioning, Nov. 22-24, 2017, Mendoza, Argentina; 50 participants (Figure 1.3.b.25) from 12 countries.

  The main objective was to follow up on the activities developed during the SIRGAS RT Workshop held in 2012 with the aim of promoting the use of the available capacity of SIRGAS and analyzing the possibilities of offering services in this context to the Latin American and international geodesic community. It was organized as an activity of the SIRGAS Working Group II "SIRGAS at national level". The main topics were: Real-time positioning systems and techniques (RTK, NetRTK, PPP), national real-time infrastructures, caster and real-time stream management, NTRIP and associated software (BNC, RTKLib, etc.), theoretical foundations of the European project AUDITOR (Improved GNSS ground-based augmentation system for precision agriculture services) with emphasis on the generation of reliable ionosphere products for the calculation of real-time corrections. Three practical exercises were developed: one for real-time measurements in the field and two for connectivity, configuration, and calculation in the cabinet.

Figure 1.3b.25. SIRGAS Workshop in RT positioning 2017, Mendoza, Argentina.

- The SIRGAS Workshop on SLR in Latin America, Nov. 30-Dec. 1, 2017, Mendoza, Argentina: 43 participants from 10 countries.

  The main objective of the workshop was to evaluate the possibility of extending the SIRGAS reference frame by means of SLR stations to improve the geocentric realization of the regional frame. Representatives of the four SLR observatories installed in South America (Arequipa, AGGO, Brasilia and San Juan) reported about the status and future improvements at the different stations. B. Sierk of the European Spatial Agency (ESA) presented the ESA plans related to new SLR developments and applications. D. Thaller (Bundesamt für Kartographie und Geodäsie, Germany) provided an overview about the SLR dataflow and analysis performed within the International Laser Raging Service (ILRS) and outlined some recommendations to start SLR data processing experiments within SIRGAS. Following these recommendations, the next activity is to prepare and distribute an input data set to be processed by the different groups installed in Argentina, Brazil, Peru and Costa Rica. Results of this experiment will be discussed during the next SIRGAS symposium in 2019.

Figure 1.3b.26. SIRGAS Workshop on SLR in Latin America 2017, Mendoza, Argentina

- Two training courses in processing GNSS observations:
  - "Processing with Bernese 5.2", July 17- 20, 2018, Universidad de Santiago de Chile, Santiago, Chile (Figure 1.3b.27)
  - "Processing with Gamit", Sept. 3-8, 2018 Instituto Geográfico Nacional de Argentina, Buenos Aires, Argentina; 27 participants (Figure 1.3b.28) from 8 countries

Figure 1.3b.27. Training course, Santiago, Chile

Figure 1.3b.28. Training course, Buenos Aires, Argentina

SIRGAS participated to the following international conferences:

- European Geosciences Union, General Assembly 2015 (EGU 2015). Vienna, Austria, April 15, 2015.
- International Union of Geodesy and Geophysics, General Assembly 2015 (IUGG2015), Prague, Czech Republic. June 22 - July 2, 2015.
- Fifth Session of the United Nations Committee of Experts on Global Geospatial Information Management. New York, USA. Aug. 3, 2015.
- A glimpse at geodetic activities in Latin America. L.P.S. Fortes. IN: GGOS Days 2016, Cambridge, MA., USA. Oct. 24 - 27, 2016.
- UN-GGIM: Global Geodetic Reference Frame (GGRF) for Sustainable Development. W. Martínez.En: XXII Semana ICG 2016, Universidad Distrital Francisco José de Caldas. Bogotá, Colombia. Oct. 24, 2016.
- Incorporation of the Caribbean to the Geocentric Reference System for the Americas SIRGAS. W. Martínez, M.V. Mackern, V. Cioce, R. Rodino, S.R. De Freitas. In: UN-GGIM: Americas Third Session. Mexico City, Mexico. Oct. 5, 2016.
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Sub-Commission 1.3c: North America (NAREF)

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

Introduction and structure

The objective of this sub-commission is to provide international focus and cooperation for issues involving the horizontal, vertical, and three-dimensional geodetic control networks of North America, including Central America, the Caribbean and Greenland (Denmark).

The regional sub-commission is co-chaired by representatives from the Canadian Geodetic Survey and the U.S. National Geodetic Survey, currently Dr. Michael Craymer and Dr. Dan Roman, respectively.

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 2015-2019. 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.

Members

The membership of SC1.3c consists primarily of representatives from the national geodetic agencies in North America with additional members from other government agencies and academia as needed for specific working groups. The following is a list of members organized by agency affiliation.

Michael Craymer (Co-Chair, Canada)
Dan Roman (Co-Chair, U.S.A.)
Remi Ferland (Canada)
Joseph Henton (Canada)
Mike Piraszewski (Canada)
Finn Bo Madsen (Denmark)
Kevin Choi (U.S.A.)
Theresa Damiani (U.S.A.)
Dru Smith (U.S.A.)
Mike Bevis (U.S.A.)
Geoff Blewitt (U.S.A.)
Jeff Freymueller (U.S.A.)
Tom Herring (U.S.A.)
Corné Kreemer (U.S.A.)
Richard Snay (U.S.A)

Activities during the period 2015-2017

SC1.3c-WG1: North American Reference Frame (NAREF)

The objective of this working group is to densify the ITRF and IGS global networks 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 current IGS global network.

Originally, the regional densification of the ITRF and IGS network consisted of on-going weekly combinations of several different regional weekly solutions across the entire North American continent using different GPS processing software. However, no weekly combinations have been generated since GPS week 1583 due to the large number of stations. Since that time, the Canadian Geodetic Survey (CGS) and Mexico's Instituto Nacional de Estadística y Geografía (INEGI) have continued to generate weekly solutions in the current IGS reference frame for their own regions. The U.S. National Geodetic Survey (NGS) has continued computing and archiving weekly solutions after GPS week 1631 but they are not currently aligned to the ITRF or IGS reference frames. After NGS has completed their "repro2" reprocessing of all their CORS data, these and future weekly solutions will be aligned to ITRF2014.

CGS completed a repro2 reprocessing in 2016 of data since 2000 for nearly 200 federal and provincial public GNSS tracking stations across Canada as well as over 250 high accuracy campaign stations and nearly 600 U.S. CORS in the northern conterminous U.S., eastern Alaska and GNet stations in Greenland (Ferland et al., 2016; Craymer, 2017; Craymer et al., 2018). This reprocessing used the Bernese GNSS Software v5.2 with CODE repro2 products in the IGb08 reference frame due to the unavailability of combined IGS repro2 orbits at the time. On-going processing of current weeks are aligned to the IGS reference frame of date, currently IGS14. These solutions include many new permanent GNSS stations in strategic locations targeted to improve coverage of GIA across the northern parts of Canada and the monitoring of tectonic deformation of the west coast.

CGS has also completed the combination of all weekly solutions since 2000 into a multi-year cumulative solution that is aligned to IGS14 and updated monthly (see Figure 1.3c.1). These cumulative solutions are based on newly developed SINEX combination software that allows for the estimation of coordinates, velocities, annual and semi-annual terms for seasonal signals, exponential and logarithmic terms for post-seismic deformation, together with position and velocity discontinuities. In addition to solutions for public GNSS tracking stations, CGS has been computing weekly coordinate solutions and monthly updated multi-year cumulative solutions for nearly 900 Canadian commercial RTN base stations in support of compliance agreements between the federal government and commercial RTN service providers (see Other Activities below). CGS is presently investigating the suitability of these RTN stations to densify sparse regions of the public network for improved modelling of crustal dynamics.

NGS also began "repro2" reprocessing of their entire NOAA CORS Network (NCN) in 2017. The processing includes data spanning 1996 to 2016 (weeks 0834 to 1933), a total of 1100 weeks or 21 years, and includes about 3050 CORS, IGS and other (e.g., NGA) stations across the conterminous U.S., Alaska, Hawaii, American Samoa, Guam, the Northern Mariana Islands, Puerto Rico, the U.S. Virgin Islands, and a handful of non-U.S. locations. The reprocessing used IGS repro2 orbits and is presently available online for user testing. The final weekly solutions are set to be released for production use in the summer of 2019. Weekly solutions up to week 1933 will be combined into a multi-year cumulative solution, a preliminary version of which is given in Figure 1.3c.2.

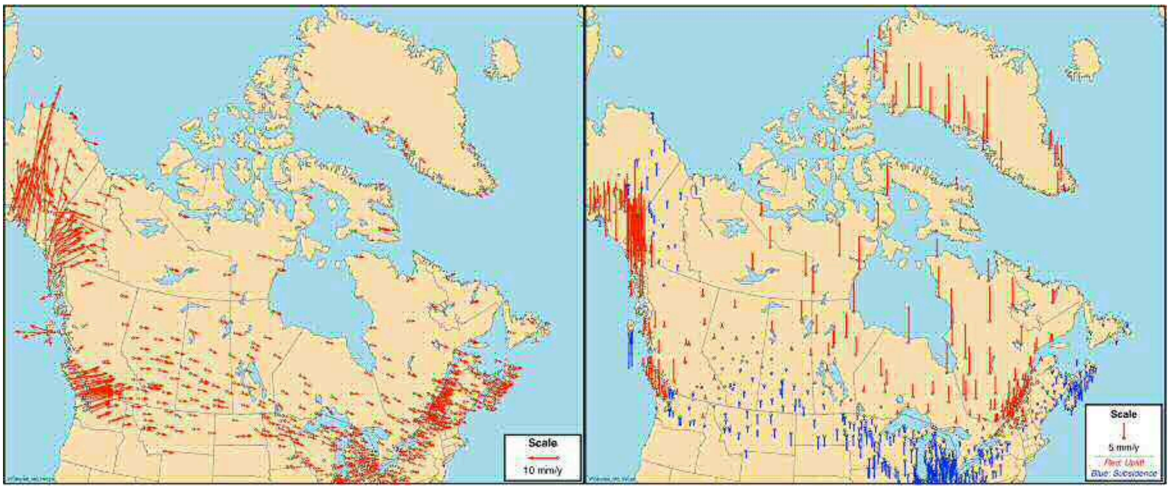

Figure 1.3c.1. Horizontal (left) and vertical (right) velocities from Canadian multiyear cumulative solution transformed to NAD83(CSRS) using weekly solutions to GPS week 1929. Vertical velocity vectors in red represent uplift while those in blue represent subsidence.

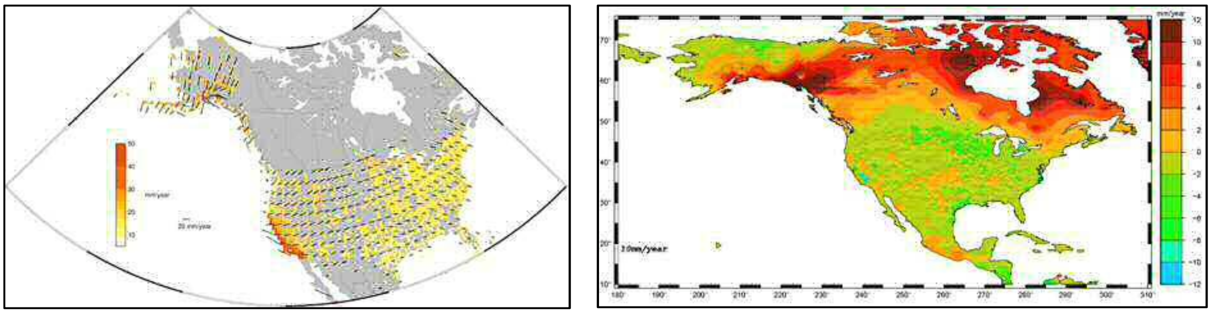

Figure 1.3c.2. Horizontal (left) and vertical (right) velocities in ITRF2014 from a preliminary multi-year cumulative solution of “repro2” weekly solutions to GPS week 1933. In the vertical plot, warm colors represent uplift and cool colors represent subsidence.

SC1.3c-WG2: Plate-Fixed North American Reference Frame

The objective of this working group is 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 the existing, non-geocentric North American Datum of 1983 (NAD 83) reference system 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. Consequently, the U.S. has been making plans to replace NAD 83 in 2022, 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 be based on the latest ITRF realization at a specific epoch and fixed to the

North American plate. Discussions are also underway in Canada to adopt the same frame sometime after 2022. Regardless whether or not the new frame is officially adopted, the Canadian Geodetic Survey will make coordinates and velocities available in both NAD83(CSRS) and the new frame and provide a transformation between the two.

The new reference frame will be defined by aligning it exactly 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.

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)

SC1.3c-WG3: Reference frame transformations in North America

The objective of this working group is 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.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a new velocity model and transformation software was developed by Snay et al. (2016) for North America. 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.

More recently, 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, 2016, 2017a,b). 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.

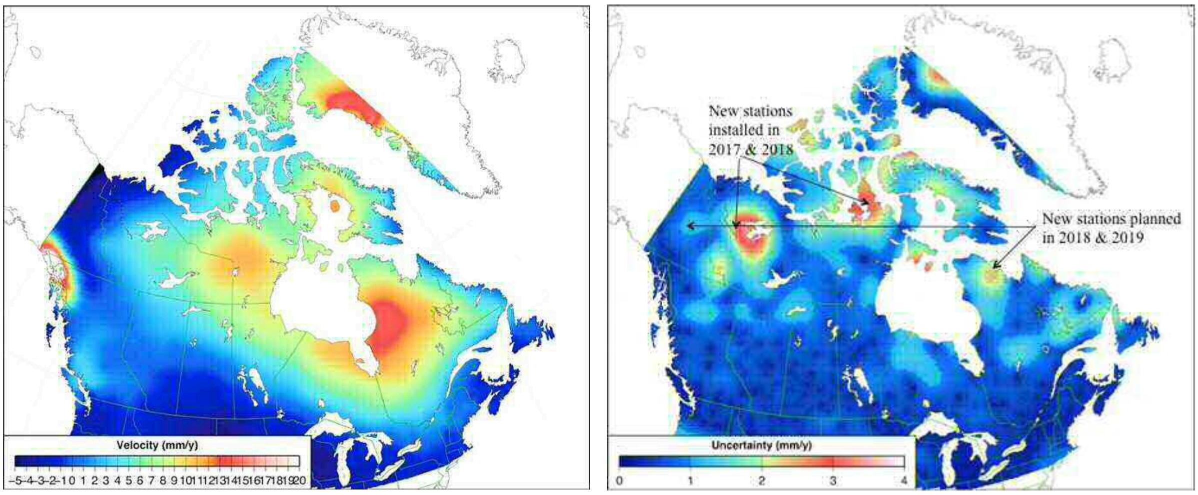

Figure 1.3c.3. Canadian vertical velocity model in NAD83(CSRS) (left) obtained from an integration of GNSS velocities with a GIA model. Velocity model uncertainties (right) indicate areas for improvement

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). 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 also been working towards a major enhancement of their geodetic infrastructure similar to that implemented in Australia (see Figure 1.3c.5). The primary objective of the so-called PNT initiative is to densify the existing CORS network with many more real-time stations in partnership with industry and the provincial governments, and at least one multi-technique GGOS station. The resiliency of the network would be improved through redundancy and integrity monitoring. More consideration will also be given to non-geodetic uses of the GNSS data, such as meteorology. Although still in the proposal stage, it has received much support.

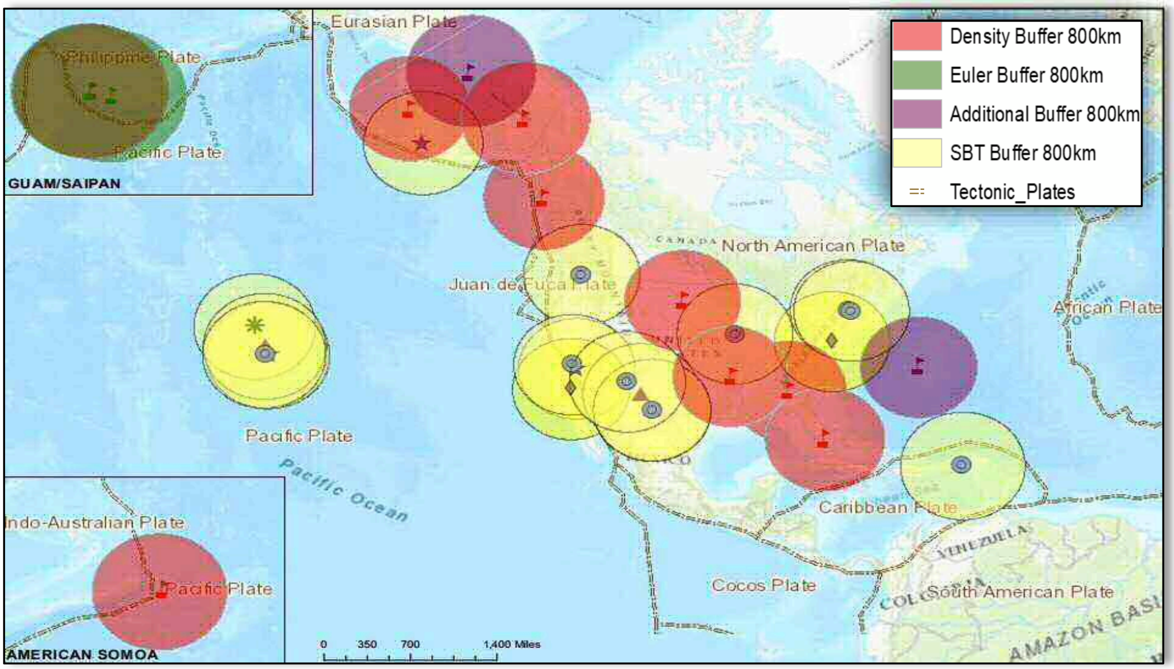

Figure 1.3c.4. Planned Foundation CORS network showing stations collocated with other techniques, densification stations, stations for Euler pole determination and other addition stations. Two additional stations on the Caribbean plate are yet to be determined.

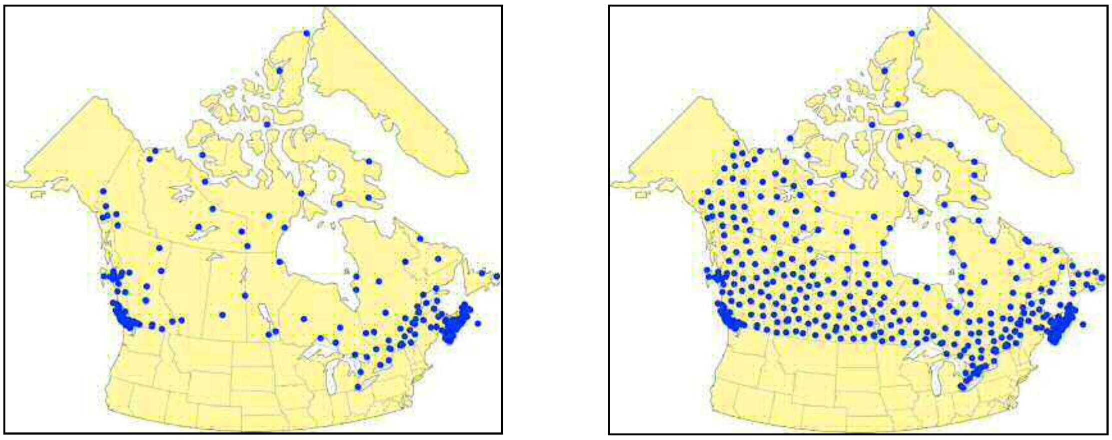

Figure 1.3c.5. Current CORS station distribution in Canada (left) and proposed PNT densification (right).

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 is now providing 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.6). Compliance agreements have 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.

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.

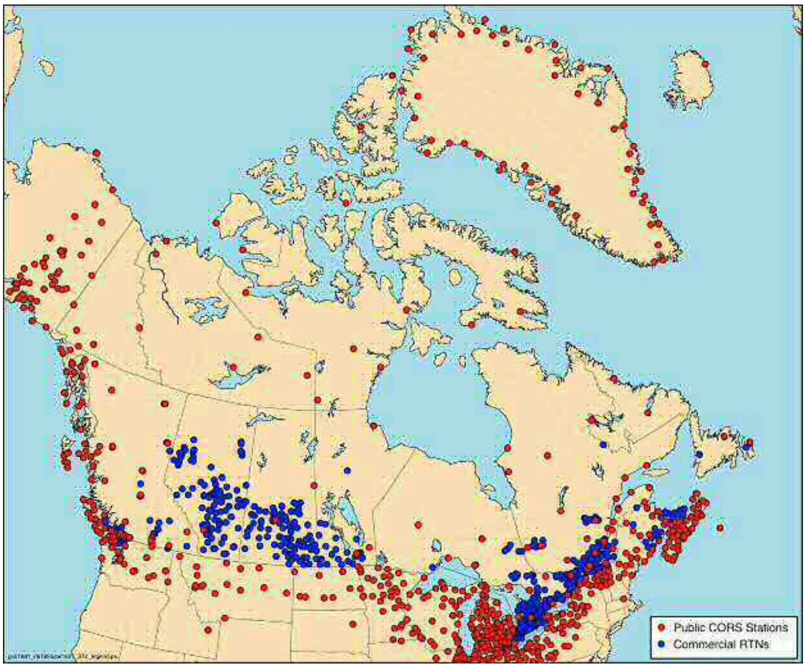

Figure 1.3c.6. Distribution of the six largest commercial RTK networks in Canada (blue dots) in relation to public federal and provincial networks of permanent GNSS stations (red dots). The commercial RTN stations significantly densify the public network in the Prairies.

Cooperation with other organizations and international integration

There has been much international coordination between NAREF and other groups. In particular, NAREF is looking to foster closer cooperation and collaboration with the SIRGAS Sub-Commission 1.3b for South and Central America. To this end, the U.S. has become a member of SIRGAS and has participated in recent meetings.

Members of NAREF participated as members in both the UN-GGIM Americas regional committee and the SIRGAS Sub-Committee 1.3c. UN-GGIM-Americas focuses on the regional implementation of the GGRF for all of the Americas. SIRGAS was originally tasked with this implementation for the Americas. However, it is no longer clear how this governance will be handled since the creation of the UN-GGIM Sub-Committee on Geodesy, which now has the responsibility for implementing the GGRF. Regardless, SIRGAS has been briefed on NAREF activities and plans to ensure coordination in any implementation of the GGRF. At the urging of NAREF members and others, UN-GGIM-Americas is also developing a new Working Group 4 on Geodetic Reference Frames to balance the scientific input and requirements of SIRGAS countries with those of the other Member States in the Americas. The WG4 will act as the liaison for the UN-SCoG within the UN-GGIM Americas regional committee.

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 while M. Craymer has been chairing the Working Group on Data Sharing, Standards and Conventions.

Related to the SCoG standards working group are NAREF contributions to the development of ISO standards and the ISO Geodetic Registry. The Registry is an authoritative collection of definitions of international reference frames and the transformations between them, similar to the privately run EPSG registry. Both CGS and NGS have made a significant effort to populate 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. The Registry is available at the following link: http://registry.isotc211.org

Outreach and capacity building

SC1.3c-WG1: North American Reference Frame:
Meetings of the working group were held on an ad hoc basis in 2015, 2016 and 2018 during the AGU Fall Meetings in San Francisco and Washington. A status report on the activities of WG activities was presented during the References Frames for Applications of Geosciences (REFAG2018) symposium held concurrently with the 2018 COSPAR Scientific Assembly.

The weekly coordinate and annual cumulative coordinate/velocity solutions are available from the NAREF website at http://www.naref.org/

SC1.3c-WG2: Plate-Fixed North American Reference Frame:
A variety of well organized outreach and capacity building efforts by NGS to support the implementation of the new North American reference frame has been underway in the U.S. since 2010. A "New Datums" website has been created to inform the public and provide supporting material to education users on the definition and use of the new NATRF2022 reference frame.

The definition, implementation and use of NATRF2022 and the accompanying new vertical datum NAPGD2022 have been published in the following three "blueprint" documents:

Blueprint for 2022, Part 1: Geometric Coordinates
Blueprint for 2022, Part 2: Geopotential Coordinates
Blueprint for 2022, Part 3: Working in the Modernized NSRS

There have also been informative discussions with the public during four Federal Geospatial Summits organized by the NGS in 2010, 2015, 2017 and 2019. These well-attended meetings informed the public about the new reference systems, the status of their implementation, and solicited valuable feedback. To ensure the public kept up to date with progress on the implementation of NATRF2022 and NAPGD2022, NGS has published regular NSRS Modernization Newsletters at a rate of about 3 to 4 every year since 2015. The Blueprint documents and presentations and video recordings from the Summits are available online from the NGS website at http://www.ngs.noaa.gov/datums/newdatums/.

Scientific meetings and workshops have also been organized to address the significant scientific and practical challenges of realizing these regional reference frames, including the definition, maintenance and future evolution of plate-fixed regional reference frames for North America; the effects and modelling of crustal motions, including glacial isostatic adjustment and tectonic motions along plate boundaries on the western coast of North America and in the Caribbean; and standards needed for accurate geodetic positioning in time-dependent reference frames. The following sessions and workshops were organized to discuss these issues included:

- 2016 AGU Fall Meeting, San Francisco, Dec. 12-16; Session: Scientific and practical challenges of replacing NAD 83, NAVD 88 and IGLD 85
- 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 10-14; Session: Further Evolution of North American Reference Frames

- North American Reference Frame Workshop, 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 14
- 2018 AGU Fall Meeting, Washington, DC, Dec. 12-16; Session: Modernizing Regional Reference Frames and Vertical Datums for North America

For other outreach efforts, see the list of publications and presentations.

Publications and presentations

Craymer, M. (2017). Canadian Geodetic Networks. CCArray Workshop, Sidney, BC, March 20-21.

Craymer. M. R. Ferland, E. Lapelle, M. Piraszeski, C. Robin, Y. Zhao (2018). An Updated Realization of NAD83(CSRS) for Canada. 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 10-14.

Ferland, R., M. Piraszeski, M. Craymer (2016). An update to the analysis of the Canadian Spatial Reference System. Abstract G23B-1069, AGU Fall Meeting, San Francisco, Dec. 14-18.

Kreemer, C., W.C. Hammond, G. Blewitt (2017). A Robust Estimation of the 3-D Intraplate Deformation of the North American Plate From GPS. Journal of Geophysical Research: Solid Earth, Volume 123, doi:10.1029/2017JB015257.

National Geodetic Survey (2017a). Blueprint for 2022, Part 1: Geometric Coordinates. NOAA Technical Report NOS NGS 62, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 21.

National Geodetic Survey (2017b). Blueprint for 2022, Part 2: Geopotential Coordinates. NOAA Technical Report NOS NGS 64, National Geodetic Survey, National Oceanic and Atmospheric Administration, Nov. 13.

National Geodetic Survey (2019). Blueprint for 2022, Part 3: Working in the Modernized NSRS. NOAA Technical Report NOS NGS 67, National Geodetic Survey, National Oceanic and Atmospheric Administration, April 25.

Robin, C., M. Craymer, R. Ferland, E. Lapelle, M. Piraszeski, Y. Zhao, T.S. James (2016). Improved Modelling of Vertical Crustal Motion in Canada for a New North American Reference Frame. Abstract G21B-1002, AGU Fall Meeting, San Francisco, Dec. 12-16.

Robin, C., M. Craymer, R. Ferland, E. Lapelle, M. Piraszeski, Y. Zhao, T.S. James (2017a). A hybrid crustal velocity model for Canada: combining GPS data with GIA models. IAG GIA Workshop, Reykjavik, Sept. 7.

Robin, C., M. Craymer, R. Ferland, E. Lapelle, M. Piraszewski, Y. Zhao (2017b). Integrating GIA models with GNSS data: Testing models against a new Canadian velocity field. Abstract G21B-0867, AGU Fall Meeting, New Orleans, Dec. 11-15.

Roman, D. (2017a). Implementation plan for the UN-GGIM GGRF Resolution. 2017 SIRGAS Symposium, University of CUYO, Mendoza, Argentina, Nov. 28.

Roman, D. (2017b). A Modernized National Spatial Reference System in 2022: Focus on the Caribbean Terrestrial Reference Frame. Abstract G13A-07, AGU Fall Meeting, New Orleans, Dec. 11-15.

Roman, D. (2018a). United States NSRS 2022: Terrestrial Reference Frames. International Federation of Surveyors Congress, Istanbul, Turkey, May 9.

Roman, D. (2018b). Criteria for Selection of Continuous GNSS Sites Throughout North America in Support of NATRF 2022. 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 10-14.

Roman, D. (2018c). Aspects of the Intra-Frame Velocity (Deformation) Models for the U.S. N.S.R.S. GeoPrevi 2018 International Symposium, Bucharest, Romania, Oct. 29.

Roman, D., M. Craymer (2018). Regional Reference Frames for North America: Current Status & Future Plans of Regional Sub-Commission SC1.3c. Reference Frames for Applications in Geosciences (REFAG) COSPAR 2018 Scientific Assembly, Pasadena USA, July 14-22.

Smith, D., D. Roman (2017). Error Propagation in the four terrestrial reference frames of the 2022 Modernized National Spatial Reference System. Abstract G13A-06, AGU Fall Meeting, New Orleans, Dec. 11-15.

Snay, R.A., J.T. Freymueller, M.R. Craymer, C.F. Pearson, and J. Saleh (2016). Modeling 3-D crustal velocities in the United States and Canada. Journal of Geophysical Research – Solid Earth, Volume 121, doi:10.1002/2016JB012884.

Snay, R.A. J. Saleh, C.F. Pearson (2018). Improving TRANS4D's model for vertical crustal velocities in Western CONUS. Journal of Applied Geodesy, Volume 12, Issue 3, doi:10.1515/jag-2018-0010.

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Craymer, M.R., R. Ferland, R. Snay (2000). Realization and Unification of NAD83 in Canada and the US via the ITRF. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), Towards an Integrated Global Geodetic Observing System (IGGOS), IAG Section II Symposium, Munich, Oct. 5-9, 1998. International Association of Geodesy Symposia, Volume 120, Springer-Verlag, Berlin.

Soler, T., R.A. Snay (2004). Transforming Positions and Velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983. Journal of Surveying Engineering, Vol. 130, No. 2, May, doi:10.1061/(ASCE)0733-9453(2004)130:2(49)

Sub-Commission 1.3d: Africa

Chair: Elifuraha Saria (Tanzania)

Introduction and Structure

The African Geodetic Reference Frame (AFREF) was conceived as a unified geodetic reference frame for all 54 countries in Africa, fully consistent and homogeneous with current International Terrestrial Reference Frame (ITRF). AFREF will be the fundamental basis for the national and regional three-dimensional reference networks to make it easier to coordinate planning and development activities within the 54 countries in Africa and across national boundaries.

The major goal of Sub-Commission 1.3d is to establish a permanent GNSS network of base stations in support of an effort to unify the reference frames in Africa. The project has been under the support of the United Nations Committee for Development Information, Science and Technology (CODIST) with the following objectives:

- Define the continental reference system of Africa. Establish and maintain a unified geodetic reference network as the fundamental basis for the national 3-D reference networks fully consistent and homogeneous with the global reference frame of the ITRF;
- Establish continuous, permanent GPS stations such that each nation or each user has free access to, and is at most 500km from, such stations;
- Determine the relationship between the existing national reference frames and the ITRF to preserve legacy information based on existing frames;
- Realize a unified vertical datum;
- Provide a sustainable development environment for technology transfer, so that these activities will enhance the national networks, and numerous applications, with readily available technology and assist in establishing in-country expertise for implementation, operations, processing and analyses of modern geodetic techniques, primarily GPS;
- Sensitize African countries to the aims and objectives of AFREF.

In pursuance of these objectives, sparse continuous operating reference stations (CORS) GNSS networks have been established in Africa, and managed by some member States, IGS and other partners conducting research in Africa.

Members and Steering Committee

The organizational structure of the AFREF Steering Committee was decided during the 2nd AFREF WG meeting which was held from 20-24 Nov. 2017 in the United Nation Economic Commission for Africa (UNECA). The meeting was attended by about twenty-five experts in the geospatial field from Africa and other parts of the world. The structure is yet to be finalized and the names will be submitted once the document is approved. The structure is as shown in Fig. 1.3d.1.

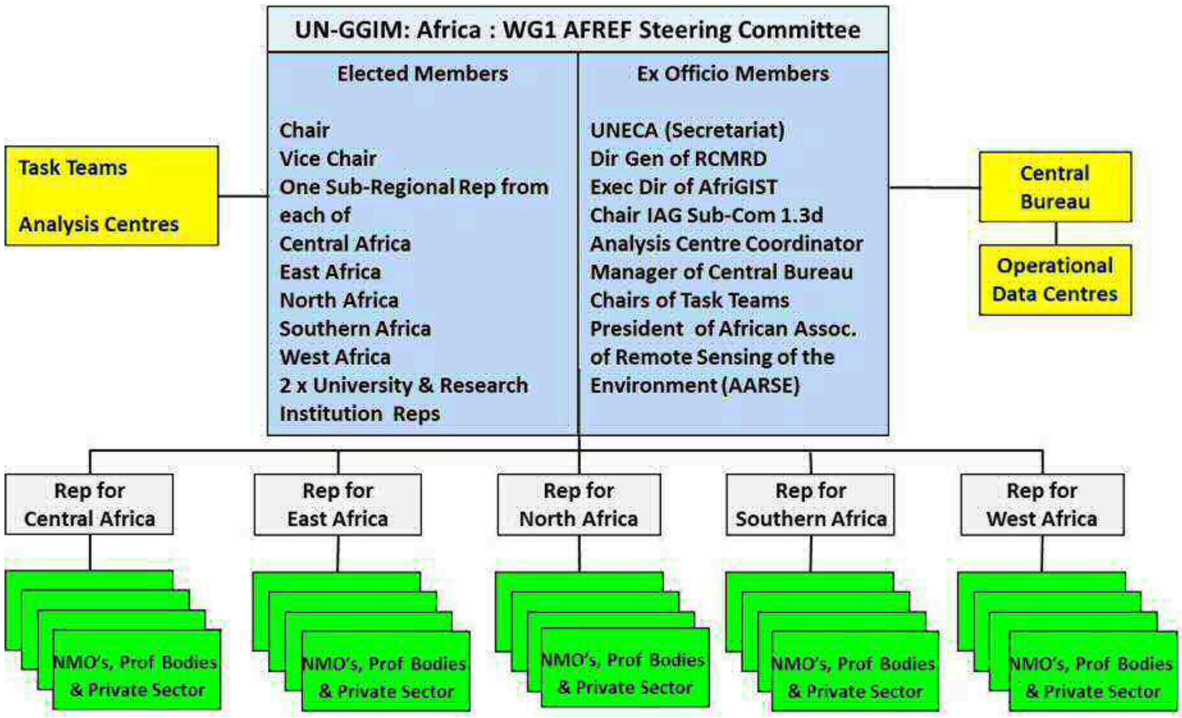

Figure 1.3d.1. Proposed structure of the AFREF Steering Committee.

Activities and publications during the period 2015-2019

Data and GNSS network

Various institutions, governmental agencies, organizations, and research projects installed permanent GNSS sites in Africa for various purposes including tectonic or volcano deformation, meteorology and ionosphere monitoring, as well as survey and mapping. A number of National Mapping Authorities has also established CORS networks in their countries. The AFREF Operational Data Centre (ODC, afrefdata.org) is archiving subsets of all these GNSS networks with an average of 40 sites each day. There are also other portals that have African data, however they have fewer data than the ODC. These include data-out.unavco.org, cddis.gsfc.nasa.gov, geoid.hartrao.ac.za, and www.station-gps.cea.com.eg. In addition, there are number of CORS whose data are not available online, but kept in individual countries. These data are shared through personnel communications.

A recent study on Africa investigated the rigidity of Nubia by dividing it in three sections and comparing the Euler pole obtained when using sites located in each section, or when using the whole set of Nubian stations (Njoroje, 2015). The results show discrepancy of at most 1 degree. However, it is too early to draw firm conclusions since almost 80% of Nubia has no GNSS data.

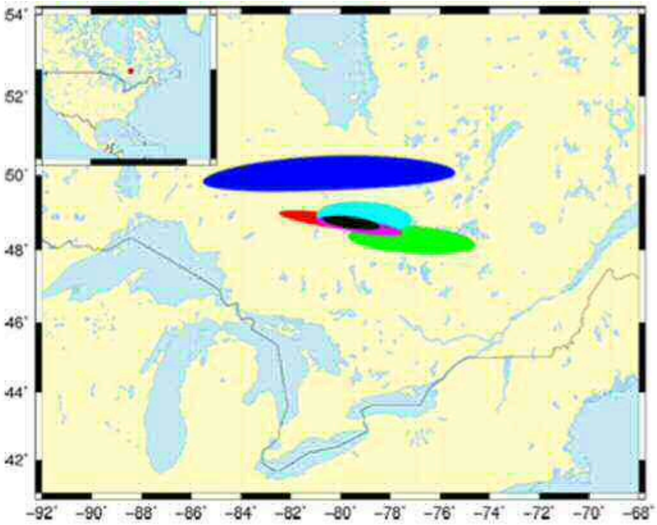

Figure 1.3d.2. Nubian Euler pole location using GPS sites at three divided Nubian sections and using all GNSS sites in Nubia. Using only West is Blue, South is red, Central is green, West Central is cyan and South Central is magenta and using all Nubian sites is black.

A second recent study investigated the optimal locations of new AFREF stations based on the criteria in the AFREF objectives (Muzondo et al., 2015). This study also documented the freely available GNSS stations as of 2015 for each country in Africa, where South Africa and Nigeria contributes the most data in the region (Figure 1.3d.3).

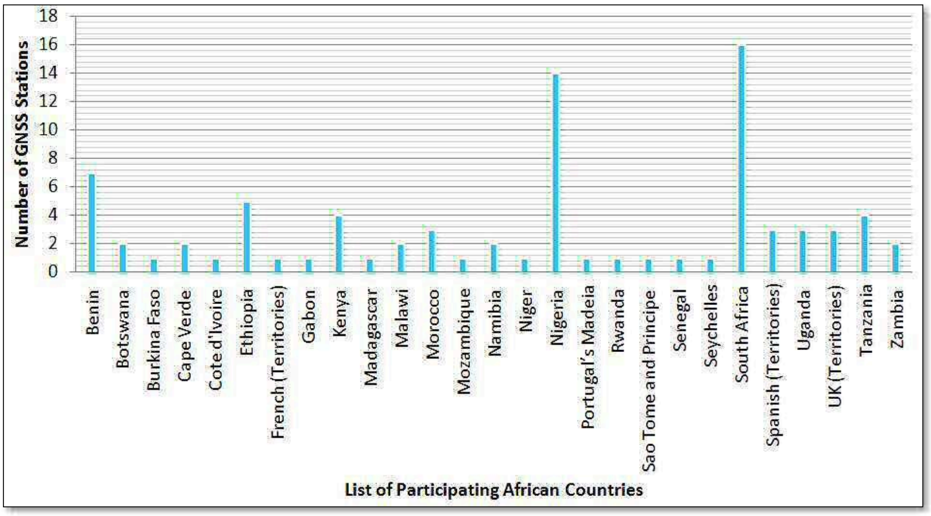

Figure 1.3d.3. Number of GNSS stations located in each African country as of 2015 (Muzondo et al., 2015).

Although progress in increasing the number of GNSS stations in Africa has been slow, it has a positive trend, since the available GNSS stations are ranging now between 70 – 85 compared to 65 – 70 in 2016. Despite this increase, the lack of adequate funding and maintenance has affected some of the GNSS sites and reduced their capability to acquire data and provide these data to the ODC. Africa is thought to have more GNSS sites to complement the freely available GNSS sites, but, as already mentioned, some African countries do not share data, thereby making it difficult when it comes to AFREF solution computations. AFREF is expecting that through upcoming meetings, we may have representatives from those countries that may facilitate data sharing. Figure 1.3d.4 shows the current distribution of freely available GNSS stations that contribute to AFREF.

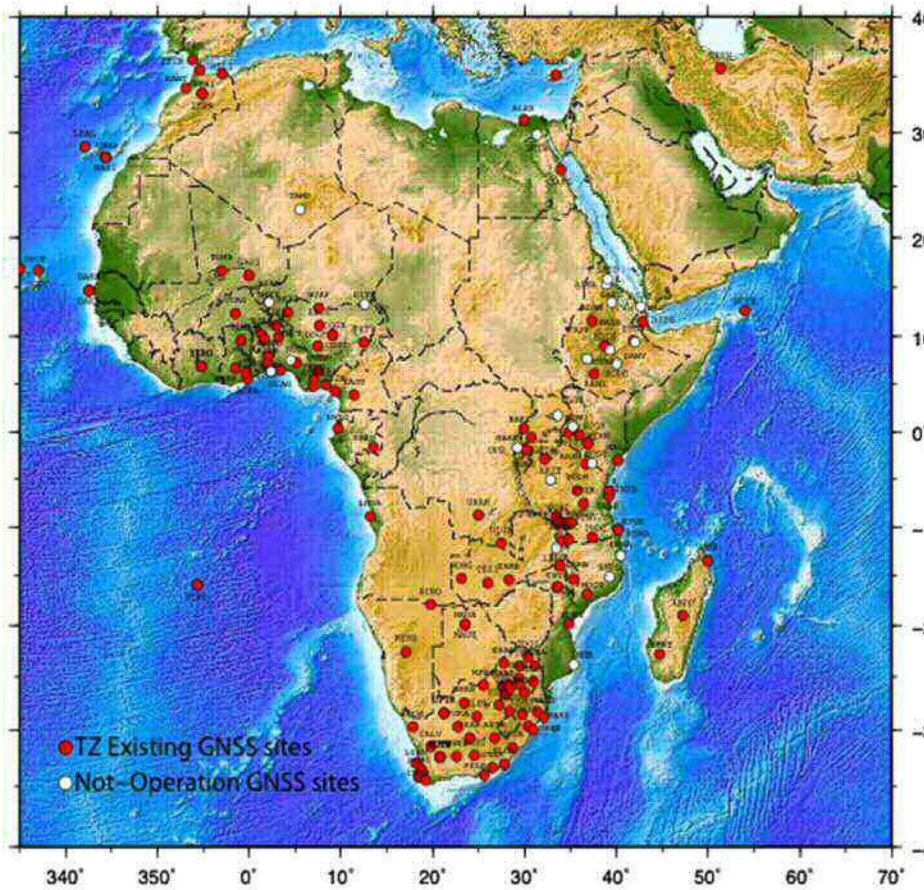

Figure 1.3d.4. GNSS CORS with freely available data operating in Africa as of 2017. Red dots show the active GNSS sites and white dots show the inactive GNSS sites (their data are still being used). The lack of freely available CORS data in the area from Angola through Central Africa, Sudan and Sahara and North African countries remains a concern.

Reference frame solution

Most of the GNSS CORS stations in Africa are used to generate AFREF solution. Some of these data were processed by 5 analysis centers to produce AFREF static solution in 2012 – 2013. The solution was expected to be published, however it is not yet. AFREF plans to produce a combined AFREF solution which will include both a static solution and velocity solution only for GNSS sites that are publicly available. AFREF expects to write to all analysis centers to ask them to produce weekly solutions since 1996 to 2019. The plan is to ask IGN France to do the combination, or do the combination in one of the analysis centers. The analysis centers will be identified after the call for participation, which will be released early 2020.

AFREF meeting and Establishment of Africa Geodetic Commission (AGC)

The United Nations Economic Commission for Africa (UNECA) prepared a workshop of the UN expert group on the GGRF between 20 – 24 Nov. 2017 at Addis Ababa, Ethiopia. The unification and modernization of the current national reference frames aiming at creating a uniform geodetic reference for Africa has been included in ECA's annual work plan. The main aim of the workshop was to enhance regional and national expertise for implementation, operations, processing, and analyses of modern geodetic techniques, and discuss the future development of the AFREF initiative. Particularly the workshop aimed at

- Provide updates on the status and on-going activities of the AFREF Project.
- Review of the project objectives and milestones and come up with tasks for the future of AFREF
- Discuss and formalize the coordination arrangements between the various partners and stakeholders.
- Contribute to develop technical capacity in Africa for the successful implementation of AFREF.

The meeting agenda comprised a review of the available computations, the development of guidelines for the computation of independent solutions and the combined AFREF velocity fields, and the African Geoid Model. The meeting also discussed the Development of an Action Plan for Revamping AFREF Programme's Coordinating Arrangement, Operational Protocol, Resources Mobilization and Global Partnership, as well as the development of the Africa Geodetic Commission (AGC). The AGC responds to the need of African geodesists and geophysicists to have an organ to manage, monitor, and disseminate their views. It has been a culture for African geodesists and geophysicists to meet in other meetings that are organized by other organs. Given the development in technology on geodetic instrumentation and software, as well as the increased geodetic activity in Africa, it is time now to establish the AGC. The commission aims at harnessing the hidden potentials that abound in the continent, and thereby will contribute to the global geodetic community. The meeting agreed on the establishment of the AGC and recommended that, to establish the ACG, a letter of intent should be sent to IAG for comment and advice. Communications were opened with IAG, through the Secretary General. It was observed that, the IAG does not have general Regional Commissions, but instead, continental Sub-commissions for geometric, reference frame, and gravity and geoid where Africa is already represented. It was therefore suggested that, ACG may find its place in GGOS which is considering a new structure allowing to include Affiliates, i. e. regional organisations within GGOS that coordinate geodetic activities. It is expected that GGOS will consider the establishment of the African Geodetic Commission or African Geodetic Association under its umbrella.

Capacity Building

There haven't been any new workshops on GNSS processing since the 2015 workshop at Regional Centre for Mapping of Resources for Development in Nairobi, Kenya. A small workshop is planned during the AfricaArray workshop in South Africa in June 2019.

Challenges

Since its inception, AFREF progress has been slow due to the lack of funding for training and meetings amongst African geodesist, as well as computational facilities among African institutions. The AFREF goal to have a geodetic infrastructure with a spatial distribution of 500 to 1000 kilometers spacing is not yet realized and will need more attention. It is caused by many factors, some of them may be related to lack funding, ignorance or challenges depending on the political situation in individual countries, as well as some countries not willing to share their data. Encouraging is however, the fact that the number of young African geodesists is growing and attention is well nurtured to make AFREF successful.

Acknowledgements

We acknowledge and thank all organizations and individuals for their efforts towards AFREF initiatives, in particular UNECA, IAG, IGA and all governmental initiative. This includes all organizations and governmental agencies that make their data openly available to AFREF ODC particularly the Nigerian GNSS Reference Network (NIGNET), Ethiopian Mapping Agency (EMA), the Regional Centre for Mapping of Resources for Development (RCMRD), the TRIGNET in South Africa, the Tanzania Geodetic Reference Frame (TAREF), and AfricaArray (via UNAVCO archive). Other includes individual projects particularly AMMA project in Benin, SEGMENT project in Tanzania, Malawi and Zambia as well as initiatives from SEGAL Portugal for installation in Mozambique.

In particular, AFREF thank the officer-in-charge of Geoinformation Systems Section at UNECA Mr. Andre Nonguierma for continuous support on AFREF initiative.

Publications

Muzondo I. F, L. Combrinck, C. Munghemezulu, J.O. Botai (2015), Optimal Locations for Additional GNSS Stations within the African Geodetic Reference Frame Network, SAJG.

Mary Wambui Njoroge M W (2015), Is Nubia Plate Rigid? A Geodetic Study of the Relative Motion of Different Cratonic Areas within Africa. MSc Thesis University of South Florida

Sub-Commission 1.3e: Asia-Pacific

Chair: John Dawson (Australia)

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 Framework for Sustainable Development 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 GPS, 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)
Farokh Tavakoli (Iran)
Basara Miyahara (Japan)
Yi Sang Oh (Republic of Korea)
Azhari bin Mohamed (Malaysia)
Enkhtuya Sodnom (Mongolia)
Graeme Blick (New Zealand)

National mapping agencies of the Asia-Pacific region are listed here:
http://www.un-ggim-ap.org/abountunggimap/mc/201602/t20160224_97787.shtml

Activities during the period 2015-2019

APREF
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 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;
- A source of 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.

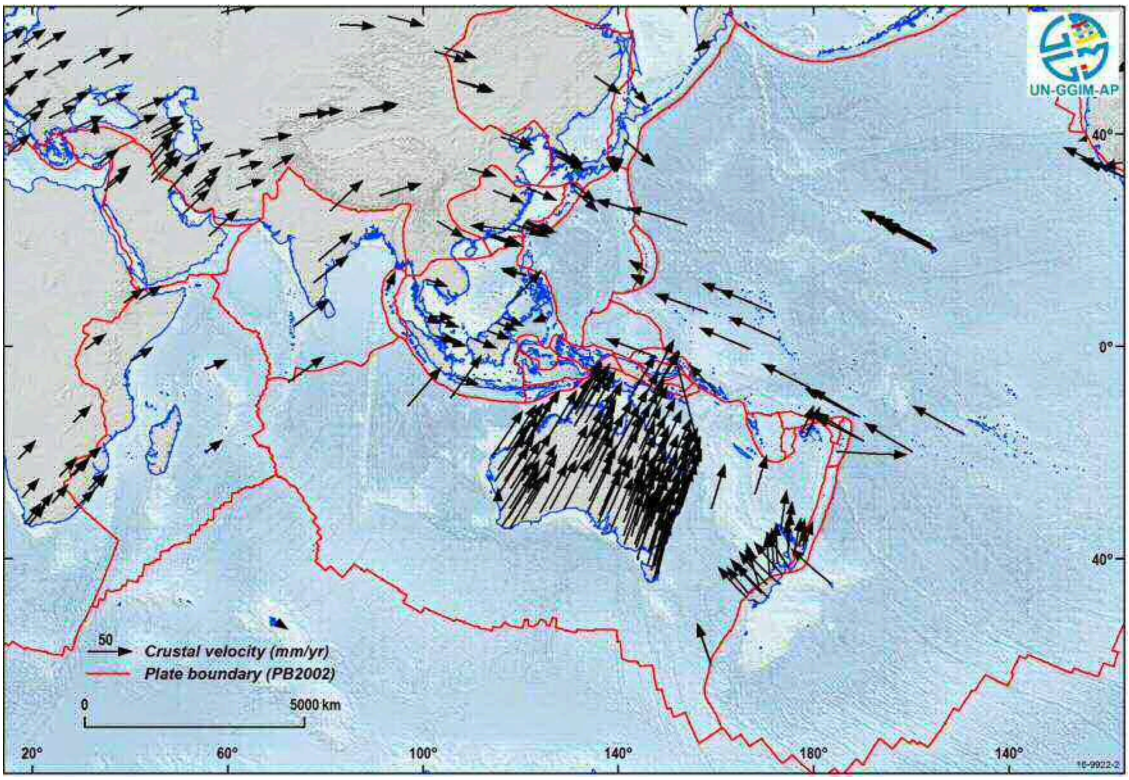

Figure 1.3e.1. APREF GNSS stations

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

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
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	✓		103
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	RTKNetWest			12
Australia	IPS Radio and Space Services			3

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
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			1
Cook Islands	Geospatial Information Authority of Japan			1
Federated States of Micronesia	Geoscience Australia			1
Fiji	Geoscience Australia			1
French Polynesia	Geospatial Information Authority of Japan			1
Guam, USA	National Geodetic Survey (USA)			1
Hong Kong, China	Survey and Mapping Office			14
Indonesia	Bakosurtanal			4
Iran	National Cartographic Centre, Iran			6
Iraq	National Geodetic Survey (USA)			6
Kazakhstan	Kazakhstan Gharysh Sapary			2
Kiribati	Geoscience Australia			1
Kiribati	Geospatial Information Authority of Japan			2
Macau, China	Macao Cartography and Cadastre Bureau			3
Marshall Islands	Geoscience Australia			1
Malaysia	Department of Survey and Mapping Malaysia, JUPEM			7
Micronesia	Geoscience Australia			1
Mongolia	Administration of Land Affairs, Construction, Geodesy and Cartography (ALACGaC)			8
Nauru	Geoscience Australia			1

Country/Locality	Responding Agency	Contribution		
		Analysis	Archive	Stations
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			1
Solomon Islands	Geoscience Australia			1
Tonga	Geoscience Australia			1
Tuvalu	Geoscience Australia			1
Vanuatu	Geoscience Australia			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.ga.gov.au/geodesy-outgoing/gnss/data/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/
- APREF network and time-series plots, see http://192.104.43.25/status/solutions/analysis.html

Asia Pacific Regional Geodetic Project

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 2015, 2016, 2017, and 2018. A campaign is planned for 2019.

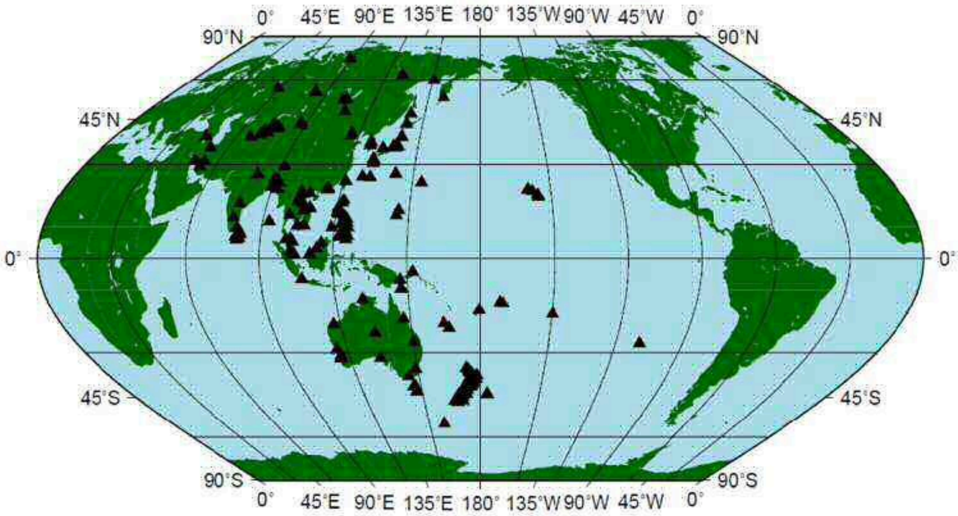

Figure 1.3e.2. Participating stations of the APRGP 2015 GNSS campaign.

Cooperation with other organizations and international integration

Sub-Commission 1.3e made a significant contribution towards the development of the UN-GGIM Global Geodetic Reference Frame Roadmap document prior to the Sixth Session of UN-GGIM at the UN Headquarters, New York.

Outreach and capacity building

Efforts to build capacity in the region have included:

- A UN-GGIM-AP, FIG, IAG, ICG and NZIS Technical Seminar on Reference Frame in Practice: Reference Frames, Datum Unification and Kinematics was held in Christchurch, New Zealand, 1-2 May 2016.

Figure 1.3e.3. UN-GGIM-AP, FIG, IAG, ICG and NZIS Technical Seminar on Reference Frame in Practice, 1-2 May 2016

- Support for the establishment of the Pacific Geospatial and Surveying Council (PGSC) and the associated reference frame development in the South Pacific. The PGSC represents the Pacific Island Countries. More information on the PGSC can be found at their website, http://pgsc.gem.spc.int/.

Figure 1.3e.4. Pacific Geospatial and Surveying Council

- A joint UN-GGIM-AP, IAG, FIG and JUPEM forum on Geospatial and GNSS CORS Infrastructure was undertaken 16 – 17 Oct. 2016, Kuala Lumpur – Malaysia. The forum compromised of 6 sessions, and 22 presentations. The forum hosted by JUPEM (Department of Survey and Mapping, Malaysia) had over 150 delegates from 21 countries. Over the 2 days, the forum attracted over 100 participants each day and these attendees actively engaged and contributed to the program. Presentations are here: http://www.fig.net/organisation/networks/capacity_development/asia_pacific/index.asp

Figure 1.3e.5. UN-GGIM-AP, IAG, FIG and JUPEM forum on Geospatial and GNSS CORS Infrastructure 2016, Malaysia

- A joint technical seminar of UN-GGIM-AP, FIG, IAG, Japan Federation of Surveyors, International Committee for GNSS (IGC), Geospatial Information Authority of Japan (GSI) was held 29-30 July 2017 before the IAG-IASPEI 2017 in Kobe, Japan. The programme focused on geodetic reference frames and crustal deformation. The programme included theory, ITRF, APREF, UN Initiatives, monitoring and modelling of crustal deformation, case studies and software dealing geodetic adjustment. Meeting presentations can be found here: http://www.fig.net/resources/proceedings/2017/2017_07_refframe_japan.asp

Figure 1.3e.6. Technical seminar of UN-GGIM-AP, FIG, IAG, Japan Federation of Surveyors, International Committee for GNSS, Geospatial Information Authority of Japan, 2017 in Japan.

- Jointly with the IAG, the Geospatial Information Authority of Japan (GSI), and the FIG Asia Pacific Capacity Development Network convened a meeting for Asia Pacific member states on "Regional Challenges, Benefits and Opportunities of Exchanging Geodetic Data". This forum was held prior to the UN-GGIM-AP Plenary Meeting on the 16 Oct. 2017 at the Kumamoto City International Centre, Kumamoto Prefecture, Japan. Forty-four delegates from 14 countries attended. The meeting program and presentations can be found here http://www.fig.net/resources/proceedings/2017/2017_10_ARN.asp.

Figure 1.3e.7. Forum on "Regional Challenges, Benefits and Opportunities of Exchanging Geodetic Data", 2017, Japan.

- Support for the Pacific Geospatial and Surveying Council (PGSC) including helping with the development of their strategic plan. The WG1 Chair attended the PGSC meeting in Suva, Fiji, in Nov. 2017 and the PGSC meeting in Nuku'alofa, Tonga, in April 2018. The PGSC is facilitated by the Geoscience, Energy and Maritime Division of Pacific Community (SPC) and their Strategy for 2017 – 2027 was launched at special function officiated by the Prime Minister of the Kingdom of Tonga on 10 April 2018.

- The International Workshop on Legal and Policy Frameworks for Geospatial Information Management – Licensing of Geospatial Information, held in Nuku'alofa, Tonga, from 10 – 13 April 2018. This International Workshop raised awareness among the 42 participants from 12 Member States and one Pacific Island Territory on the evolving and increasingly complex legal and policy environment that will impact the availability, accessibility and application of geospatial and geodetic data.

Figure 1.3e.8. International Workshop on Legal and Policy Frameworks for Geospatial Information Management – Licensing of Geospatial Information, 2018, Tonga.

- Contributed to the FIG Reference Frame in Practice series in Suva, Fiji 18-20 Sept. 2018. The theme and objectives of the seminar was to provide perspectives and case studies on technical matters relating to the "Operational Aspects of GNSS CORS" infrastructure. Presenters also delivered content on the - "what, why and how" to build a sustainable and modernised geodetic reference frame and datum; challenges faced in the Pacific in relation to geospatial information management and data sharing; legal, policy, and codes of practice (including standards); and the issues pertaining to developing the capacity of surveyors in the discipline of geodetic surveying. There were 23 presentations and 2 exploratory "question and answer" workshops over the 3 day event. The quality of all presentations was of a high standard, which often stimulated involvement and interaction amongst the seminar delegates. The registrations and attendance to the event totalled just below 100, comprising of surveyors, engineers, town planners, students and geospatial experts from 14 different countries in the region. The technical program and presentations can be found here http://www.fig.net/resources/proceedings/2018/2018_09_rfip.asp.

Figure 1.3e.9. FIG Reference Frame in Practice series, 2018, Fiji.

Publications

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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 large 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 in geodetic GNSS activities in Antarctica.

Martin Horwath (Germany, Chair of SC 1.3f)
Alessandro Capra (Italy, Co-chair of SCAR EG GIANT)
Mirko Scheinert (Germany, Co-Chair of SCAR EG GIANT)
Manuel Berrocoso (Spain)
Graeme Blick (New Zealand)
Jan Cisak (Poland)
Beata Csatho, Brendan Hodge, Larry Hothem, Erik Ivins, Terry Wilson (U.S.A.)
John Dawson, Matt King (Australia)
Giorgianna De Franceschi, Angelo Galeandro, Monia Negusini (Italy)
Koishiro Doi, Kazuo Shibuya (Japan)
Rene Forsberg (Denmark)
Thomas James (Canada)
Aspurah Kamburov (Bulgaria)
Christoph Knöfel (Germany)
Jeronimo Lopez-Martinez (Spain)
Jaakko Mäkinen, M. Poutanen (Finland)
Kenichi Matsuoka (Norway)
Alexey Matveev (Russia)
Gennadi Milinevsky (Ukraine)
Elizabeth Petrie (United Kingdom)
Goncalo Prates (Portugal)
Yves Rogister (France)
Lars Sjoberg (Sweden)
Norbertino Suarez (Uruguay)
Andres Zakrajsek (Argentina)

Activities during the period 2015-2019

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).

Reprocessing of GNSS data in Antarctica (GIANT-REGAIN)

At the SCAR Meeting 2016 in Kuala Lumpur, an initiative was launched by M. Scheinert (Germany) and M. 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). Collection of data and metadata was just finalized in early 2019. 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 will be reported at the 27th IUGG General Assembly in Montreal, 2019.

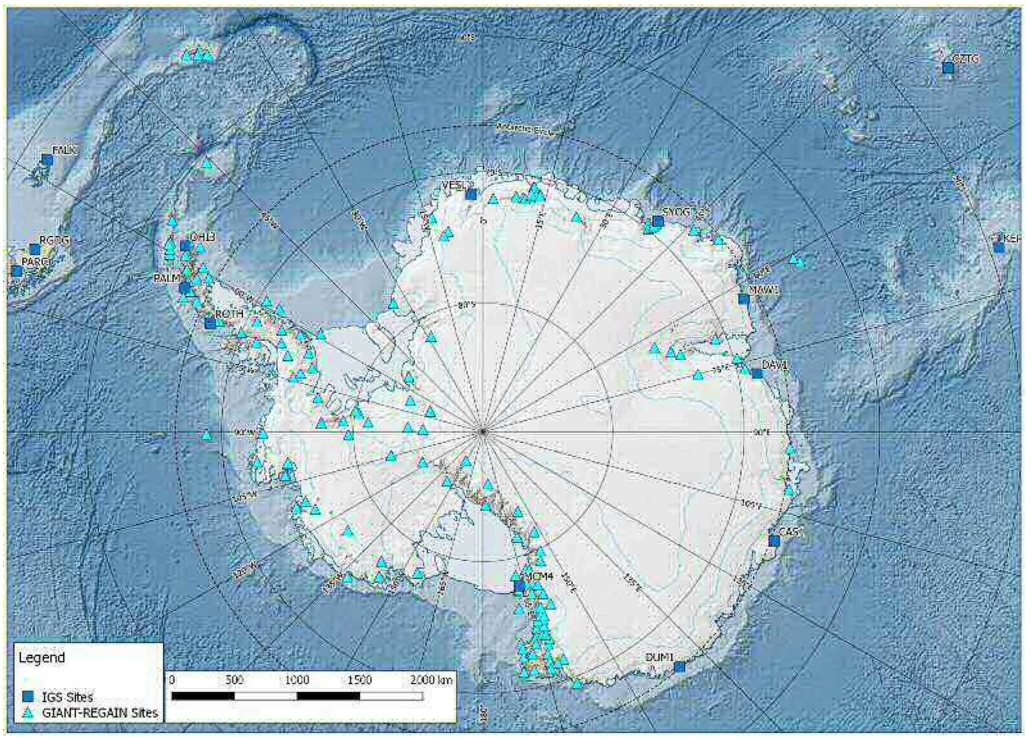

Figure 1.3f.1. Overview of geodetic GNSS sites on bedrock in Antarctica utilized for the GIANT-REGAIN project, © TU Dresden / SCAR EG GIANT. Map source: Quantarctica 3, QGIS 2.18.

Cooperation with other organizations and international integration

Endorsement of UN Resolution:

The group supported the endorsement of the UN resolution on *A Global Geodetic Reference Frame for Sustainable Development* that was finally approved on 18 February 2015 (see also unggrf.org).

Outreach and capacity building

2nd SCAR Summer School on Polar Geodesy:

Mirko Scheinert (co-chair of SCAR EG GIANT) and Martin Horwath (chair of SC 1.3f) organized a 2nd SCAR Summer School on Polar Geodesy that was held at AARI Ladoga Base, Ladozhskoe Ozero, Russia, 10–19 May 2018. This summer school was locally organized by colleagues from the Arctic-Antarctic Research Institute (AARI), St. Petersburg (especially A. Klepikov, Head of the Russian Antarctic Expedition, and A. Ekaykin, AARI Glaciology). It was supported by IAG, SCAR, Germany Society of Polar Research (DGP), AARI, Aerogeodesya (St. Petersburg) and TU Dresden. 12 young scientists (Master and PhD students) from 7 different countries took part in this summer school. A focus was given to the application of geodetic GNSS techniques in polar research, both in lectures and practical exercises.

Group meetings:

Related to SC 1.3f business meetings of SCAR EG GIANT were organized at the SCAR Meetings in Kuala Lumpur (2016) and Davos (2018).

Participation in related meetings, conferences and workshops:

Group members took part in relevant meetings, conferences and workshops. Besides the annual EGU General Assemblies and AGU Fall Meetings, the following meetings are most relevant.
- International Symposium on Antarctic Earth Sciences, Goa (India), 2015
- XXXIV SCAR Meeting and Open Science Conference, Kuala Lumpur (Malaysia), 2016
- IAG – IASPEI Joint Scientific Assembly, Kobe (Japan), 2017 – Organisation of IAG-IASPEI Joint Symposium "Monitoring of the Cryosphere" (Convenors: M. Kanao, J. P. Winberry, E. R. Ivins, M. Scheinert)
- Workshop "Glacial Isostatic Adjustment and Elastic Deformation", Reykjavik (Iceland), 2017
- XXXV SCAR Meeting and SCAR/IASC Open Science Conference, Davos (Switzerland), 2018

Publications

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King, M., P. Whitehouse, W. van der Wal (2016): Incomplete separability of Antarctic plate rotation from glacial isostatic adjustment deformation within geodetic observations, *Geophys. J. Int.*, 204, 324-330, doi: 10.1093/gji/ggv461

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Zanutta, A., M. Negusini, L. Vittuari, P. Cianfarra, F. Salvini, F. Mancini, P. Sterzai, M. Dubbini, A. Galeandro, A. Capra (2017): Monitoring geodynamic activity in the Victoria Land, East Antarctica: Evidence from GNSS measurements, J. Geodynamics, 110: 31–42, doi: 10.1016/j.jog.2017.07.008

WG 1.3.1: Time-Dependent Transformations Between Reference Frames

Chair: Richard Stanaway (Australia)

Introduction and structure

The main aim of the WG has been to focus research in deformation modelling into the rapidly emerging field of regional and local reference frames used in applied geodesy, particularly positioning and GIS. Deformation models and time-dependent transformation schema provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for land surveying and mapping.

A rapidly emerging issue that the WG research has addressed is the misalignment of precise GNSS positions and derived spatial data over time. GNSS positions are intrinsically defined in a kinematic reference frame (RF) such as ITRF or closely aligned RF. Spatial data on the other hand, is intrinsically static in nature being essentially a snapshot of a RF at the epoch of data acquisition or capture. The volume of spatial data being created is increasing almost exponentially as laser scanning technologies and high-resolution imagery acquired by UAV/drone become mainstream. These massive datasets are fixed epoch representations of a positioning RF used to acquire the data. Consequently, the data are effectively "stale" in the context of later data acquired using a kinematic RF used in GNSS positioning for example.

Precise time-dependent transformation models are required to enable spatial data acquired at different epochs to be aligned at a common epoch for visualization and analysis. Furthermore, GNSS positions requires a time-dependent transformation to be applied in order to be used in the context of spatial data defined in a static or fixed epoch RF, or vice versa. Addressing these practical issues is an urgent requirement as precise GNSS positioning becomes more accessible to a wider spectrum of users of RF, many of whom have limited or no geodetic expertise.

The WG has developed a time-dependent transformation model concept that can be used for kinematic and semi-kinematic RF transformations, even in tectonically complex plate boundary regions subject to frequent earthquakes. The approach also supports realization of regional and local reference frames from ITRF to support GIS and positioning technologies through integration of positioning with spatial data. The concept can form a basis for implementation of complex time-dependent RF transformations by international registries of geodetic parameters such as those hosted by ISO/TC 211 and EPSG (European Petroleum Survey Group).

WG 1.3.1 has worked closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members have comprised a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

Members

Richard Stanaway (Chair, Australia)
Hasanuddin Abidin (Indonesia)
Sonia Alves, (Brazil)
Graeme Blick, Chris Crook, Paul Denys, Nic Donnelly, Christopher Pearson (New Zealand)
Miltiadis Chatzinikos (Greece)
Rui Fernandes (Portugal)
Yasushi Harada, Yoshiyuki Tanaka (Japan)
Kevin Kelly, Rob McCaffrey (USA)

Juliette Legrand (Belgium)
Daphné Lercier (France)
Martin Lidberg (Sweden)
Craig Roberts (Australia)
Laura Sánchez (Germany)
Norman Teferle (G.-D. Luxembourg)

Activities and publications during the period 2015-2019

There has been a major impetus for national and regional RF modernization since 2015 with many countries implementing or considering time-dependent reference frames. The impetus has been driven by increasing adoption of precise GNSS positioning, especially at the mass market level, precision GIS and the United Nations 2015 resolution in support of a Global Geodetic Reference Frame (GGRF).

One of the main aims of WG 1.3.1 has been to develop a framework for time-dependent reference frame transformations, especially in plate boundary regions with complex tectonic settings. At present, the 14-parameter model is widely used (e.g. for transformations between different realizations of ITRF, ETRF, GDA and NAD83). Plate motion models (PMM) can also be used to describe the kinematics of the stable portion (rigid) of a tectonic plate or microplate. The rotation rate parameters of the 14-parameter transformation model can be adapted from a PMM (rotation rates of the Cartesian axes). The 14-parameter and PMM approach, however, does not adequately accommodate intraplate, plate boundary, co-seismic and post-seismic deformation. Models of these forms of deformation are essential for higher precision transformations and there is a rapidly growing requirement to develop international standards for deformation model formats and application (e.g. IOGP/EPSG and ISO/TC 211). Presently, different jurisdictions in tectonically active regions have different approaches to handle these types of deformation. The lack of a standardized approach for time-dependent transformations is leading to a potentially unmanageable scenario where every jurisdiction adopts a different model format or schema. This is an undesirable situation for developers of positioning and GIS software and it is an impediment for the GGRF to be applied in practice. Many developing countries have limited budgets and technical capacity to modernize their geodetic datum to a GGRF template and require standardized approaches and schema.

WG 1.3.1 has reviewed the different approaches currently in use globally as basis for development of a conceptual model for time-dependent transformations in deforming zones.

The current consensus amongst geodetic agencies participating in this study is the adoption of a semi-kinematic RF or dual frame (kinematic + static or kinematic + semi-kinematic) until full time-dependence transformation capabilities are developed, tested and built into GIS, surveying software and spatial data management tools. The status quo of a static RF is increasingly incompatible with the current precisions achievable with GNSS-PPP for example.

North America

An updated crustal motion model has been developed (Snay et al., 2016) to support applied geodesy in the USA and Canada with the development of TRANS4D software, which will supersede the HTDP software currently being used for time-dependent transformations. The new model now includes uncertainties of estimated velocities and vertical velocities. The USA is in the process of modernizing its RF from the current NAD83 datum with the realization of four stable plate RF for the major regions and territories of the USA. The main RF will be the

North American Terrestrial Reference Frame (NATRF2022) which will be time-dependent with site velocities defined in a stable North American plate RF.

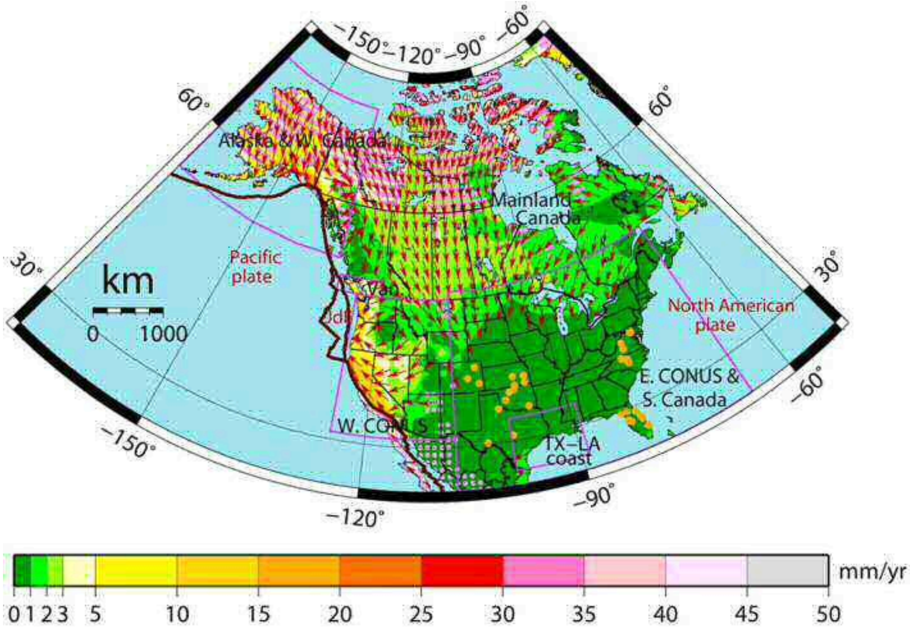

Figure 1.3.1.1. Velocities with respect to the stable North American plate (NA12 reference frame). Contour colors indicate velocity magnitude, and dark red arrows indicate velocity direction when the velocity magnitude exceeds 1 mm/yr. Orange dots represent the 30 GPS sites whose velocities were employed to define the NA12 reference frame (from Snay et al., 2016).

South America

The present SIRGAS Velocity Model (VEMOS2017; Sánchez and Drewes, 2017) was inferred from GNSS (GPS+GLONASS) measurements gained after recent earthquakes in Chile and Mexico (Sánchez et al., 2013; 2017). It is based on a multi-year velocity solution for a network of 515 continuously operating GNSS stations between 2015 and 2017. VEMOS2015 was computed using the least square collocation approach with empirically determined covariance functions. It covers the region from 55°S, 120°W to 32°N, 35°W with a spatial resolution of 1° x 1°. The average prediction uncertainty is ±1.0 mm/a in the north-south direction and ±1.7 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone (Chile) while the minimum values of about ±0.1 mm/a occur in the stable eastern part of the South American plate.

The main purpose of VEMOS2017 is to allow the translation of station positions trough time. However, this model is only valid for the time period 2015-2017. For the translation of station positions before the 2010 earthquakes, the model VEMOS2009 (Drewes and Heidbach, 2012) should be used. The earlier VEMOS2015 model includes GNSS observations over five years, some regions were affected by further earthquakes and their effects are not included in VEMOS2015 yet. Consequently, it is necessary to continue updating this model regularly. In forthcoming activities, we shall improve the distribution of the continuously operating GNSS stations, especially along the boundaries between the different tectonic features. In the analysis of the station position time series, we want to consider possible surface loading and local effects to improve the reliability of the estimated velocities. Finally, we plan also to perform detailed studies about the temporal-spatial evolution of the deformation field.

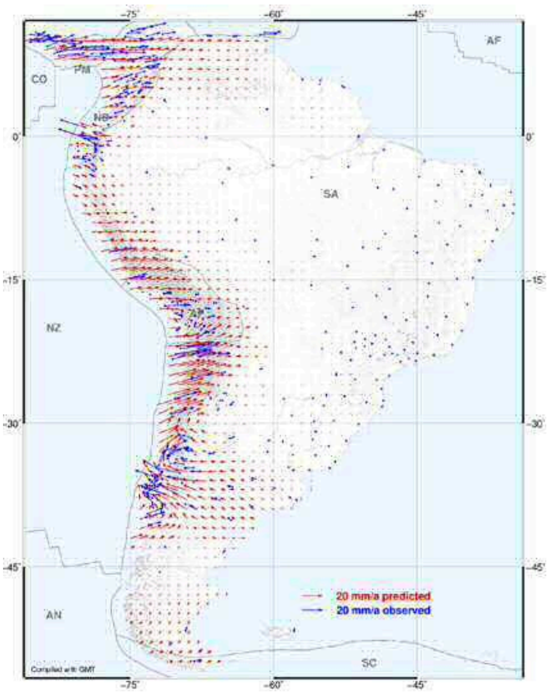

Figure 1.3.1.2. VEMOS2017 velocities in a stable South American plate reference frame (Sánchez et al., 2019), taken from www.sirgas.org.

Europe

A European deformation model grid is being developed within the EUREF WG on "Deformation models". The modelling is done using the least squares collocation (LSC) approach and are based on recent GNSS station velocity results from the EUREF WGs on "EPN Densification" and "European Dense Velocities" with about 2000 and 4500 station velocities respectively (Rebekka Steffen et al., 2019). The GNSS time series are up to about 20 years, and a minimum of 3 years are used for velocity estimation.

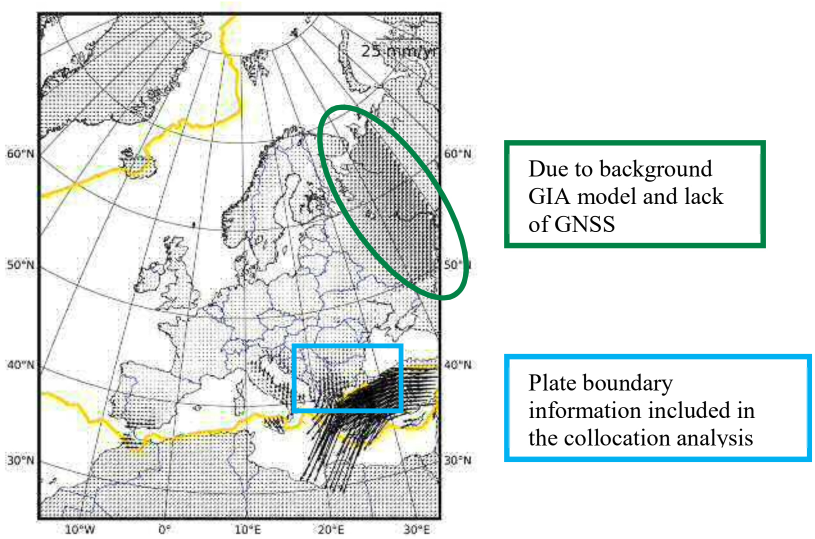

Fig. 1.3.1.3. Preliminary horizontal velocity model computed using the least square collocation (LSC) approach with empirically determined covariance functions (Steffen et al 2019). In the Fennoscandia area a background GIA-model have been considered in a "remove-compute-restore" methodology. Plate boundary information are considered by reducing the correlation between locations on different sides of a plate boundary zone.
https://www.lantmateriet.se/contentassets/ff12c6e07463427691d8bd432fc08ef6/steffen-etal-egu2019.pdf

The model will benefit from work already completed on regional dense velocity fields (former IAG WG 1.3.1, 2007-2015 - Juliette Legrand and Carine Bruyninx) and plate boundary deformation models developed by geodetic agencies and universities in Greece, Turkey and Italy. Miltiadis Chatzinikos, Stylianos Bitharis, Aristeidis Fotiou, Christopher Kotsakis and Christos Pikridas have completed extensive studies to support velocity modelling and semi-kinematic RF development in Greece. The Fennoscandian land uplift model NKG2016LU has been developed by the NKG (Nordic Geodetic Commission) to model the (Glacial Isostatic Adjustment) GIA kinematics impacting the Nordic nations of Europe. Olav Vestøl, Jonas Ågren, Holger Steffen, Halfdan Kierulf, Martin Lidberg, Pasi Häkli have been lead researchers in this effort. The use of land uplift models enables precise transformations between national realizations of ETRS89 and different realizations of ITRF at the few mm level. An important aspect to note is the smaller but significant horizontal velocities associated with GIA. A time-dependent RF is being developed for Iceland, which straddles the active plate boundary between the North American and Eurasian tectonic plates. The complexity in Iceland is exacerbated by volcanic and GIA deformation.

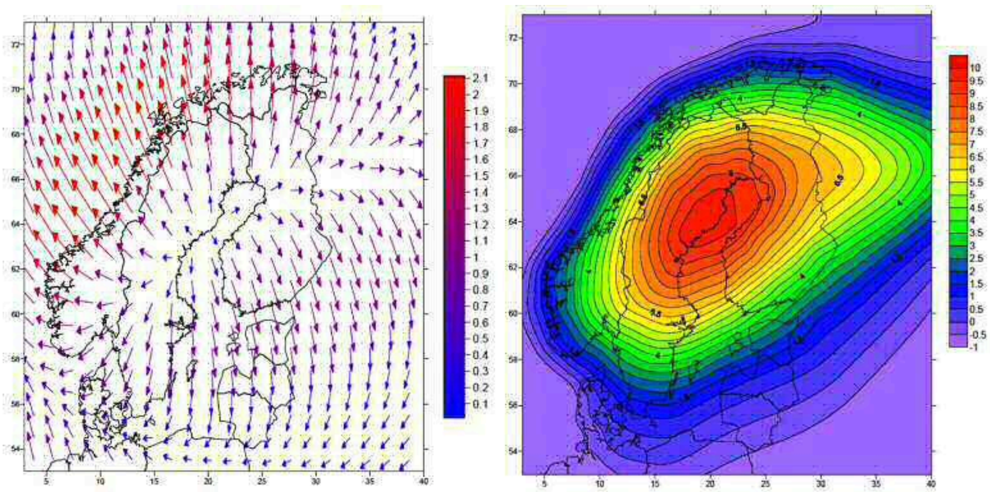

Figure 1.3.1.4. The NKG_RF03vel velocity model. Reference for the horizontal velocity field (left) is "stable Eurasia" as defined by the ITRF2000 Euler pole for Eurasia. The vertical uplift rates are "absolute" values relative the earth centre of mass. Units: mm/year (from Lidberg et al., 2017).

Indonesia

The Geospatial Agency of Indonesia has launched a new geocentric datum named the Indonesian Geospatial Reference System 2013 (IGRS 2013) (Susilo et al., 2016). This new datum is a semi-dynamic datum in nature realized by ITRF2008, with a reference epoch of 1 January 2012 (2012.0). A deformation (velocity) model is used to transform coordinates from an observation epoch to or from this reference epoch. For its initial implementation, the model considers an initial deformation model setting based on 4 tectonic plates, 7 tectonic blocks, and 126 earthquakes. At present, the velocity model of IGRS 2013 is mainly realized using repeat GPS observations on the passive geodetic control network and CORS, covering the period from 1993 to 2014. These GPS data are managed by the Geospatial Agency of Indonesia (BIG), Land Agency of Indonesia (BPN), and the Sumatran GPS Array (SUGAR). The GPS data has been reprocessed and analyzed using the GAMIT/GLOBK 10.5 processing software suite. The derived velocities field shows the spatial variation of velocity direction and magnitude, which represents various plates or blocks tectonic motion in Indonesia region. This analysis has been used for the development of the IGRS 2013 deformation model.

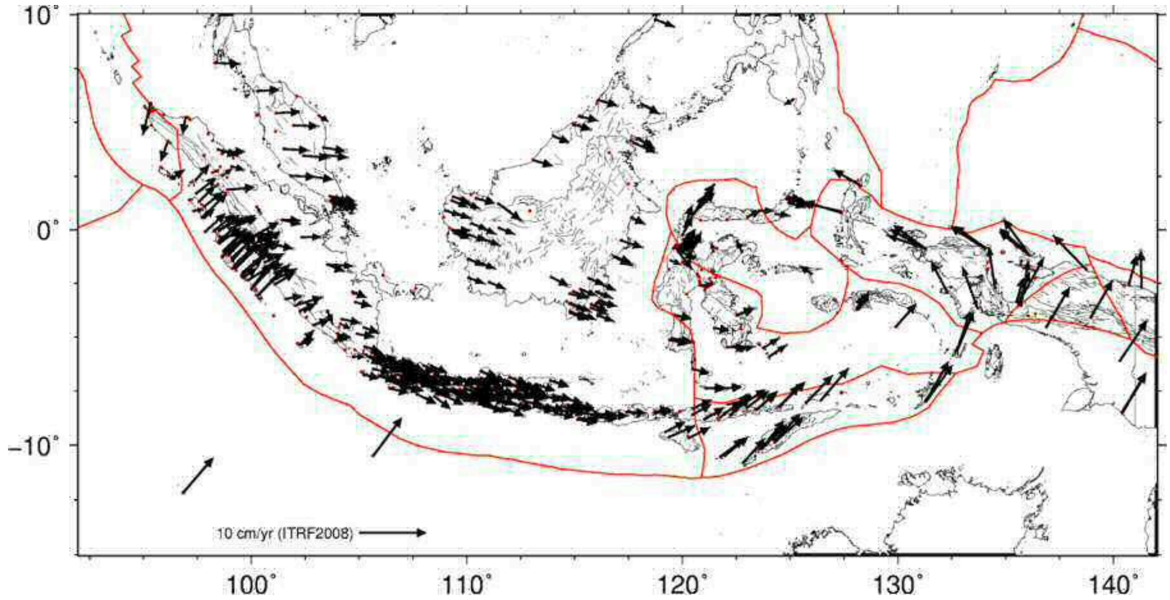

Figure 1.3.1.5. Velocity model of IGRS2013 with respect to ITRF2008 (Susilo et al., 2016). Red line is blocks boundaries from MORVEL 56 (Argus et al. 2011). Faults lineation downloaded from the East and Southeast Asia (CCOP) 1:2000000 geological map.

New Zealand

The New Zealand Geodetic Datum 2000 (NZGD2000) Deformation Model has been updated based on improved site velocities estimated from GPS observations made on both the passive geodetic network and active CORS network between 1996 and 2011 (Crook et al., 2016). Earthquake patch models of coseismic displacement have also been incorporated for a number of significant earthquakes that have occurred in New Zealand (Fig. 1.3.1.6). These displacement patches are distributed for each significant earthquake with different resolutions.

The NZGD2000 deformation model velocity field is published on a rectilinear 0.1° grid of ellipsoidal coordinates in comma separated variable (csv) format. Coseismic displacement grids (patches) have been defined with different resolutions and extents. The current model can be downloaded at: http://apps.linz.govt.nz/ftp/geodetic/nzgd2000_deformation_20180701_full.zip

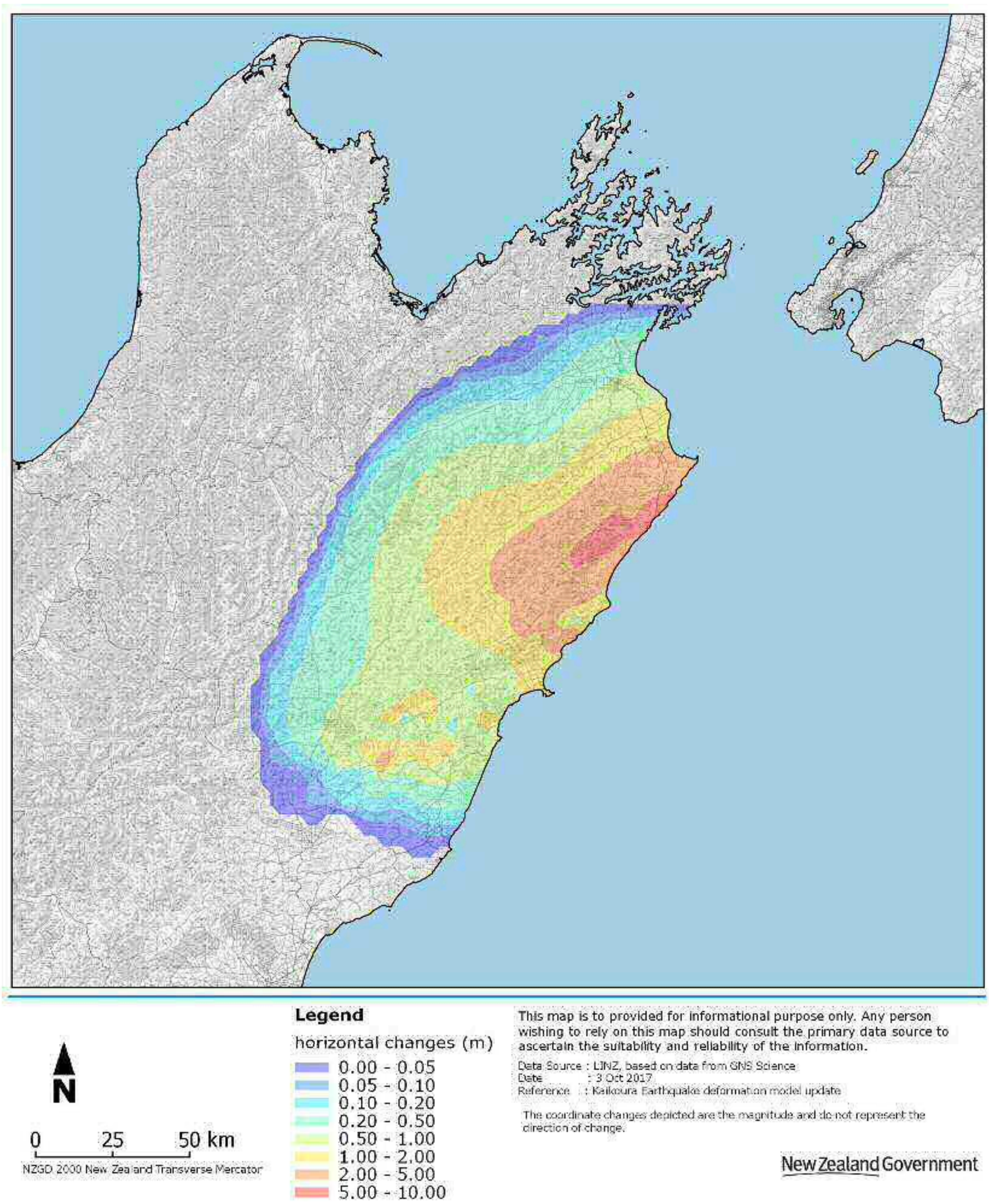

Figure 1.3.1.6: Reverse-patch for horizontal coordinate changes to NZGD2000 resulting from Nov. 2016 earthquake sequence, Kaikoura, New Zealand, LINZ, 2019.

Japan

The current Japanese Geodetic Datum 2000 (JGD2000) defined at epoch 1997.0 has been updated for the Eastern part of Japan to epoch 2011.39 to account for the very significant coseismic and postseismic deformation arising from the 2011 Tohoku earthquake sequence (Fig. 1.3.1.6). Coseismic and postsesimic corrections are updated and applied annually to the JGD2000 coordinates at the reference epoch for each part of the country. From 2014, JGD2000 has been re-realized by the 1318 station GEONET CORS network. The ongoing issues with large vertical coseismic and postseismic displacements arising from large earthquakes together with the large cost of geometrical leveling are motivating the implementation of a geoid based vertical frame in 2024.

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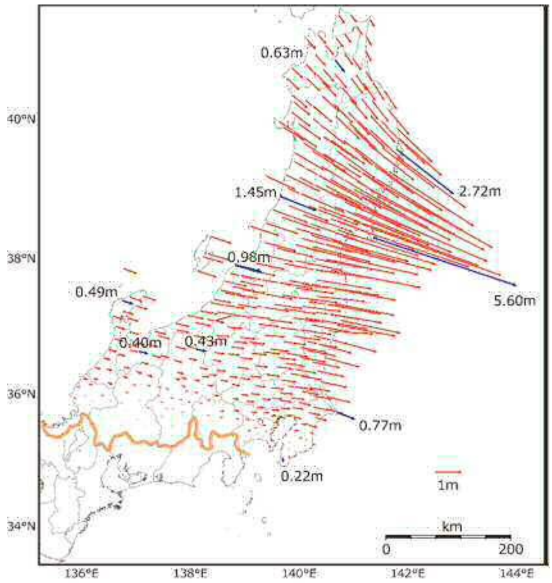

Figure 1.3.1.7. JGD2000 horizontal coordinate changes arising from the 2011 Tohoku earthquake sequence

Nepal

Following the April 25, 2015 Mw7.8 Gorkha earthquake, a new semi-dynamic datum is being developed for Nepal incorporating a secular site velocity model based on ITRF2014 (Fig. 1.3.1.7) and co-seismic deformation model to enable pre earthquake spatial data to be transformed and visualized in ITRF2014 (Pearson et al., 2016).

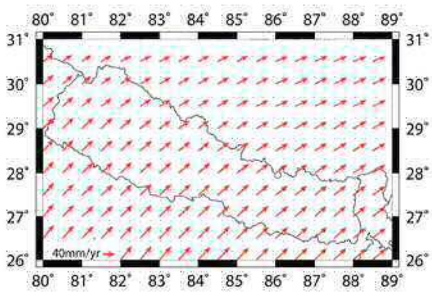

Figure 1.3.1.8. Velocity grid for Nepal and surrounding parts of India and China.

Australia

Australia implemented a modernized geodetic datum, GDA2020 in late 2018 to supersede GDA94. GDA2020 is a realization of ITRF2014 projected to epoch 2020.0 using a stable plate motion model for Australia, implemented as rotation rates in a 14-parameter transformation with zeros for other parameters. A fully kinematic RF, the Australian Terrestrial Reference Frame (ATRF) is in development; however it is anticipated that GDA2020 and ATRF will operate as a dual-frame system for some time into the future until robust time-dependent transformations within GIS and management of spatial data are developed, tested and adopted.

Other countries

Malaysia, Taiwan, The Philippines, Turkey, Israel, Vietnam, Papua New Guinea and Egypt are in the process of development of time-dependent reference frames with extensive research undertaken by researchers in these respective countries.

Complex time-dependent transformation schema

A complex time-dependent transformation schema has been developed by Richard Stanaway, UNSW, Australia. The schema includes sub-model formats for interseismic (secular) velocities, coseismic displacement, postseismic parameter grids and localized deformation. The schema includes estimation of uncertainty arising from interpolation of the different models used. The work also includes an appraisal of the effect of deformation on RF considering different requirements for end users of RF. The schema will be published later in 2019.

Outreach and capacity building

WG meetings and workshops have been held in conjunction with the technical seminars on Reference Frames in Practice (RFIP) series jointly run by the FIG, IAG, International Committee on GNSS (ICG) and the United Nations Initiative for Global Geospatial Information Management for Asia-Pacific (UN-GGIM-AP). The RFIP seminars have been very successful with great synergy between the different participating organizations, particularly Commission 5 (Positioning and Measurement) of FIG. The meetings and technical seminars have been run annually as follows:

- Christchurch, New Zealand, 1-2 May 2016.
- Kobe, Japan, 29-30 July, 2017
- Istanbul, Turkey, 4-5 May, 2018
- Hanoi, Vietnam, 20-21 April, 2019

Twelve members of WG 1.3.1 have attended and made presentations at these seminars.

Figure 1.3.1.9. RFIP, Christchurch, New Zealand, 1-2 May 2016.

Figure 1.3.1.10. RFIP, Kobe, Japan, 29-30 July 2017.

Figure 1.3.1.11. RFIP, Istanbul, Turkey, 4-5 May 2018

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

Chair: Zinovy Malkin (Russia)

Structure

Working Group 1.4.1: Consistent realization of ITRF, ICRF, and EOP

Working Group 1.4.2: Impact of geophysical and astronomical modeling on reference frames and their consistency

Working Group 1.4.3: Improving VLBI-based ICRF and link to the Gaia-based CRF (GCRF)

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 in order 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.

These issues are subject of research activity of the IAG SC 1.4.

All the three IAG SC 1.4 working groups are working in close cooperation with each other, in particular, 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:

IAG SC 1.4 Meeting on 25 April 2017 in Vienna during the EGU 2017 week

IAG SC 1.4 Meeting on 11 April 2019 in Vienna during the EGU 2019 week

At both meetings, IAG SC 1.4 Working Groups chairs prepared presentations on the current activities of their WGs. Several accompanying presentation of WG members were also given. Details of these studies and obtained results are described below in WG reports.

Other related meetings:

Several other meetings, except IUGG, IAG, IAU, AGU, and EGU General Assemblies, with active participation of the SC 1.4 members were held in 2015–2019 where the scientific problems related to the IAG SC 1.4 topics were discussed:

- 9th IVS General Meeting, March 2016, Johannesburg, South Africa;
- GAGER Meeting, May 2016, Wuhan, China;
- ROTANUT Meeting, September 2016, Brussels, Belgium;
- ICRF-3 IAU Working Group Meeting, October 2016, Haystack, USA;
- IAU Symposium 330, Nice, France
- 23rd EVGA Working Meeting, May 2017, Gothenburg, Sweden;
- Journees 2017, September 2017, Alicante, Spain;
- 10th IVS General Meeting, June 2018, Longyearbyen, Spitsbergen, Norway;
- 24rd EVGA Working Meeting, March 2019, Las Palmas (Gran Canaria), Spain.

WG 1.4.1: Consistent Realization of ITRF, ICRF, and EOP

Chair: *Manuela Seitz (Germany)*

Members
- *Claudio Abbondanza (US)*
- *Sabine Bachmann (Germany)*
- *Richard Gross (US)*
- *Robert Heinkelmann (Germany)*
- *Chris Jacobs (US)*
- *Hana Krasna (Austria)*
- *Sebastien Lambert (France)*
- *Karine Le Bail (US)*
- *Dan MacMillan (US)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Benedikt Soja (US)*

Activities and publications during the period 2015-2019

General aspects

Many applications in the geosciences, astrometry and navigation require consistency of the terrestrial and the celestial reference frame and the Earth Orientation Parameters. But ITRS, ICRS and EOP are not realized fully consistently today. In addition, the realizations of the reference systems do not take full advantage of the high precision of the space geodetic techniques due to (i) modeling deficiencies in single technique analysis and (ii) inhomogeneity w.r.t. modeling and parameterization between the techniques.
The WG 1.4.1 aims to develop and investigate the methods to generate consistent TRF-CRF-EOP solutions based on optimal modeling, analysis and combination strategies and to assess the quality of the results. The focal points of the WG are:

(1) Investigation of the impact of different analysis options and combination strategies on the consistency of TRF, CRF, and EOP derived from a joint analysis of space geodesy observations.
(2) Investigation of the consistency of the current ICRF and ITRF versions and IERS EOP C04 series.
(3) Investigation of the consistency of VLBI-only (IVS) CRF, TRF, and EOP series with the ITRF, ICRF, and C04 EOP series.
(4) Study of effects of geodetic datum realization on VLBI-derived CRF.
(5) Study of optimal use of the space-collocated techniques for the improvement of the consistency of TRF, CRF, and EOP.

Consistency of current ITRF solutions and EOP

A general scheme of the computation of the ICRS and ITRS realization is shown in Fig. 1.4.1. In 2015/2016 three new realizations of the ITRS are computed and released by the ITRS Combination Centers DGFI-TUM, IGN and JPL. The IGN solution, the ITRF2014, is computed from a combination of the VLBI, SLR, GNSS and DORIS solutions. In the ITRF2014 solution non-linear station motions are approximated by estimating annual and semi-annual signals. The realization performed by DGFI-TUM, the DTRF2014, is based on the combination of normal equations of the space-geodetic techniques.

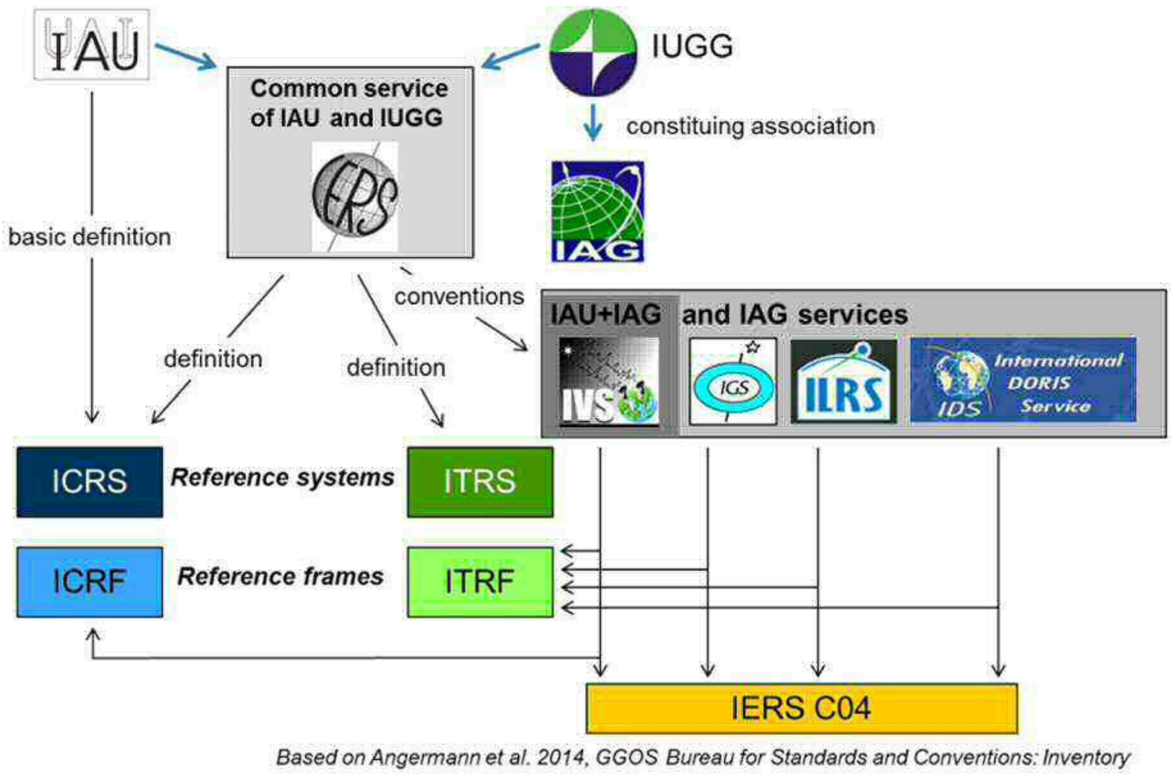

Fig.1.4.1. Infrastructure of ITRS and ICRS realization. Today ITRS and ICRS are realized independently by different Combination/Product Centres and based on different observation data.

In DTRF2014 computation non-linear station motions caused by hydrologic and atmospheric loading are reduced. The loading signals are considered by model values based on the hydrology model GLDAS and the atmospheric model NCEP, respectively. The time series of model values are derived and provided by Tonie van Dam. JPL computes an ITRS realization, the JTRF2014, by applying a Kalman filter approach. The resulting station position time series approximate the non-linear station motions very well.

In order to investigate the consistency of the current ITRS realizations, the GFZ group computes EOP series and global CRF solutions by fixing the station coordinates to the previous ITRS realization ITRF2008 and the new realizations ITRF2014, DTRF2014 and JTRF2014. The individual EOP series obtained from a session-wise analysis are compared using the series based on the ITRF2014 coordinates as a reference. The EOP series obtained by fixing the station coordinates to DTRF2014 show the smallest differences. The difference series of the terrestrial pole coordinate series show small drifts in the very early years of VLBI observation and a slightly increased scatter in 2013/2014. The WRMS values are 0.004 mas and 0.002 mas for x- and y-pole, respectively. For UT1 and nutation no systematic occur. The WRMS values are 0.10 µs for UT1 and 0.09 and 0.11 mas for X- and Y-pole, respectively. The EOP series computed by fixing ITRF2008 coordinates show a larger scatter compared to the ITRF2014 based series than the DTRF2014 based series. This can be related to the fact that ITRF20014 and DTRF2014 are computed from the same input data. The scatter of the ITRF2008 based series increases strongly after 2008 when coordinates are extrapolated. For the JTRF2014 based EOP series a larger scatter than for DTRF2014 series was obtained which might be a result of the different approximation of station motions. But also, systematic effects are identified which can be related to the handling of seismic events.

In a second step global CRF solutions are computed by again fixing the station positions and velocities to the three reference frames and by fixing also the EOP. The CRF solutions obtained from fixing ITRF2014 and DTRF2014, respectively, agree very well. The WRMS values are 2.06 µas and 9.67 µas for RA*cos(DE) and DE, respectively. Only small systematics in declination and declination rate are found. For JTRF2014 the differences are larger, in particular for sources in the high southern declinations. For ITRF2008 also larger differences are obtained which can be explained by the 6 more years of data used for the 2014 realizations.

Realization of ITRS and ICRS from VLBI data

VLBI is the only space-geodetic technique which observes extra galactic objects and thus allows for a consistent realization of TRF, CRF and the EOP. Therefore, it is very important to investigate the impact of different VLBI analysis options on the resulting TRF and CRF. In the period 2015-2019, three analysis options were investigated: the reduction of non-linear station motions, an improved modelling of tropospheric a priori parameters and the effect of combining different VLBI solutions on the stability of source positions.

In the ITRS realizations ITRF2014, DTRF2014 and JTRF2014 for the first time non-linear station motions are considered. TU Vienna investigated the impact of non-linear station motions in VLBI-based TRF-CRF-EOP solutions on source positions and EOP. The results indicate that the seasonal signals do not propagate into the orientation of celestial reference frame but they can cause significant position changes for radio sources observed non-evenly over the year. On the other hand, it was found that the harmonic signals in station horizontal coordinates propagate directly into the ERP by several tens of microarcseconds.

VLBI solutions depend on the quality of the a priori values of tropospheric parameters as these parameters are slightly constrained in the VLBI solutions. Therefore, TU Vienna tested different types of a priori modelling (see report of WG 1.4.2). It was found, that the different modelling options lead to significant differences in the declination biases which occurs around 30°S.

BKG performs the combination of different VLBI solutions routinely in its function as IVS Combination Centre. Up to now, station positions and EOP were combined on a routine basis. In order to investigate the benefit of a combination of source positions for the CRF, BKG includes source positions in the combination process. The results look very promising. The WRMS of session-wise estimated source positions were improved by the combination as shown in Fig. 1.4.2. Figure 1.4.3 displays the homogeneity of position residuals of all contribution solutions w.r.t. ICRF-2 exemplarily for one R1 session. The impact of the combination of sources on the TRF was found to be not significant.

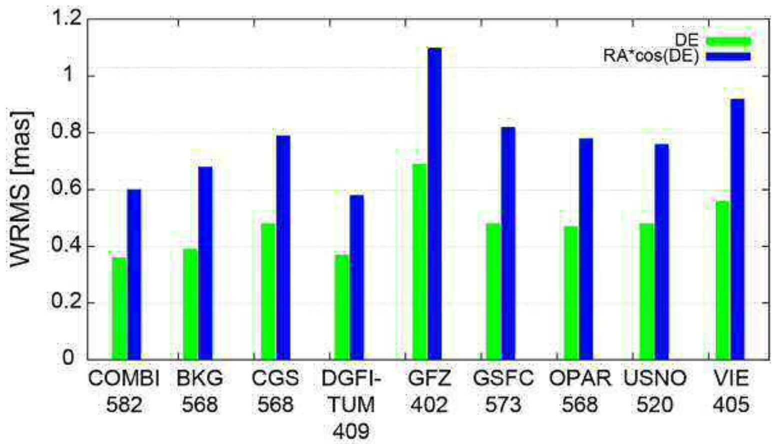

Fig.1.4.2. WRMS over all sources for individual and combined solutions. Only sources with ten sessions and a time span of more than 2 years were considered. The number of sources is given below the name of the analysis center (AC).

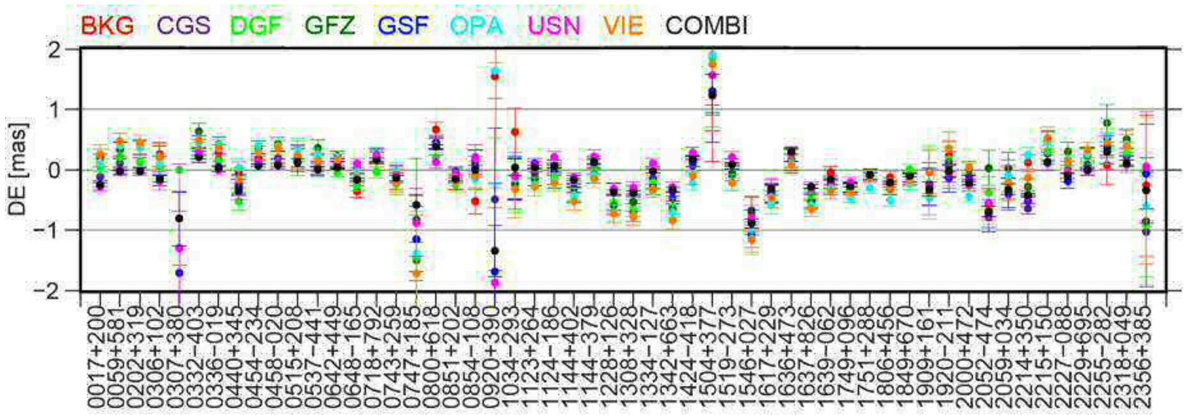

Fig.1.4.3. Source position residuals w.r.t. ICRF2 for individual and combined solution for session 14MAY27XA (R1637).

Two further VLBI analysis options are investigated by WG 1.4.2: the spline parameterization for special handling sources that allows to include these sources in the NNR conditions and the minimization of source structure effects on the CRF.

Consistent realization of ITRS and ICRS

Two groups are working on the consistent realization of ITRS and ICRS, namely JPL and DGFI-TUM.

In the recent years JPL developed a Kalman filter approach (KALREF) for the realization of the ITRS and became an ITRS Combination Centre. JPL provided the solution JTRF2014 in the framework of the ITRS realization. For this purpose, JPL improved their TRF solution by using GRACE data and loading models to include statistics of regional ground deformation in the Kalman filter's stochastic model of process. In a second step, the Kalman filter approach was extended to compute also CRF solutions. Therefore, radio source coordinates were modeled as random walk processes and a source-based process noise model was developed. The special handling of sources featuring measurable motions, benefit most from this time series approach. Physical properties of radio sources, such as the direction of the jet, have been obtained from radio source images and incorporated in the process noise models.

A new software, SREF, has been developed at JPL. It is based on KALREF, but more flexible in terms of parameterization and stochastic treatment. SREF adopts a sequential time series approach to parameter estimation, but uses a square-root information filter (SRIF) instead of a Kalman filter. The SRIF algorithm performs the state updates – and hence the combination – at the normal equation level. Furthermore, it is more robust numerically. In addition to the capability of determining TRF solutions, SREF includes the possibility to estimate radio source position and nutation parameters.

SREF has been successfully used to compute consistent TRF/EOP/CRF solutions. The input data for GNSS, SLR, and DORIS was based on the input for JTRF2014. Instead of the IVS VLBI contribution to ITRF2014, the GSFC VLBI operational solution (gsf2016a) was used since it contains radio source positions. Compared to JTRF2014, the number of stations was reduced to 510 in order to efficiently compute and experiment with different solution set-ups. For the same reason, a rather small number of 298 radio sources was selected. The origin was defined by SLR and the scale by SLR and VLBI. Comparisons of the station and source coordinates to frames like ITRF2014 and ICRF3 revealed a reasonable agreement. EOP from the SREF solutions were compared to IERS C04 14 and the EOP series from ITRF2014, DTRF2014, and JTRF2014. The next steps will be to compute solutions with larger terrestrial networks and a greater number of radio sources.

At DGFI-TUM, consistent realizations of ITRS and ICRS were performed by combining the space geodetic techniques on normal equation level. For the most recent solution, VLBI and SLR normal equations from DGFI-TUM and the routinely provided normal equations of the IGS Analysis Centre CODE were combined, covering the time span from January 2005 – December 2016. The parameters that were included in the combination are shown in Table 1.

Table 1.4.1. Parameters estimated in the consistent realization of ICRS and ITRS at DGFI-*TUM*.

		VLBI	SLR	GNSS
TRF	Station coordinates	X	X	X
	Station velocities	X	X	X
	Origin	NNT	intrinsic	NNT
	Scale	intrinsic	intrinsic	NNS
	Orientation	NNR	NNR	NNR
CRF	Source coordinates	X		
	Orientation	NNR		
EOP	Terrestrial x/y-pole	X	X	X
	Celestial X/Y-pole	X		
	ΔUT1 *	X	(X)	(X)

(*) for the satellite techniques, one ΔUT1 value per solution is fixed to a priori

The parameters common to all techniques are station coordinates and EOP. Detailed studies are performed to investigate the impact of the combination of these parameters on the CRF. While the combination of the station coordinates has only a small effect on the CRF (see Kwak et al., 2018), the combination of EOP leads to significant changes in two different ways. Figure 1.4.4 shows the change of source position standard deviations by the combination of EOP. The mean effect (more than 90%) is by the combination of x- and y-component of the terrestrial pole. In particular, the VCS sources and the newly added sources (not included in ICRF-2) benefit from the combination of the EOP.

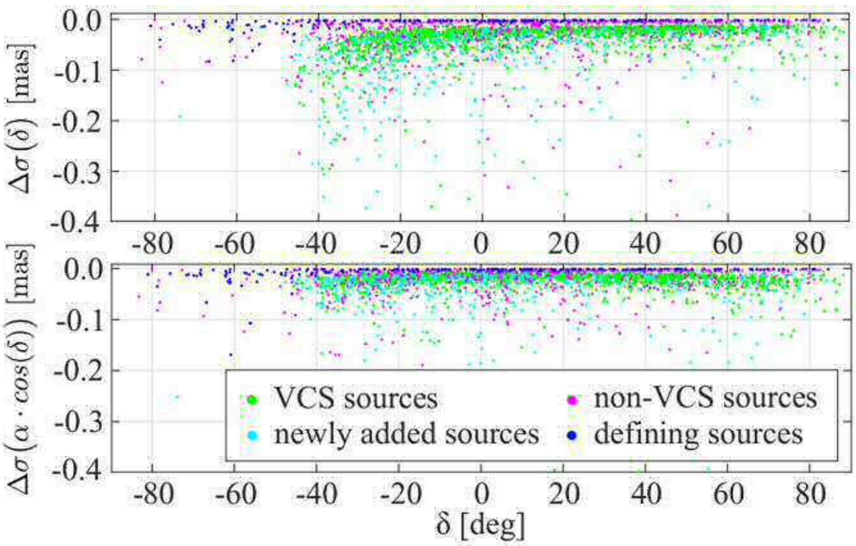

Fig. 1.4.4. Change of source position standard deviations due to the combination of EOP.

Also, the WRMS values of the EOP series w.r.t. IERS 08 C04 are improved by the combination. Figure 1.4.5 shows the WRMS values for two test scenarios weighting the VLBI normal equation in the combination with the factor 1.0 and 0.1 (down weighting), as well as for the VLBI-only solution. It can be seen very clearly, that for x- and y-component of the terrestrial pole the WRMS but also the weighted mean offset (wmean) decrease significantly in the combination. The combination of LOD, however, leads to an expected increase of the ΔUT1 WRMS value compared to the VLBI-only solution, due to the interpolation to a continuous series (daily values). The down weighting of the VLBI contribution further enhances this effect.

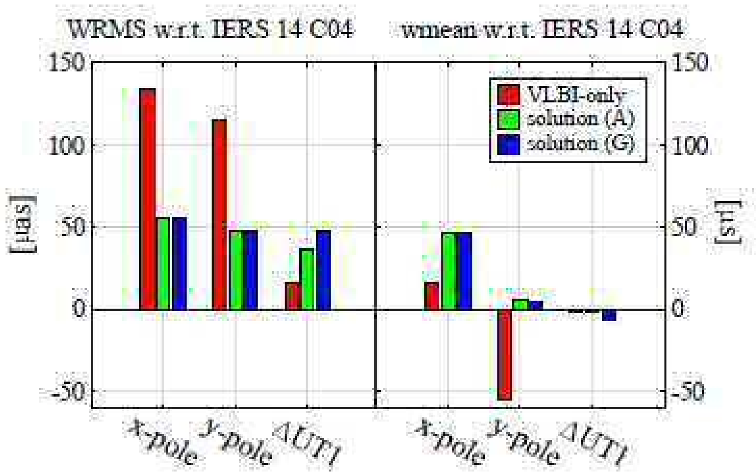

Fig.1.4.5. WRMS and wmean values of EOP time series derived from two combination setups and the VLBI-only solution w.r.t. IERS 08 C04. Solution (A): VLBI is weighted in the combination by factor 1.0; solution (G): VLBI is down weighted in the combination by using a factor of 0.1.

In order to further validate the CRF part of the combined CRF/TRF solution transformation parameters w.r.t. the VLBI-only solution are estimated. Figure 1.4.6 shows the parameters for four different combination setups. It becomes evident that the combination of LOD (in fact we use a piece-wise linear representation of ΔUT1) lead to a systematic rotation of the frame, in particular around the third axis (A_3). On the other hand, it is beneficial that the combination of LOD lead to a continuous ΔUT1 series. It is a task for the future to study how the rotational effect can be reduced.

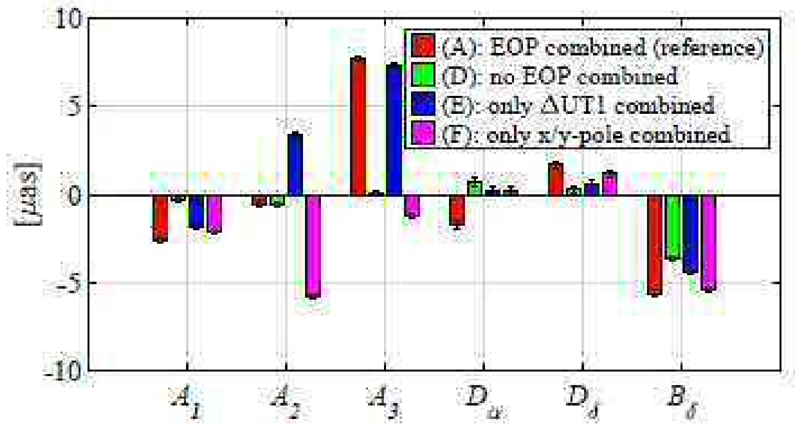

Fig. 1.4.6. CRF transformation parameters and their standard deviations (error bars) of different EOP combination setups w.r.t. VLBI-only solution.

Summarizing the results from the consistent realization of ICRS and ITRS we can state the following:

- The combination of the techniques lead to a reduction of standard deviation of the estimated parameters due to the larger number of observations
- The impact of the local ties on the CRF and the EOP is small
- The CRF benefits from the combination of the terrestrial pole coordinates, which reduces the standard deviations of a large number of sources significantly.
- The combination of LOD leads to a z-rotation of CRF. However, it is beneficial that the ΔUT1 series become continuous. It is a task for the future to better study and reduce the rotational effect.

The consistent realization of ICRS and ITRS performed at DGFI-TUM is presented in detail in Kwak et al, 2018.

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IAG WG 1.4.2: Impact of Geophysical and Astronomical Modeling on Reference Frames and Their Consistency

Chair: *Dan MacMillan (USA)*

Members

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

Introduction

Working Group 2 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. Over the last four years there have been several published papers and presentations on topics including source position time series stability, radio source structure, galactic aberration, ICRF3, accuracy of radio source catalogs, correlations between VLBI observations due to troposphere noise, and VLBI+GNSS combination solutions. Several of the group members (D. MacMillan, S. Lambert, H. Krásná, and Z. Malkin) are also 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.

Modeling Source Structure Variation

Karbon et al. (2016) addressed the issue of systematic variation of radio source positions, which is likely due to source structure, and its effect on the TRF and EOP in VLBI solutions. They employed an efficient automated recursive spline fitting procedure to determine spline parameters for each source. The spline parametrizations are then applied as a priori models for each source (see Fig. 1.4.7). This allows sources with significant systematic variation, e.g., the ICRF2 "special handling" sources, to be included in the CRF NNR condition. In the ICRF2 solution, these sources were excluded from global estimation and were estimated as local session parameters, thereby weakening their contribution to estimated CRF. Depending on the distribution of sources in the NNR condition, this spline procedure expands the number of datum sources by 114-146% for 1980-1990 and 27-46% for 1990-2013. Benefits of this parametrization are an improvement in nutation precision with respect to the IAU 2006/2000 precession model of 10-12% and a reduction in position series precision of up to 2.5-4 mm for high latitude sites (likely due to sources at high declination), e.g., NyAlesund, but less than 0.05 mm for other sites.

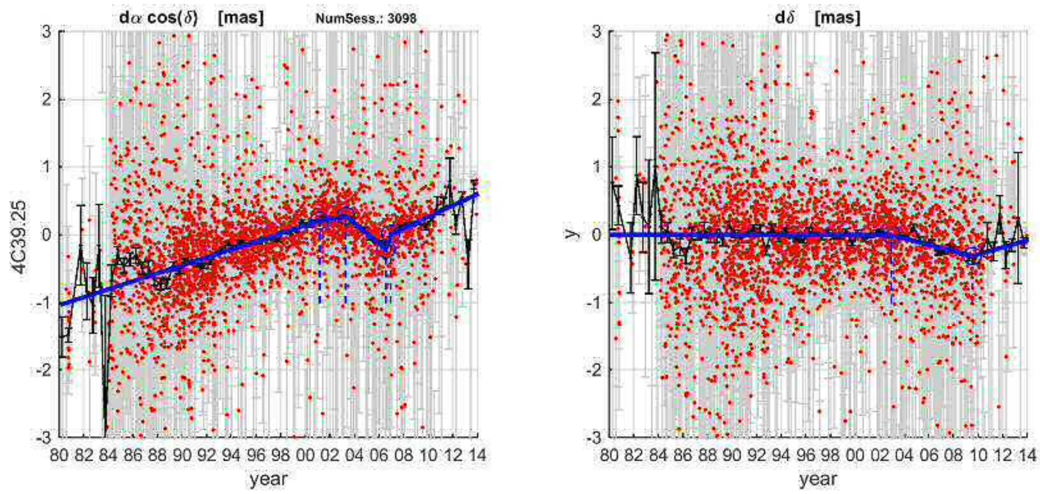

Fig. 1.4.7. Session-wise estimates of the radio source 4C39.25 position right ascension and declination (red points, semi-annual means (black curve), and the spline fits (blue curve) to the estimates (Karbon et al. 2016).

Plank et al. (2016) investigated the effect of source structure on the CRF. In simulations, they applied 2-component source models and determined the resulting shift in source position estimates. For sources with structure index of 2 or 3, these shifts tend to be aligned with the source jet direction. Based on this result, they investigated a method of source position estimation that tries to minimize the effect of source structure by estimating the component in the direction of the jet for each 24-hr observing session and the component perpendicular to the jet as a global parameter. In simulations using observing schedules for the operational R1/R4 sessions, the median effect of structure is reduced for sources with structure indices 2-3. It remains to try the method with observed data.

For perspective, there has been considerable recent work done on the effect not modeling source structure in VLBI analysis. 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. Work is continuing on 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.

ICRF3 and Other ICRF Accuracy/Precision Investigations

Krásná and Titov (2017) have investigated an alternative method of estimating galactic acceleration (secular aberration drift). They estimate for each source a global scale parameter relative to the a priori terrestrial reference frame. Considering the RA and DEC dependencies of the scale parameter, it turns out that the galactic acceleration vector (GA) can be derived from the scale parameter estimates for each source. Krásná and Titov then investigate the dependence of GA on the minimum number of observations required for a source to be included in the estimation. They obtained the same results with VieVS and with OCCAM software. Several estimates of the galactic aberration amplitude were then compared: 1) All VLBI data 1979-2016, standard estimation, 6.1 ± 0.2 µas/year; 2) VLBI R1/R4/NEOS/CONT sessions 1993-2016, standard estimation, 5.4 ± 0.4 µas/year; and 3) All VLBI data 1979.7 to 2016.5, scale parameter method, number of observations/source > 50, 5.2 ± 0.2 µas/year.

The IVS Aberration Working Group completed its investigation and recommended a galactic aberration constant of 5.8 µas/yr for the ICRF3 solution. The aberration constant is the galactocentric acceleration scaled by the velocity of light. This constant was derived from a

Calc/Solve solution using all of the 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. The epoch 2015.0 is close to the Gaia DR2 reference epoch of 2015.5. 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) (submitted).

Ma C. et al. (2016) discussed different issues that needed to be addressed in the development of ICRF3. The site observation data distribution has improved significantly so that southern hemisphere sites contribute 40% of all observations compared with 10-20% from 1995 to 2009. The average source position noise (uncertainty computed by decimation test) have improved since ICRF2 (2009) from (52 µas, 62 uas) to (32 µas, 43 µas). One of the significant systematic effects that has been found in recent global CRF solutions is that there is a systematic bias in declination that peaks at about 0.1 mas at 30ºS between current solutions using all data through 2016 and ICRF2 positions that were based on data from 1980 to 2009. This bias disappears if the Australian AUSCOPE network data observed during the period since ICRF2 is removed from analysis solutions. It is not clear whether the addition of the southern hemisphere stations has improved the observing geometry for southern declination sources relative to the source geometry available for ICRF2 or whether some AUSCOPE station errors cause the bias. Tests indicated that troposphere delay modeling does not cause the systematic. There was some evidence that application of phase calibration correction at two of the AUSCOPE stations had the effect of causing the declination systematic. The group delay calculated from the phasecal correction appeared to indicate cable stretching that increased with the antenna azimuth difference (and thereby the delay error) from the cable zero (neutral) point. There has not been time to derive a reasonable method of correcting this error in all of the AUSCOPE data.

Mayer et al. (2017) studied the relationship between the VLBI tropospheric delay modelling and source positions. In particular, the effect of a priori ray-traced slant delays on source declination was investigated. Global source coordinates of 5830 geodetic VLBI sessions incorporating about 10 million group delay measurements were estimated. This data set was used for the International Celestial Reference Frame 3 (ICRF3) prototype solutions as of December 2016. They found a significant bias in source declination of about 50 µas; which can be found between a normal solution and a solution where a priori ray-traced slant delays are used. More traditional tropospheric delay modelling techniques, such as a priori gradients, were tested as well. Significant differences of about 30 µas in declination can only be found when absolute constraints are used for a priori gradient models.

Figure 1.4.8 shows the effect of different troposphere modeling options on the CRF declination bias of current solutions relative to ICRF2 that was based on data until 2009 (smoothed over declination). The options tested were 1) standard wet zenith and gradient parameter estimation, 2) troposphere ray-traced delays applied without gradient estimation, 3) ray-traced delays applied with gradient estimation, 4) standard solution with elevation weighting, 5) standard solution using DAO gradient as *a priori* but with constraints, and 6) standard solution with DAO gradients with gradient constraints. The difference in declination bias between the standard solution (1) and the solutions (2 and 3) that used ray-traced delays yields a declination bias that peaks at about 60 µas at about 30ºS. The rms variability of this difference is significantly greater if gradients are not estimated in the ray-traced delay solution. The conclusion from Fig. 1.4.8 is that none of the models make any significant reduction in the declination bias implying that the declination bias is not due to tropospheric delay modeling errors.

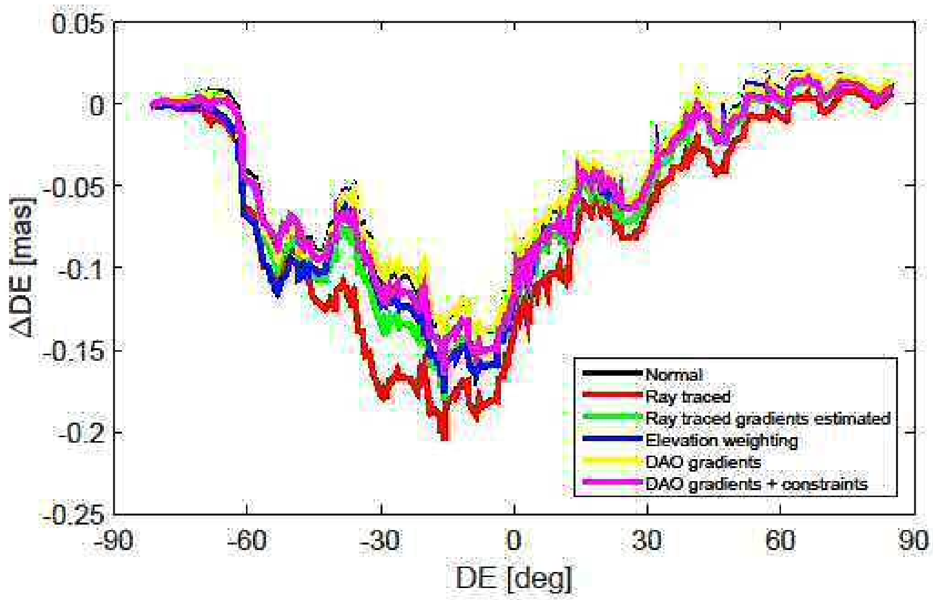

Fig. 1.4.8. Difference between declinations from each solution and ICRF2 declinations (Mayer et al., 2017).

Liu et al. (2018) estimated the accuracy of radio source catalogs by analysis of decimation VLBI solutions. This involved a computation of the 'precision' of a catalog using two methods of analysis. The derived noise floor was 20-25 µas for sources observed in at least 10 24-hour observing sessions. The paper expanded on the analysis done for the ICRF3.

Gattano et al. (2018) investigated radio source stability and the VLBI celestial reference frame by using Allan standard deviation analysis of source position time series. They found that the concept of a 'stable source' is not realistic and that very few source coordinate series are white noise. Most series are exhibit flicker/red noise indicating that accumulating observations will not necessarily improve the astrometric position. Figure 1.4.9 provides an example of source position (right ascension and declination) time series and the corresponding Allan standard deviation (ASD) as a function of time scale. As the time scale increases, the ASD increases and essentially becomes unstable meaning that increasing the number of observations does not improve precision. In terms of the VLBI geodetic observing program, we should try to minimize the effects of instability by modifying the VLBI geodetic observing source list by removing sources that are currently exhibiting instability. For the next ICRF, the Allan variance should be used rather than assuming that noise in source position time series is Gaussian.

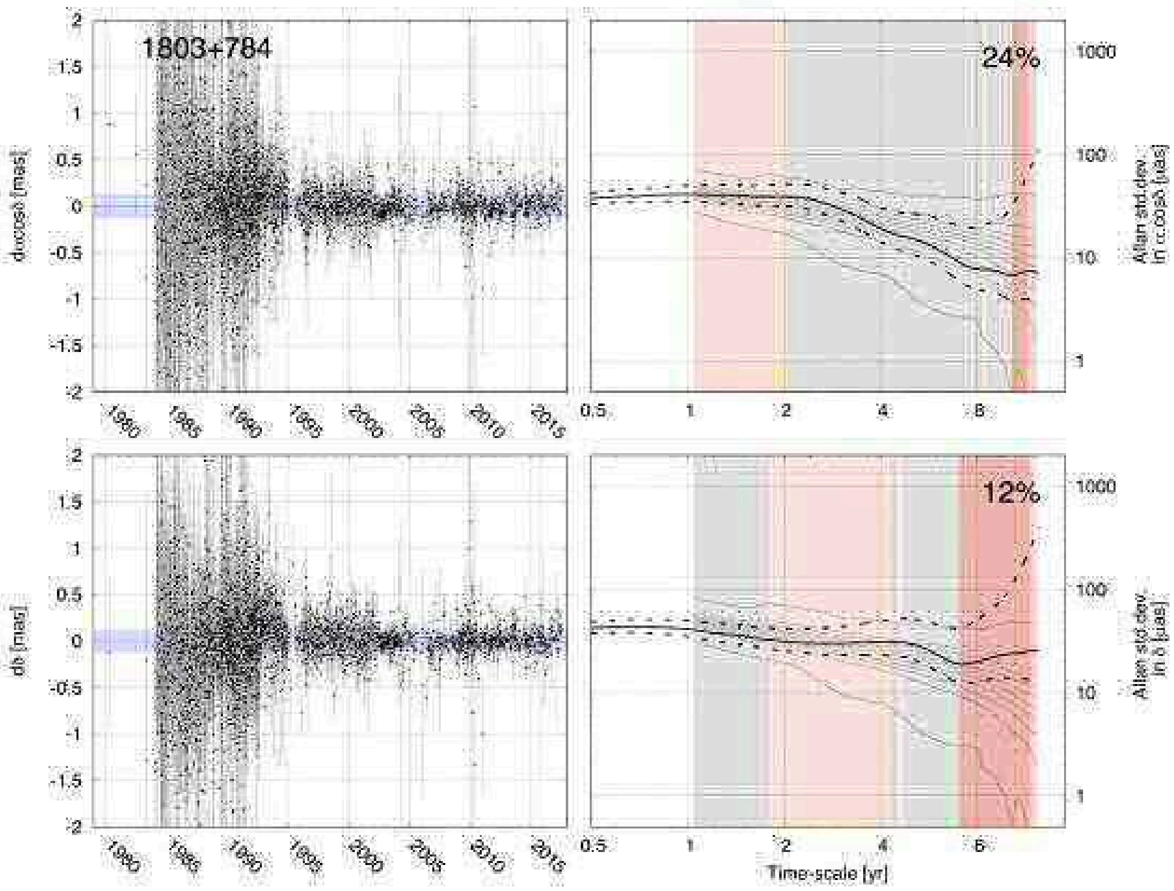

Fig. 1.4.9. The four-quadrant plot shows (left panels) coordinate time series with their standard deviation given by the blue area and (right panels) the Allan standard deviation as a function of the averaging timescale (black solid line), where the colored background indicates the behavior of the dominating noise (stable in gray, unstable in red, intermediate in pink), the black dotted lines represent the interval of confidence (at 90%) on the estimated Allan standard deviation at each timescale, and the gray lines represent the boundaries of deciles as computed from the Monte Carlo test. The percentage in the top right corner gives the probability that the source is AV0 (stable and not dominated by unstable noise). (Gattano et al., 2018)

Effect of A Priori High Frequency EOP models on Nutation Estimation

Panafidina et al. (2017) and Panafidina et al. (2019) investigated the propagation of polar motion and UT1 models into nutation offsets estimated by VLBI. Earth orientation parameters connect the terrestrial and celestial reference frame. Within the analysis of space geodetic observations, errors of the applied subdaily Earth rotation model can induce systematic effects in different estimated parameters. They focused on the error propagation from the subdaily model for Polar Motion and Universal Time in the estimated Celestial Pole Offsets in the processing of VLBI observations. It was found that, even though the subdaily model for polar motion does not contain any retrograde daily terms, a part of the signal from the subdaily model is numerically mistaken for a retrograde daily signal, which contributes to the estimated nutation offsets. They showed that the variations in UT1 with daily periods and the estimated nutation offsets influence each other. The presented model of error propagation from the subdaily UT1 into the daily CPO allows one to predict and explain the behaviour of CPO estimates of VLBI solutions computed with different subdaily Earth rotation models, which can be used to test the accuracy of different subdaily tidal models.

Modeling Troposphere Noise in VLBI Analysis

Krasna and Gipson (2017) investigated the effect of correlated noise between observations involving the same antenna. The standard assumption in the routine VLBI analysis is that the observations are station and time independent which manifests itself in a diagonal observation covariance matrix. But this simplification causes a mis-characterisation of the measured group delays leading to incorrect estimation of parameters and too optimistic formal errors. In the first step they compared the estimated baseline length scatter from CONTinuous VLBI campaigns using two way of reweighting obsevations, i.e. adding baseline dependent and elevation dependent noise. In the second step they introduced correlations into the observation covariance matrix focusing on mis-modeling of the atmosphere and taking into acount correlations between observations at a common time. They demonstrated that this reduces the baseline length scatter, indicating that the results are more consistent day-to-day. They also showed that introducing the correlations improves the agreement between VLBI and GPS measured polar motion.

VLBI + GNSS combination

Lambert et al. (2018) (conference presentation) investigated the rigorous combination at the normal equation level of GNSS and VLBI to improve Earth orientation and reference frames. Comparison of polar motion and LOD with atmospheric angular momentum showed a slight increase in the correlation after the combination of GNSS and VLBI. The addition of GNSS to VLBI appeared to improve the determination of nutation for weak sessions. It is expected that this work will be published in 2019.

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IAG WG 1.4.3: Improving VLBI-based ICRF for Geodesy

Chair: *Sébastien Lambert (France)*

Members

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

Introduction and context

The IAG working group (WG) 1.4.3 was formed mid-2016 with the title "Improving VLBI-based ICRF for Geodesy" and membership including. The IAG WG 1.4.3 was not mandated for building any final product but rather designed for discussing the recent evolution of the VLBI celestial reference frames and raise some questions for the future. The studies that are mentioned below were not realized in the framework of IAG WG 1.4.3 but either in the frame of other WGs and consortia or independently from any formal structure.

In fact, some of the IAG WG 1.4.3 members were involved in critical actions related to the establishment of the new global reference frames via the IAU Division A WG on the *Third Realization of the International Celestial Reference Frame*[1] (S. Lambert, Z. Malkin) and the *Data Processing and Analysis Consortium* of the ESA *Gaia* mission[2] (F. Mignard, S. Lambert). These two structures gave birth to the ICRF3, the latest and the currently most accurate celestial reference frame, adopted by the IAU as fundamental reference frame in August 2018, and to the second data release (DR2) of *Gaia*, published in April 2018. Besides these two major products, several works were achieved to improve the accuracy of the VLBI-based CRF or understand the sources of error. We present here a summary of these achievements.

Progress in sub-milliarcsecond realizations of the ICRS by VLBI

The ICRF3 was released mid-2018 by an international team formalized by an IAU working group (IAU Division A WG on the *Third Realization of the International Celestial Reference Frame*) chaired by P. Charlot. The ICRF3 catalog was produced by a direct fit of the radio source coordinates to VLBI delays over 1979-2018 along with all the geodetic parameters traditionally estimated in a standard solution (Earth rotation parameters and rates, station coordinates and velocities, sub-daily troposphere wet delays and gradients, sub-daily clock drifts). The astronomical and geophysical modeling used the state-of-the-art models and was compliant with the IERS Conventions 2010. Two novelties make the ICRF3 different from earlier releases: (i) the Galactic aberration was included in the astrometric modeling based on a value recommended by a dedicated IVS working group (MacMillan et al. 2019), and (ii) it is provided at three wavelengths (8 GHz, 22 GHz, and 32 GHz). Another important point is the release of the *Gaia*-CRF2 catalog (Mignard et al. 2018; see also Prusti et al. 2016, Brown et al. 2018, Lindegren et al. 2018) that is an independent realization of the ICRS in the optical with

[1] https://www.iau.org/science/scientific_bodies/working_groups/192/
[2] https://www.cosmos.esa.int/web/gaia

an accuracy comparable with VLBI. The comparison between VLBI and *Gaia* (studied independently by the ICRF3 WG and the *Gaia* DPAC) provided important insights into the large-scale systematics and helped considerably in the validation of the VLBI solutions. Details about the ICRF3 realization are reported in Charlot et al. (2019).

Methodologies that could improve the ICRF

Accuracy versus standard error

One important question that the geodetic community must constantly raise is the accuracy of the products. *Accuracy* means here the closeness to the true value. This quantity has to be looked versus the *standard error*. The standard error on a parameter (e.g., source coordinate) reflects the number of observations rather than the closeness to the 'truth'. In absence of measurements from an independent technique, one cannot generally get any evidence on whether the parameter is correctly determined. There exists, generally, systematics (e.g., network effect) that push the parameter away from the 'true' value by more than the standard error. To remedy this problem, one can rescale errors by adding quadratically a noise floor and a scale factor: this is a method that was applied in several studies related to ICRF (see, e.g., Fey et al. 2015) or other VLBI products (e.g., Herring et al. 2002). Once this is done, the modified standard errors generally explain the difference to the mean value and the data is more relevant for scientific exploitation.

Gattano et al. (2016) studied the nutation data as provided by the various IVS analysis centers and showed that nutation series differed significantly in comparison of their standard errors. They provide scale factors and noise floor for each series. Interestingly, the differences between series (that are supposedly obtained from the same VLBI observations!) could arise from subtle variations in the analysis configuration including CRF *a priori* and constraints. Though Gattano et al. showed that these differences impacted marginally the determination of the resonance frequency of the free core nutation, the influence was much more dramatic on the free inner core nutation, hampering its detection!

Liu et al. (2018) studied the accuracy of the VLBI catalogs versus their standard error by two methods: (i) the one used in Fey et al. (2015) and Charlot et al. (2019) for rescaling the ICRF2 and ICRF3 errors and based on difference between - somehow - independent solutions, and (ii) the one used by Lambert (2014) and Gattano et al. (2016) based on a comparison between scatter and formal errors. Both methods gave comparable results. The noise floor was estimated to be 20-25 μas for sources observed in at least ten sessions, which is consistent with the conservative noise floor of 30 μas chosen for the ICRF3, and it could be reduced down to ∼10 μas for sources which have been observed in more than 1000 sessions.

Handling the source structure and evolution

The position of the radio source is not fixed: VLBI actually measures the position of the brightest part of the jet that is moving by - for some sources - several tenths of mas per year within a structure that can be extended over a comparable angular size. Such apparent 'motion' of the radio center is caused by the ejection or flux changes of VLBI components. It turns out that considering that the ICRF is made up of fixed reference points, this can lead to an unexpectedly rotating (or distorting) frame. Such a pollution would leak into other parameters including nutation and UT1. Several works addressed the problem of handling the extended, moving radio sources.

Plank et al. (2015) simulated source structures with a two-component model to investigate the potential effect on the frame determination. They found that systematics could rise up at the level of 10-80 μas and proposed an alternative handling of source positions based on a parameterization along and perpendicular to the jet.

Many sources are variable, and flux density monitoring provides an opportunity to study source structure. Using high-cadence (many observations over a few days) flux density monitoring, Schaap et al. (2013) showed that sources which show scintillation have lower structure indices and better astrometric stability. Studying longer-term (months to years) variability, Shabala et al. (2017) showed that sources near the peak of their light curve are more compact. These investigations open up a possibility of weighting the contribution of sources to the frame by their expected structure, even if detailed structure information (i.e., VLBI images) is not available.

Karbon et al. (2016) proposed an interesting parameterization of the source positions similar to what is done for the ITRF and based on multivariate adaptive regression splines. Such a method appears particularly relevant for some very active sources. Also, this method is a good compromise, in terms of number of parameters, between the fully global solution and intermediate approaches in which one estimates (some) source coordinates as session parameters. Moreover, once the source model is known, the minimal constraint can still be applied to the full sample of sources. Karbon et al. (2016) reported that the rms of nutation offsets was improved by 10%. An optimization and a generalization of such a modeling in all VLBI analysis chains could be promising.

Although the trajectory of VLBI components is regularly monitored and model-fitted with a nice accuracy thanks to VLBI in imaging mode (e.g., Lister et al. 2019) there is no consensus on the true nature of the 'core' that could contain single or multiple black hole systems. Based on a celestial mechanics approach, Roland et al. (2015, 2019) suggested that several black holes may coexist within few hundreds of µas (see, e.g., Fig. 1.4.10 for radio source 1928+738, Roland et al. 2015). The presence of several active black holes within 1 mas has strong implications on the frame realization: the position of the radio center as measured by geodetic VLBI will move accordingly to the ratio of the fluxes of the various bright (eventually ejected) components, resulting in jumps in the apparent trajectories. This could be at the origin of the various noise types detected by Gattano et al. (2018) using advanced spectral methods. Such results can lead to interesting alternative modeling and/or parameterization of source positions in VLBI analysis, complementary to those of the studies cited earlier.

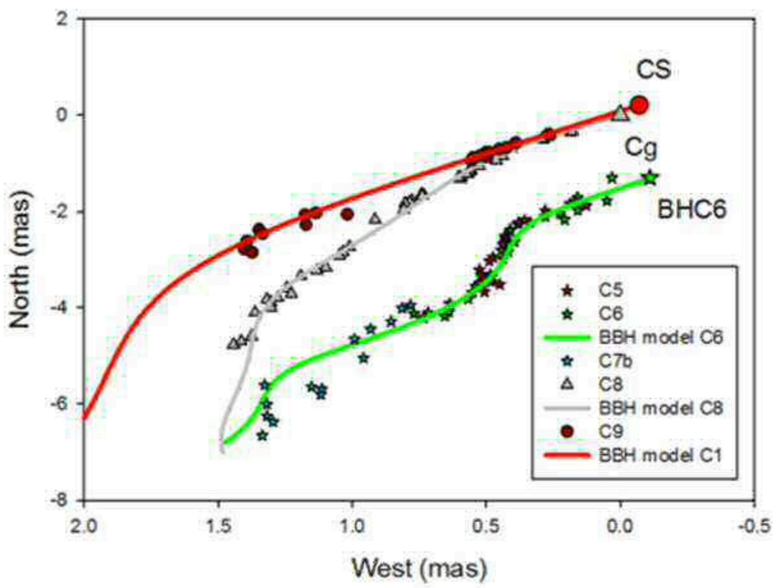

Fig. 1.4.10. As reproduced from Roland et al. (2015), showing a possible system of three black holes (denoted as CS, Cg, and BHC6) ejecting the various components observed by MOJAVE. The position measured by the geodetic VLBI lies close to the brightest component (CS) but can be significantly influenced if BHC6 is active, thereby pulling the position to the south.

A combined ICRF in the future?

The objection that ICRF is produced through a single technique – while the ITRF is obtained from four independent techniques – is regularly raised within the geodetic community. Though efforts are made in the direction of obtaining a CRF from the combination of VLBI, GNSS, SLR, and DORIS at the normal equation or the observation level, so-called 'Combined CRF' - assimilating data from techniques that are not sensitive to radio source positions but that can constrain other common parameters - still have to be assessed in terms of accuracy. There is no doubt that the next few years will be devoted to such tasks.

Kwak et al. (2018) and Soja et al. (2019) produced such consistent realization of terrestrial and celestial reference frames with associated Earth orientation parameters by processing data from the four techniques over 2006-2015 in a single software package. They demonstrated the feasibility of such a combination with a satisfactory consistency with the VLBI-only solutions at the level of tens of as. Some sources of errors (e.g., local ties) still have to be addressed.

Other teams are working on this exciting topic such the French GEODESIE project (Coulot et al. 2017) that proposes a geodetic/geophysical data assimilation within a single analysis chain to produce new references and geodetic/geophysical series (e.g., Earth orientation parameters, sea level) freed from terrestrial/celestial reference frame effects.

One must keep in mind that, if the combination of several techniques returns, in general, lower standard errors, reduced noise level and lowered correlations between parameters, this does not mean that the obtained parameters are more accurate. Systematics could still arise and lead to misinterpret the results. The accuracy of the combination products should be assessed by comparison with independent measurements or physical phenomenon measured or modeled independently (e.g., Ray et al. 2005, Lambert et al. 2017). For instance; global reference frames can be compared with realizations from independent techniques (e.g., upcoming releases of *Gaia*). The rigorous homogeneity of the geophysical and astronomical modeling between all the techniques is also mandatory, although sometimes hard to realize in practice. Setting up an operational multitechnique combination at the observation or normal equation level that meets the objectives of accuracy of one millimeter in position and one millimeter per year in stability will therefore constitute one of the challenges of the next decade for the geodetic and astrometry communities and the international services.

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Commission 1 Joint Working Group 1.1: Site Survey and Co-Location

Chair: *Sten Bergstrand (Sweden)*
Vice Chair: *John Dawson (Australia)*

Ex officio members

- *Erricos C. Pavlis, ILRS (USA)*
- *Jerome Saunier, IDS (France)*
- *Jim Long, NASA SGP (USA)*
- *Ralf Schmid, IGS (Germany)*
- *Rüdiger Haas, IVS (Sweden)*
- *Xavier Collilieux, IGN Surveying entity (France)*

Members

https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

Activities and publications during the period 2015-2019

The activities have been directed towards a common terminology in space geodesy in order to facilitate exchange of data between services. This has improved surveying practices for DORIS with a local tie uncertainty between observation and topocentric measurements now estimated to be of order 3 mm. Specially adapted programs have been developed to monitor the geometric reference points of VLBI telescopes with terrestrial total stations during observation schemes. Internal VLBI telescope deformations have also been shown to contribute significantly to position uncertainties, and further development in this field is expected. The Onsala-Metsähovi baseline was observed between the IGS and IVS stations at the sites, simultaneously with terrestrial and GNSS measurements of the local ties; processing has been delayed. Different GNSS antenna calibration methods exhibit results that prohibit the determination of local ties to the desired level; an issue which touches the scope of the WG but requires a broader approach.

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Commission 1 Joint Working Group 1.2: Modelling Environmental Loading Effects for Reference Frame Realizations

Chair (2015-2017): *T. Van Dam (Luxembourg), new vice chair (2017-2019)*
Vice Chair (2015-2017): *A. Mémin (France), new chair (2017-2019)*

Members

- *Zuheir Altamimi (France)*
- *Johannes Böhm (Austria)*
- *Jean-Paul Boy (France)*
- *Xavier Collilieux (France)*
- *Robert Dill (Germany)*
- *Pascal Gegout (France)*
- *Matt King (Australia)*
- *Anthony Mémin(France)*
- *Laurent Métivier(France)*
- *Gerard Petit(France)*
- *Jim Ray (USA)*
- *Leonid Vitushkin*
- *Xiaoping Wu (USA)*

Activities and publications during the period 2015-2019

Description of the activities including graphics, tables, literature (references to the activities)

The activity of the working group has been focused on the impact of loading deformation in GNSS time series. Several loading models have been used and compared. Loading corrections have been applied a posteriori and at the observation level. Results have been presented during a splinter meeting organized on Wednesday 26th April, 2017 at the EGU (see report in Appendix). The meeting came to the following recommendations for 2017 – 2019:

- Extend investigation of loading effects to other geodetic techniques (VLBI, SLR) and perform an homogeneous analysis with all the techniques
- Check and clearly display the strategy regarding loading effects adopted by each analysis center
- An up to date list of references should be displayed on the working group website
- This working group should be continued
- A workshop is suggested for 2018 to discuss points that have not been discuss during the splinter meeting (loading and geocenter motion, current and future approaches in modeling loading effects, recommendations to IERS)

Commission 1 Joint Working Group 1.3: Troposphere ties (joint with Sub-Commission 4.3)

Chair: *Robert Heinkelmann (Germany)*
Vice Chair: *Jan Douša (Czech Republic)*

Members

- *Kyriakos Balidakis (Greece)*
- *Elmar Brockmann (Switzerland)*
- *Sebastian Halsig (Germany)*
- *Younghee Kwak (South Korea)*
- *Gregor Möller (Germany)*
- *Angelyn W. Moore (USA)*
- *Tobias Nilsson (Sweden)*
- *Rosa Pacione (Italy)*
- *Tzvetan Simeonov (Bulgaria)*
- *Krzysztof Sośnica (Poland)*
- *Peter Steigenberger (Germany)*
- *Kamil Teke (Turkey)*
- *Daniela Thaller (Germany)*
- *Xiaoya Wang (China)*
- *Pascal Willis (France)*
- *Florian Zus (Austria)*

Activities and publications during the period 2015-2019

The new working group was established in 2015. The terms of reference and objectives were drafted, discussed and approved. The working group chair gave the first presentation about the working group objectives at the IAG Commission 4 Meeting at the Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland, on 5th of September 2016, see http://www.igig.up.wroc.pl/IAG2016/?page=2. The first regular Working Group Meeting was held on the 26th of April 2017 aside the EGU General Assembly at Vienna University of Technology, Vienna, Austria.

During past years, Geodetic Observatory Pecny (GOP) has developed a powerful database, GOP-TropDB (Gyori and Dousa, 2017), for the intra-/inter-technique comparisons for tropospheric parameters stemming from data analyses of space geodetic techniques. The database was completed with a web-gui service for interactive exploration of site/pair metadata and comparison statistics.

It is under construction within the IGS Tropospheric WG (Hackman et al, 2016).
The current database is ready to accommodate tropospheric path delays in zenith and horizontal gradients estimated using data of GNSS, VLBI and DORIS, Numerical Weather Model (NWM) re-analysis and radiosondes at least. For inter-technique comparisons of nearby stations, tropospheric parameters usually refer to different locations and thus require vertical, time-dependent correction between site reference altitudes. We developed and assessed several

models for calculating tropospheric ties/corrections and vertical scaling with support of different parametrization, vertical approximations and different meteorological data.

The tropospheric ties are optimally separated into two components - zenith dry and wet delays - and we thus focused on developing new model particularly for the wet scaling (Dousa and Elias, 2014). Different strategies for both wet and dry scaling were evaluated in the scenario using numerical weather data fields only, i.e. by approximating NWM differences in vertical profile by using new models for parameter scaling. Additionally, the impact of tropospheric ties was assessed in a comparison of GNSS and radiosonde tropospheric parameters and it will be finally evaluated by applying tropospheric ties specifically for GNSS and VLBI intra/inter-technique site collocations.

The online service has been developed for calculating tropospheric parameters from NWM reanalysis which can be directly used for several scenarios of calculating tropospheric ties.
The web is currently available at http://www.pecny.cz/Joomla25/index.php/gop-tropdb/tropo-model-service and it is under preparation to become a part of the IGS Tropospheric WG web-pages (http://www.igs.org).

Swisstopo is since years active in generating information which allow to extract tie information. With the enhancement from GPS to GPS/GLO in 2008, 9 from 30 site antennas and receivers were not switched to the new technology: parallel to the continued GPS-only station double stations were build. Furthermore, local tie measurement linked these double stations on a precision of a millimeter (baselines of some 10 meters).

In May 2015, all permanent stations (with the exception of the old GPS-only stations) were enhanced to GPS/GLO/GAL/BDS and a data flow based on RINEX3 was established in summer 2015. Since summer 2016 the complete processing chain is switched to Multi-GNSS using a special development version of the Bernese Software and using CODES MGEX orbit products. The tie information is extremely helpful, because the antennas were "only" calibrated on GPS/GLO.

Routinely, so-called inter system transformation parameters are calculated on a daily basis, showing the differences of coordinates and troposphere parameters between GPS and the satellite systems GLO/GAL/BDS. Troposphere biases are extremely sensitive to analysis models (especially the antenna PCVs for receiver and satellite antennas). These parameters are made available online. Example ZIM2:
http://pnac.swisstopo.admin.ch/pages/en/qsumzim2.html#TRA_LONG

Local refraction effects in space geodetic techniques are normally investigated by small scale GNSS networks. However, with the new pair of radio telescopes at the Geodetic Observatory Wettzell in Germany, the Institute of Geodesy and Geoinformation, University of Bonn, is now able to carry out similar investigations with geodetic VLBI observations, which are affected by the same refraction phenomena. The main objective is to analyse systematic effects between the tropospheric parameters in space and time. In a further step, this scenario is augmented by a local GNSS network set up on the Wettzell area in order to investigate the systematics between different measurement techniques.

The Vienna University of Technology contribution to JWG 1.3 aims at improving the understanding of systematic effects in tropospheric delay modelling between various satellite techniques. First action is related to the modelling of hydrostatic effects.

Comparisons between in-situ measurements of pressure and global HRES weather model data (as provided by ECMWF) reveal in general high accuracy in pressure within 0.5 +/- 1 hPa. Slightly worse agreement was found between in-situ data and regional weather model data (60% larger standard deviation). However, independent from the pressure sources high consistency can only be guaranteed if comparable data processing methods are applied. In particular, vertical interpolation methods and distance dependent pressure variations are further investigated and compared at co-located sites.

Further activity is related to the modelling of wet delays. The GNSS tomography technique allows for estimation of accurate wet refractivity fields in the lower atmosphere. By vertical integration or ray-tracing through these fields, accurate tropospheric wet delays can be derived. Introduced into the parameter estimation process of various space-geodetic techniques their impact on the station coordinates is analysed. Therefore, the wet delays are either treated as a priori information or as replacement of the tropospheric parameters.

ASI/CGS is going to contribute to objective 1 through VLBI and GNSS inter-technique comparison of atmospheric parameters at the eight European co-located sites. These sites are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA). We plan to compute long-term time series of the differences between the EPN-Repro2 (Pacione et al. 2017) for the period 1996-2014 completed with the EPN operational products afterwards and the EVGA combined solutions.

The German Space Operations Center (GSOC) of the German Aerospace Center (DLR) performs precise orbit and clock determination for satellites of the global and regional navigation systems GPS, GLONASS, Galileo, BeiDou, and QZSS on a routine basis. A global network of about 150 stations is processed with the NAPEOS software to solve for station coordinates, troposphere and Earth rotation parameters, receiver and satellite clocks as well as satellite orbit parameters. DLR/GSOC provides normal equations obtained from the multi-GNSS analysis in SINEX format including station coordinates, troposphere, and Earth rotation parameters for analysis and combination studies of the joint working group.

In last year Shanghai Astronomical Observatory, Chinese Academy of Sciences, studied the possibility of common tropospheric parameters as another 'local ties' of TRF. The work mainly includes the following:

1) We compared the tropospheric parameters obtained by different techniques at co-located sites and found the VLBI tropospheric zenith delay is approximately consistent with that of GNSS. But there exists a big constant term and a long period (about 1 year) term in the tropospheric zenith delay difference between SLR and GNSS.
2) We compared the mapping function used in SLR (FCULa mapping function) and GNSS (GMF) at all co-located sites, we found the difference is very small.
3) Compared with the strategy used in GNSS, our SLR orbit determination didn't consider estimating the ZTD parameters. So, we change our software to estimate the ZTD parameters in SLR. The results show that there are big differences between the dry zenith delay models of SLR and GNSS. We analyzed the difference and found that it is almost approximately a scaling factor between the two kinds of dry zenith delays. The factor is equal 1.061392746364195.
4) Then we compare the wet delays obtain by SLR and GNSS. And there was still a big offset exiting in SLR and GNSS zenith wet delay because the radio wavelength technique is more sensitive to water vapor in troposphere than optical wavelength technique. The SLR zenith wet delay is very small.

5) Next step, we decide to consider the effect of the horizontal gradients of atmosphere on tropospheric delay in SLR, which is described by G. C. Hulley (2007). We will adopt the parameterization used in GNSS to our SLR data processing, then estimate the horizontal gradient parameters and , finally compare them with GNSS. We will continue to find the rules of the ZTD offsets between SLR and GNSS which is of great help to apply tropospheric ties for a combination of the space geodetic techniques.

At GFZ Potsdam we installed a service which provides Numerical Weather Model (NWM) based tropospheric parameters valid for radio frequencies. The station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~800 GNSS stations. Recently we updated our ray-trace algorithm (Zus et. al 2014) in order to derive tropospheric parameters valid for optical frequencies. Therefore, station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~100 SLR stations as well. The tropospheric parameters are derived from short range forecasts and are available with no latency. The underlying NWM is the NCEP Global Forecast System (0.5 deg resolution, 31 pressure levels). The epochs 0, 6, 12 and 18UTC are based on 6h forecasts whereas the epochs 3, 9, 15, 21UTC are based on 9h forecasts. The data and a short description (how to use) are available at ftp://ftp.gfz-potsdam.de/pub/home/kg/zusflo/TRO/.

Currently we do not fully exploit the information from NWMs. For example, we use model level (or pressure level) fields but we do not take into account the near surface fields. Within this working group we will update our algorithms to extract the near surface pressure, temperature and humidity. We will derive the corresponding lapse rates which can then be used as tropospheric ties.

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Commission 2 – Gravity Field

https://www.bgu.tum.de/iapg/iag-c2/

President: Roland Pail (Germany)
Vice President: Shuanggen Jin (China)

Structure

Sub-Commission 2.1:	Gravimetry and Gravity Networks
Sub-Commission 2.2:	Methodology for Geoid and Physical Height Systems
Sub-Commission 2.3:	Satellite Gravity Missions
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Joint Working Group 2.6.1:	Geodetic observations for climate model evaluation
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Overview

This report presents the activities of the entities of Commission 2 for the reporting period 2015-2019. 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. 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 2015-2019

Commission 2 fostered and significantly supported main tasks and objectives of the present IAG period, which were expressed in the two IAG Resolutions adopted at the IUGG General Assembly 2015, Prague:

- **IAG 2015 resolution no. 1**: The realization of an International Height Reference System (IHRS)
  An executive report on the status and planned next steps for the establishment of the IHRS will be presented to the IAG and GGOS at the IUGG General Assembly 2019. I preliminary selection of IHRS reference points has been made. Processing strategies for gravity potential values are converging. The support by SC 2.2 and associated JWG 2.2.2 ("1 cm geoid experiment") has been shown to be highly beneficial.

- **IAG 2015 resolution no. 2**: The establishment of a Global Absolute Gravity Reference System
  A concept of the International Gravity Reference System (IGRS) and the corresponding Frame (IGRF) was developed. It should serve as a long-term basis to monitor the time variable gravity field as one of the keys to understanding the changing Earth and is a valuable tool observing crustal deformations and mass transports. The system definition will be completed by the end of this IAG period. The establishment of the frame shall be realized during the next IAG period 2019-2013.

Additionally, Commission 2 was also very active in supporting several IUGG resolutions:

- **IUGG 2015 resolution no. 2**: Future Satellite Gravity and Magnetic Mission Constellations

  During this IAG period, Commission 2 has been advocating future gravity field missions. It contributed and supported the satellite mission proposal *Earth System Mass Transport Mission² (e.motion²)* in response to the ESA Earth Explorer 9 (EE9) call, the proposal *Mass variation observing system by high-low inter-satellite links (MOBILE)*, and by increasing the visibility towards EU/Copernicus by co-organizing the high-impact event "Observing water transport from space – a vision for the evolution of Copernicus" (31 Mai 2017, Brussels).

- **IUGG 2015 resolution no. 3**: Global Geodetic Reference Frame (following UN Resolution 69/9)

  Commission 2 contributed to several strategy documents. It also contributed significantly and fostered the establishment of the IAG position paper on the Global Geodetic Reference System, which was accepted by the IAG EC.

Commission 2 and its elements also triggered the setting-up of new IAG Projects and Inter-Commission Committees, which shall be adopted by the IAG Council at the IUGG Montreal (2019):

- *Inter-Commission Committee on "Geodesy for Climate Research"*: This initiative was triggered by the work of the Joint Working group 2.6.1 "Geodetic Observations for Climate Model Evaluation".
- *IAG Project on "Novel Geodetic Sensors and Technologies"*: This project is based on the work of the Joint Working Group 2.1 "Relativistic Geodesy: Towards a new geodetic technique".

Commission 2 also supported further ideas on an *Inter-Commision Committee on "Marine Geodesy*, and and IAG Project on "Seismo-Geodesy".

Commission 2 also very actively contributed to GGOS-related activities. A keynote presentation at the GGOS Days 2016 on the role of gravity field products in the context of the

Global Geodetic Observing System was given, with special emphasis on height unification and integration of gravity/height into a modern GGRF concept (following the corresponding IAG position paper). Several invited papers were presented in the respective GGOS session at international conferences, such as EGU 2016 (Vienna; "Retrieving hydrological signals with current and future gravity missions"), IAG 2017 (Kobe; "Observing the Earth's gravity field as integral component of GGOS"), and IUGG 2019 (Montreal; "Global gravity field modelling as a fundamental component for the precise height determination and the monitoring of the Earth System").

Commission 2 also performed several consulting activities, e.g., regarding a recommendation on the future mission operation of Jason-2 as geodetic mission, and for several entities of GGOS, such as the Satellite Mission Standing Committee as part of the Bureau of Networks and Observations, the Bureau of Products and Standards, and the GGOS Committee on the Establishment of the GGRF. Commission 2 was also actively involved in the transition of the H2020 project European Gravity Service for Improved Emergency Management (EGSIEM) to the International Combination Service for Time-variable Gravity Fields (COST-G) as a Production Center of IGFS.

Commission 2 was involved in the organization of several scientific conferences and workshops, as well as sessions at EGU and AGU. More details on this issue will be provided in the following section.

Conferences and Meetings

Gravity, Geoid and Height Systems (GGHS) 2016, Thessaloniki, Greece

The official Commission 2 symposium was held between September 19-23, 2016, in Thessaloniki, Greece, at the premises of the Aristotle University of Thessaloniki (Figure 1). It was the first Joint Commission 2 and IGFS Symposium co-organized with GGOS Focus Area 1 "Unified Height System". GGHS2016 was composed by 6 sessions spanning the entire 5 days of the program. For GGHS2016, 211 abstracts have been received, out of which 94 have been scheduled as oral presentations and 117 as posters. 204 participants from 36 countries participated in the conference. It should be particularly emphasized that this symposium was able to attract also the young generation of scientists, since 35% of the total number of participants were either MSc Students or PhD candidates. Related papers will be published as a special volume of the IAG Symposia Series, which is currently in preparation.

Figure 1 GGHS 2016, Thessaloniki, Greece

In addition to the scientific part, GGHS2016 has also hosted a number of splinter meetings, where vibrant exchange of ideas took place. The following splinter meetings have been organized:

- IAG Commission 2 Steering Committee meeting
- IGFS meeting
- JWG 0.1: Strategy for the Realization of the International Height Reference System (IHRS)
- GGOS Committee on Satellite Missions
- GGOS Committee on Establishment of the Global Geodetic Reference frame
- SC 2.1: Gravimetry and Gravity Networks
- SC 2.2: Methodology for Geoid and Height Determination
- SC 2.3: Satellite Gravity Missions
- JSG 0.11: Multi-resolutional aspects of potential field theory
- GEOMEDII Project Meeting

IAG/IASPEI General Assembly 2018, Kobe, Japan

Commission 2 was also deeply involved in the preparation of the scientific program of the IAG/IASPEI General Assembly 2018, Kobe, Japan. The organization of the two main gravity-related sessions have been coordinated by the president ("Static gravity field") and vice-president ("Temporal gravity field") of Commission 2, and it also supported the preparation of several joint and union sessions.

Gravity, Geoid and Height Systems (GGHS) 2018, Copenhagen, Denmark

The GGHS2018 "Gravity, Geoid and Height Systems 2018" meeting was the second Joint IAG Commission 2 and IGFS Symposium. It took place in Copenhagen, Denmark, on September 17-21, 2018, at the "Black Diamond" conference building, which is part of the Royal Library of Copenhagen. Its main focus was on methods for observing, estimating and interpreting the Earth's static and time-variable gravity field as well as its numerous applications. GGHS2018 was structured in 7 sessions spanning the entire 5 days of the program. For GGHS2018, 164 abstracts have been received, out of which 87 have been scheduled as oral presentations and 77 as posters. 155 participants from 35 countries participated in the conference. It should be particularly emphasized that also the second GGHS symposium was able to attract also the young generation of scientists, since about 1/3 of the total number of participants were either MSc Students or PhD candidates.

Figure 2 GGHS 2018, Copenhagen, Denmark

IUGG General Assembly 2019, Montreal, Canada

Commission 2 contributed to the preparation of the scientific program of the IUGG General Assembly 2019, Montreal, Canada. The organization of the two main gravity-related sessions have been coordinated by the president (G02: Static gravity field and height systems) and vice-president (G03: Time-variable gravity field) of Commission 2, and it also supported the preparation of several joint and union sessions.

Further theme-specific events

During the reporting period 2015-2019, Commission 2 initiated, 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 Gravimetry and Gravity Networks

SC 2.1 together with its associated JWG 2.1.1 and SG 2.1.1 concentrated on the realization of the IAG Resolution no. 2 for the establishment of a global absolution gravity reference system, and on the realization of a Consultative Committee on Mass and Related Quantities (CCM-IAG strategy). The SC 2.1 activities also focussed on the investigation and further development of the instrumentation and methods of absolute and relative gravity measurements, including those based on cold atom technologies, showing notable developments in many parts of the world. SC 2.1 also organized the fourth IAG Symposium “Terrestrial gravimetry – Static and mobile measurements”, which was held in April 2016 in St. Petersburg, with 123 participants from 18 countries, and is currently organizing the 5th IAG symposium TGSMM-2019, to be held also in St Petersburg on 1-4 October 2019.

SC 2.2 Methodology for Geoid and Physical Height Systems

SC 2.2 contributed significantly to the activities on the realization of the IHRS, and provided active support to the respective JWG 0.1.2, addressing open issues such as agreed standards for geoid computation, and fostering further methodological development related to geoid determination and physical height systems. The associated JWG 2.2.2 on the "1 cm geoid experiment" (Colorado experiment) was very active in benchmarking various regional geoid determination approaches and assessing them, with the goal to achieve high-accuracy gravity potential values at IHRS reference stations. Another topic of interest is how to merge and validate local and regional geoid models, which is performed by JW 2.2.1.

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 time-variable field solutions, with the purpose to provide unique and user-friendly gravity products to a wider user community, was developed in the frame of the Horizon 2020 Framework Program of the European Commission, and was installed under the name COST-G as a Product Center as integral component of the IGFS infrastructure. Members of SC 2.3 initiated and actively contributed to proposals for future gravity missions in response to several ESA Earth Explorer calls. In order to increase the visibility towards EU/Copernicus and to emphasize the importance of sustained observation of gravity field changes reflecting mass transport processes in the Earth system, SC 2.3 was deeply involved in the organization of two EU events held in Brussels. Additionally, SC 2.3 contributed to the recommendations of the ESA Geodetic Missions Workshop 2017 in Banff, Canada.

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. Highlights of the reporting period are a complete re-computation of the European quasi-geoid (EGG2015) based on the newest version of global GOCE models, the generation of a new South American geoid model, and a DTM as well as a new geoid model for the whole continent of Africa. Another focus was the modernization of the US National Spatial Reference System. In almost all regions the data coverage could be improved. As an example, the first Antarctic-wide gravity anomaly dataset was published. Albeit the continuous progress, many activities still suffer from restrictions regarding data access, and also from the fact that the willingness to contribute to international (IAG) activities and data exchange is very low in several regions of the world.

SC 2.5 Satellite Altimetry

The main activities of SC 2.5 include algorithm development for processing of both conventional and new satellite altimetry missions, and the use of improved satellite altimeter data and products in various applications, such as the improvement of global marine gravity field models. SC 2.4 also focussed on the investigation of sea level, sea level change and especially sea level extremes, also connecting the results with the understanding of its causes. Special emphasis was also given to retracking solutions and calibration/validation methods to improve the performance of altimetry especially in coastal regions and for inland water applications. Another focus was on monitoring vertical land motion and glacier dynamics from altimetry. Additionally, SC 2.4 provided consultancy for the recommendation on the Jason-2 geodetic mission issue to the committee of the Jason-2 Steering Group, targeting with a densified Jason-2 ground track for a better resolution of gravity anomalies with narrow east-west content. Also it was proposed to establish an International Altimetry Service (IAS)

SC 2.6 Gravity and Mass Transport in Earth System

During 2015-2019, SC 2.6 was mainly active via its two (joint) working groups, JWG 2.6.1 "Geodetic observations for climate model evaluation", and WG 2.6.1 "Potential field modelling with petrophysical support". Together with JWG 2.6.1 and 4.3.8, a workshop on "Satellite Geodesy for Climate Studies" had been held on September 19-21, 2017 in Bonn, , with the goal to bring together geodetic experts and climate modellers, and thus to foster the use of geodetic products for climate studies. This led directly to the proposal of a new IAG ICCC (Geodesy for Climate Research).

Activities of Study Groups

There is one SG (SG 2.1.1) which reports via SC 2.1 to Commission 2, and in 8 JSGs Commission 2 is involved as a partner, but none of these reports directly to Commission 2. Their reports can be found in the ICCT section (7 JSGs), and the Commission 3 section (1 JSG).

Activities of Working Groups

1 WG and 7 JWGs are reporting to Commission 2. Their reports can be found in the corresponding chapters. Two out of these 6 JWGs (JWG 2.1, JWG 2.2) are attached directly to Commission 2, the five others to the SCs 2.1, 2.2 and 2.6, respectively. One JWG (JWG 2.1.2) has been established only recently (IAG EC no. 7, Dec. 2018). Commission 2 is involved in another JWG on the realization of the IHRS, which is reporting to GGOS.

Sub-commission 2.1: Gravimetry and Gravity Network

Chair: *Leonid F. Vitushkin (Russia)*
Vice Chair: *Akito Araya (Japan)*

Overview

In the period 2015-2019 Sub-Commission 2.1 with its Joint Working Group JWG 2.1.1, a new JWG 2.1.2 and Study Group SG 2.1.1 was concentrated on the realization of the IAG Resolution No. 2 for the establishment of a global absolute gravity reference system (IGRS) (http://www.iugg.org/assemblies/2015prague/2015_Prague_Comptes_Rendus_Part1.pdf, page 69), related work on the development of appropriated standards and on the realization of common Consultative Committee on Mass and Related Quantities (CCM) – IAG Strategy for metrology in absolute gravimetry.

The Sub-commission activities strongly focused on the investigations of the instrumentation and methods of the absolute and relative terrestrial gravity measurements, including those based on a new cold atom technologies, on the support and development of the gravity networks as well as on the development of new GAGRS.

The development of measurement techniques for gravimetry and the development of the gravity networks are interrelated. The growing number of absolute gravimeters (AG) changes the strategy in the measurement and formation of gravity networks. The superconducting gravity measurement technology makes possible permanent monitoring of temporal variations of free-fall acceleration.

Symposiums, the meetings of JWGs and WG dedicated to the topics of ToR of SC2.1 were organized in the current period including the 4th IAG Symposium "Terrestrial gravimetry. Static and mobile measurements-TGSMM-2016" in 2016 in St Petersburg, Russia and currently organized the 5th IAG symposium TGSMM-2019 also in St Petersburg on 1-4 October 2019.

Common work of Sub-commission and CCM on the establishment of traceability to SI units (Realization of CCM-IAG Strategy)

The significant aspect of the Sub-commission is the attention to the confidence in gravity measurements provided by close cooperation of Sub-commission JWGs and WG with the metrological community presented by the Working group on gravimetry (WGG) of the Consultative committee on mass and related quantities (CCM). CCM WGG, Regional metrology organizations in cooperation with SC2.1 continue the organization of the comparison of absolute gravimeters. The regional comparison of EURAMET (European Association of National Metrology Institutes) was organized [Metrologia, 2017, 54, Tech. Suppl., 07012] was organized with the participation of 4 National metrology institutes and 13 geodetic and geophysical institutes at the new campus of the University of Luxembourg in Belval in November 2015. The comparisons of AGs extended over North America and Asia. The comparison in North America organized by the CCM and SIM (Inter-American Metrology System) at the Table Mountain Observatory (Boulder, Colorado, USA) in 2016. The 10th international comparison of 30 AGs under auspices of the CCM was organized in the Changping Campus of the National institute of metrology (NIM) of China in 2017. To link these results to the European absolute gravimeters a EURAMET comparison of 16 AGs was organized at the Geodetic Observatory Wettzell, Germany in spring 2018.

It is of importance that the gravimetry sites for the comparisons can be used as the absolute gravity reference stations of the GAGRS because of high precision of the values of free-fall acceleration at these stations obtained in the comparisons. The CCM-IAG Strategy provides the possibility of calibration of AGs by means of the national primary measurement standards of acceleration unit in gravimetry (i.e. in the measurement of free-fall acceleration). For example, such a calibration of the AG FGL and AG GBL-M was performed by the primary measurement standard in gravimetry of Russian Federation and the national calibration certificates were issued. The calibrations of AGs against of national measurement standards in gravimetry allow to provide the traceability of AGs to SI units. With a growing number of AGs the calibrations will make possible to confirm the metrological characteristics of AGs without the participation in the CCM and RMO comparisons of AGs which are not always suitable because of transportation problem, time table and other problems.

Five National metrology institutes and designated laboratories have the calibration and measurement capabilities (CMC) in the field of absolute gravimetry. These are the BEV (Bundesamt für Eich- und Vermessungwesen) with the uncertainty in calibration of 10 μGal in Austria, the FGI (Finnish Geospatial Research Institute) with the uncertainty in calibration of 8 μGal in Finland, the INRIM (Istituto Nazionale di Ricerca Metrologica) with the uncertainty in calibration of 15 μGal, the METAS (Federal Institute of Metrology) with the uncertainty in calibration of 8 μGal in Switzerland and the NSC (National Scientific Centre "Institute for Metrology") in Ukraine with the uncertainty in calibration of 20 μGal (https://kcdb.bipm.org/appendixC). These NMIs have the right to issue the calibration certificates which should be recognized by 105 institutes from 59 Member States and 42 Associates of the Metre Convention and four international organizations (see information on the Mutual Recognition Arrangement of the International Committee of Weights and Measurements (CIPM) on the https://www.bipm.org/en/cipm-mra/).

Currently the outlined above uncertainties of calibration in the NMIs look higher than that which can be obtained in the international comparisons of AGs but these uncertainties of the CMCc will be hopely diminished in the future and the number of the NMI's with the CMC in absolute gravimetry will be definitely increased. The advantage of the calibration with respect to international comparisons is relatively simple access to such a procedure. With increasing number of AGs in the future (probably some hundreds) the implementation of calibrations of AG looks unavoidable at least for the AGs with the uncertainties for in the field measurements.

The IV-th and V-th IAG Symposiums "Terrestrial gravimetry. Static and mobile measurements. TG-SMM-2016" and TG-SMM-2019

The Sub-commission organized the IV-th IAG Symposium "Terrestrial gravimetry. Static and mobile measurements. TG-SMM-2016" in St Petersburg, Russian Federation on 12-15 April 2016. The slogan of the symposium was "Advancing gravimetry for geophysics and geodesy". The International Scientific Committee chaired by Vladimir G. Peshekhonov (Russia) and Urs Marti (Switzerland) consisted of the members from 12 countries. The symposium was held at the State Research Center of Russian Federation Concern CSRI "Elektropribor" from 12 to 15 April 2016. According to the field of the activities of Sub-commission 2.1 the TG_SMM-2016 consisted of four thematic sessions:

- Terrestrial, shipboard and airborne gravimetry.
- Absolute gravimetry.
- Relative gravimetry, gravity networks and applications of gravimetry.
- Cold atom and superconducting gravimetry, gravitational experiments.

The proceedings of the symposium included 43 papers. 58 presentations have been included in the program. 123 participants from 18 countries – Argentina, Austria, Brazil, China, Czech Republic, Denmark, Finland, France, Germany, Italy, Japan, Kazakhstan, Norway, Russia, Sweden, Switzerland, Ukraine, USA attended the symposium. Together with the presentations on the development of the absolute and relative gravimeters based on "familiar" physical principles and mechanisms (springs, macroscopic test objects, etc.) the quantum principles and atomic test objects (the clouds of cold atoms) used for the design of new gravity measuring instruments were a major idea of many other talks.

Next, the Sub-commission is currently organizing the V-th IAG Symposium "Terrestrial gravimetry. Static and mobile measurements. TG-SMM-2019" will be held in St Petersburg, Russian Federation on 1-4 October 2019 (http://www.elektropribor.spb.ru/en/conferences/265/). The topics of the symposium include instrumentation and methods for absolute and relative static and mobile measurement of gravity field at all kind of mobile platforms – shipborne, airborne (airplanes, helicopters, airships), satellites.

Regional activities in gravimetry

<u>South America</u>

Superconducting Gravimetry: In July 2015 the Argentine-German Geodetic Observatory (AGGO) was inaugurated (Figure 3). It is set up in La Plata city (Buenos Aires, Argentina) and it is unique in its type in South America. AGGO is a joint project between the National Scientific and Technical Research Council of Argentina (CONICET) and the Federal Agency for Cartography and Geodesy (BKG). The Observatory has new measurement instrumentation that will be part of the global infrastructure for the observation of the Earth. A superconducting gravimeter SG038 is one of the instruments installed in AGGO, currently the unique of its kind in Latin America and the Caribbean (Figure 4). SG038 data, under the name of La Plata Station, are available through the database of the International Geodynamics and Earth Tide Service (IGETS).

The absolute gravimeter FG5-227 was set up at the gravity laboratory of AGGO La Plata and monthly measurements were performed since spring 2018.

Figure 3 AGGO gravity laboratory

Figure 4 FG5-227 absolute gravimeter and superconducting gravimeter SG038 (below).

Gravimetry and Gravity networks: Considerable effort was made by the National Geographic Institute of Argentina (IGN) members on measuring, processing and publishing data belonging to new gravity control networks in Argentina:

- Absolute gravity control network (acronym in Spanish is RAGA): it is composed of 36 points measured from 2014 to 2017 using two Micro-g LaCoste A10 AGs (see http://www.ign.gob.ar/content/tipos-de-redes). This is a project of IGN in close cooperation with the Argentine National Universities of La Plata, Rosario and San Juan, the University of San Pablo and the Institut de recherche pour le développement (IRD), France.
- First order gravity network (RPO-Ar): 30 gravity monumented point stations were measured. This network consists of 229 points mostly matching monumented stations of the Argentine levelling network. The standard deviations of the adjusted gravity values are lower than 0,04 mGal.
- Second order gravity control network (RSO-Ar): 10 new point stations. RSO-AR consists of approximately 14,000 points coinciding with monumented stations of the high precision levelling network. The historical field notebooks were digitized, reprocessed and then fixed to RPO-Ar network.
- Third order gravity network in Argentina (RTO-Ar): 633 new point stations. RTO-AR is composed of about 6,000 points belonging to precision levelling lines and stations without monumentation.

First National Workshop of AGGO: The workshop was successfully held in the city of La Plata (Argentina) from April 14 to 16, 2016 with more than 80 participants. It was organized with the assistance of CONICET and RAPEAS (Argentine Network to the Study of the Upper Atmosphere). A total of 24 oral presentations were given with the main goals of exchange information, discuss ideas and establish plans of work oriented to the use of the AGGO data and products.

Europe

- *Austria:* Regular annual AG determinations are carried out on 9 stations across the country. All determinations are co-located with EPN stations with addition to other locations.
- *Czech Republic:* Currently 427 gravity stations are considered as the gravity control system. This is based upon 17 AG stations that in years 2016 – 2017 will be re-measured with the recently acquired FG5X-251 gravimeter from the Pecny Observatory. Pecny observatory also takes part in the EPOS project also in terms of gravimetry. Systematic errors of FG5/X absolute gravimeters are investigated. A new measurement system (Křen et al. 2016) has been developed that includes independent fringe signal detection system and zero-crossing determination based on FFT swept filtering (Křen et al. 2019). This system identified e.g. unaccounted distortion effect reaching up to 5 µGal in the original signal processing method used by FG5/X gravimeters. Further new methods and approaches have been developed to investigate systematic effects due to the verticality alignment, determination of Eötvös/Coriolis effect (Křen et al. 2018), coaxial cable effects (Křen et al. 2017). The most critical part is the determination of the diffraction effect (Křen and Pálinkáš 2018). The Czech Republic, has submitted CMCs for both absolute measurements and calibration of absolute gravimeters.
- *Finland:* The First Order Gravity Network of Finland, FOGN, was re-measured with the A10-020 in 2009-2010. During the measurement campaigns the measurements were controlled by visiting FG5-sites every 1-2 times/week. The FGI maintains the national measurement standard of the acceleration unit in the measurement of free-fall acceleration (AG FG5X-221). There are the comparison facilities at the Metsähovi observatory. At the observatory the old superconducting gravimeter SG-T020 stopped working in autumn 2016. The new superconducting gravimeter iOSG022 was installed in the end of 2016 and is now working well and producing high-quality data. The iGrav013 is also registering at Metsähovi since spring 2016.
- *Germany:* Since 2005 in the frame work of updating the gravimetric gravity control, more than 500 AG stations have been established with A10 absolute gravimeters by the BKG (A10-002, A10-012 and A10-033). Also 64 AG stations measured with FG5 gravimeters are established and repeated measured since 1993. The German Gravity Base Network DSGN94 was extended and named DSGN2016 by including 20 gravity sites next to GREF permanent GNSS-stations. This network DSGN2016 is now in the process of reorganization and evaluation. The German main gravity network DHSN2016 replaces now the DHSN96. The DHSN2016 field stations in general will be measured with A-10 absolute gravimeters. The DHSN2016 is now in the process of completion and evaluation. An EURAMET comparison of 16 Absolute Gravimeters was organized in spring 2018 in Wettzell to link the results of CCM.G-K2.2017 to the European absolute gravimeters. Also in 2018 the Absolute Quantum Gravimeter AQG-02 was purchased by BKG from µQuans and installed at Wettzell station in a first application. Two relative gravity and leveling networks were installed in Thuringia and Hamburg to monitor subsurface mass variations by subrosion. (Kobe, M. et al, 2019)
- *Ireland/Northern Ireland:* Expresses strong interest in establishing a new gravity network possibly based on AG techniques. A joint collaboration for both countries is planned on the whole Ireland island. As to this time there was no serious gravity network works in Ireland since IGSN71 establishment. Also there is no known gravimeter (of any kind)
- *Lithuania:* Large scale works are planned (relative surveys on nearly 700 stations) in the next years in order to update the gravity network reference level. Idea is to have 2 stations per 1 km^2. Works are planned to be performed mainly by Scintrex CG-5 gravimeters.

- *Norway:* In 2016 an A10 absolute gravimeter have been purchased by the NMA of Ireland. A plan to re-measure the Norway gravity control is planned in 2017-2019, mainly focused on the coastal areas. Firstly the A10 gravimeter was used for measurements in Ny-Alesund in a newly established geodynamical observatory. Also for the Ny-Alesund location an iGrav superconducting gravimeter is planned to be installed in 2017-2018 season.
- *Poland:* The iGrav-027 gravimeter is operating smoothly with full three years of operation behind it. Currently no surveys related to the gravity control maintenance are planned in Poland. As of beginning of the 2017 EPOS-PL project started in Poland. Within the framework of the project regular A10-020 absolute gravimeter campaigns have started in the Silesian region on active mining areas. This this time 3 independent campaigns have been performed on 10 stations. Absolute determinations will serve as reference for extensive relative gravimeter surveys on nearly 200 stations. Relative surveys will be performed with Scintrex CG5 and CG6 (purchased late 2018). This will form a hybrid gravimetric survey (AG and RG) carried out at least two times per year. Additionally within the project three gPhoneX gravimeters have been purchased (two in late 2018, one in mid 2019) and installed on mining areas for gravity variation monitoring, one unit is installed near Wroclaw. Borowa Gora Observatory is suitable for AG comparisons with 3-4 points that could be measured at the same time. Currently one internal comparison with A10-020 and FG5-230 is planned on annual basis. Other teams are much welcome to participate. In 2017 one such comparison was carried out in Borowa Gora Observatory, in 2018 one was also carried out in Jozefoslaw Observatory.

  In 2018 IGiK started cooperation with Ordnance Survey Ireland (OSi) for the establishment of a new gravity control in Ireland. Within the framework of this project a single absolute gravity (with the A10-020) and vertical gravity gradient campaing had been performed covering 27 stations in the Island of Ireland. Additionally a LaCoste&Romberg gravimeter had been setup for earth monitoring near Dublin, Ireland.

  In 2018 IGiK also with cooperation of DTU Space (Denmark) performed absolute gravity determinations on 8 stations in Denmark as well as supported the small AG comparison between A10-020 and A10-019 gravimeters at DTU.
- *Spain:* Measurement on the Spanish Absolute Gravity Network (REGA) are carried out since 2001 with A10 and FG5 gravimeters, 44 and 32 stations respectively. Additional new measurement were carried out in the recent years on the Canary Islands (1x FG5 and 49 A10 stations) and Balearic Islands (3x A10 stations).
- *Turkey:* In 2016 Turkey began a very big project for the complete renovation of the national gravity control (to be finished in 2020). The whole project estimated at 5 million Euros assumes the new measurements of the whole country with A10 and FG5 gravimeters (as reference stations) and densification surveys with Scintrex CG5 gravimeters. Within the project new A10 and FG5 gravimeters were purchased as well as 8 Scintrex CG5 gravimeters.

<u>Russian Federation</u>

A new prototype of a laser interferometric absolute ballistic gravimeter with the instrumental uncertainty of 2 microGal was developed and investigated at the D.I. Mendeleev Institute for Metrology (VNIIM), St Petersburg.

A superconducting gravimeter “GWR iGrav” № 38 was installed and put into operation in November, 2018, on the gravimetric site “Lomonosov” in the Lomonosov branch of VNIIM (40 km from St Petersburg).

Japan and Asia-Pacific

Absolute gravimetry: TAG-1 is an AG developed at ERI (Araya et al., 2014). It includes a silent-drop mechanism for a free-fall mirror and a built-in accelerometer for the correction of seismic disturbances. Accuracy of TAG-1 is evaluated from the comparative observation with FG5's carried out in April, 2016 at the Ishioka Geodetic Observing Station, GSI of Japan. TAG-1 was operated with a frequency stabilized fiber laser at 1550 nm on a trial basis to evaluate a potential to construct a network with a number of absolute gravimeters for monitoring volcanic activity. (Araya et al., 2017). In relation to the development of a compact AG, a short-distance rise-and-fall launch system for an AG is developed. The current system can throw up a mirror with 3 mm in height using a piezo-electric actuator, and its recoil reduction mechanism counteracts the vibration using a counter mass. Earth tides were successfully observed with the system (Sakai et al, 2016), and a test observation was carried out near an active volcano. Absolute gravity measurement campaigns were conducted in New Zealand in 2015-2016. In January and March 2016, the measurements using an FG5 #210 (of Kyoto University) were conducted. The measurements in North Island were made at two existing points (the Warkworth Radio Astronomy Observatory and Wellington A) and at one newly established point in Wairakei Research Centre, Taupo. The gravity measurements in South Island were made at five existing AG points of Godly Head, Mt John, University of Otago, Helipad and Bealey Hotel. To complement the AG measurements, relative measurements have been conducted in 2017, using LaCoste Romberg G-meters (#680 and #805) for most AG points and spare points as gravity connections. For planning the AG measurements in the area of 2016 Kaikoura earthquake (Mw 7.8), test measurements were carried out at a few points where huge uplifts have been observed. (Fukuda et al., 2017).

Relative gravimetry: Superconducting gravimeter observation at Ishigakijima, Japan was launched in 2012 with the purpose of detecting potential signals associated with slow slip events. To date, distinguishing slow slip signals from surface water disturbances has not been successful, because interactions between the ocean and the underground water make it difficult to model their effects on gravity. Detailed analysis taking into account the interactions between the ocean, underground water and atmosphere, and their effects on gravity was performed. (Imanishi et al., 2016). Continuous gravity data, using a Scintrex CG-3M relative gravimeter, at Arimura Observatory, Sakurajima Volcano (Kagoshima Prefecture, Japan) have been obtained to monitor volcanic activity. The gravimeter was first installed in May 2010, and it also records the tilt values of the gravimeter, which are utilized to correct the apparent gravity changes due to the tilt. Significant tilt changes associated with the volcanic event on 15 August 2015 can be identified clearly. (Kazama et al., 2016). Continuous gravimetric observations have been made with three successive generations of superconducting gravimeter (SG) over 20 years at Syowa Station (39.6E, 69.0S), Dronning Maud Land (DML), East Antarctica. Non-tidal gravity variations derived from the OSG#058 data showed significant correlation with the accumulated snow depth observed at Syowa Station. The relation between the heavy snowfall in DML and the weakening of Chandler Wobble, which were observed with OSG#058, was discussed. (Aoyama et al., 2016). Performance evaluations for a SG (iGrav #003) and a spring gravimeter (gPhone #136) were conducted at the Mizusawa VLBI Observatory of the National Astronomical Observatory of Japan in comparison with a SG TT #70. Calibration of iGrav #003 had been carried out by colocation with an AG FG5, and that of gPhone #136 was provided by the manufacturer. Colocation observation showed that amplitudes and phases of each major tidal constituent mutually agreed well. iGrav and gPhone will be deployed for monitoring volcanic activity. (Miura et al., 2017)

An *underwater gravity measurement system* using an autonomous underwater vehicle (AUV) has been developed to search for sub seafloor density signatures associated with massive ore deposits. A model calculation showed a gravity anomaly > 0.1 mGal and a gravity gradient anomaly > 10 E are expected from a survey ~50 m above a typical seafloor deposit. The system comprises a gravimeter and a gravity gradiometer mounted in AUV (Urashima, JAMSTEC) which has stable navigation performance and enough space to install both of the gravimeter and the gravity gradiometer. Operation of the system was successful for several observations in the sea, and sub seafloor gravity anomaly was estimated (Shinohara et al., 2015; Araya et al., 2015).

A portable *laser-interferometric gravity gradiometer* for volcanological studies has been developed. The gravity gradiometer measures differential accelerations between two test masses that are in free fall at different heights. Because its principle of operation is based on the differential measurements, measured values are insensitive to the motions of observation points. The laboratory test showed that its resolution of measuring vertical gravity gradients was about a few μGal/m in two seconds measurements. The prototype was moved to the Aso Volcanological Laboratory (AVL) of the Kyoto University in July 2012. Since then, its further development, to be used at an observatory in a volcanic area, has been carried out at the AVL, and trial measurements at the Sakurajima Volcanological Laboratory of the Kyoto University (Kyushu, Japa) were performed (Shiomi et al., 2015).

An *airborne gravity gradiometry survey* was conducted by the Japan Oil, Gas and Metals National Corporation (JOGMEC) in the Kuju volcano and surrounding area, Oita prefecture, Japan. The density structure modeling was conducted using gravity data and the six components of airborne gravity gradiometry data. The high-density (2400 –2550 kg/m^3) areas were estimated below the middle and late Pleistocene volcanoes in the southern part of the study area at a depth of 0 to 2000 m below sea level. These high-density areas correspond to the distributions of the older Hohi volcanic rocks (Nishijima and Yanai, 2016).

Geopotential measurements with an uncertainty of 5 cm were demonstrated by determining the height difference of master and slave optical lattice clocks separated by 15 km. A subharmonic of the master clock laser is delivered through a telecom fiber to synchronously operate the distant clocks. Taken over half a year, 11 measurements determine the fractional frequency difference between the two clocks to be $1{,}652.9(5.9)\cdot 10^{-18}$, consistent with an independent measurement by levelling and gravimetry (Takano et al., 2016).

Gravity networks: Geospatial Information Authority of Japan (GSI) established a new gravity standardization network of Japan, named the Japan Gravity Standardization Net. 2013 (JGSN2013), from the latest AG and relative land gravity measurements covering the whole country. The accuracy of JGSN2013 is evaluated around 10 μGal in standard deviation from the residuals of network adjustment and the leave-one-out cross validation, and this means that the JGSN2013 achieves more accurate gravity standard than the former gravity standard, the Japan Gravity Standardization Net. 1975 (JGSN75), by an order of magnitude. (Miyazaki, 2016). GSI of Japan constructed a gravity measurement facility for domestic comparison of AGs at the Ishioka Geodetic Observing Station, GSI of Japan. The granite test bench in the facility is firmly coupled to the support layer with concrete piles and is isolated from the building in order to reduce the effect of ground vibration. It is designed to set up six AGs simultaneously on each point that has precise coordinates determined by GNSS and leveling before the construction. Since the Ishioka station also has the VLBI facility, the distributed hydrogen maser's signal can be used to minimize clock errors between AGs (Kato et al., 2017).

Conclusions on the currents state of measurement techniques in gravimetry and on the development of gravity networks

Recently there is a growing number of absolute gravimeters and absolute determinations of free-fall acceleration. There is a progress in the elaboration of absolute gravimeters including that based on a cold atom gravimetry are under the development. Several reports inform on the renovation of gravity networks and on the establishment of new gravity networks over the world. New gravity measurement techniques as gravity gradiometers and the techniques of geopotential measurements based on the precise quantum (cold atoms, cold ions) clocks are under the development. The number of gravimetry sites with collocated AG, superconducting gravimeter and terrestrial GNSS stations increases. Despite of increasing role of absolute AG measurements in the gravimetry survey the role of relative gravimeters is still significant.

Nevertheless, some remarks should be made. The realization of the CCM-IAG strategy in metrology for absolute gravimetry is not completed and it does not cover all the geodetic services and it is not implemented to all geodetic projects related to gravity measurements. There are only a few cases of calibration of absolute gravimeters. Not all the gravimetry teams participate in the comparisons of AGs or calibrate their AGs. There is a progress in the improvement of AGs as the increased repeatability in the measurements free-fall measurements with a cold atom gravimetry and in the improvement of laser interferometric absolute gravimeters. However, there are still the needs for further investigations of the sources of the instrumental systematic uncertainties in the measurements using the AGs. There is still the need for the development of improved more compact AG for in the field gravity measurement.

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Study Groups of Sub-commission 2.1:

SG 2.1.1: Techniques and metrology in terrestrial (land, marine, airborne) gravimetry

Chair: *Derek van Westrum (USA)*
Vice Chair: *Christoph Förste (Germany)*

Members

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- *Ludger Timmen (Germany)*
- *Michel Van Camp (Belgium)*
- *Leonid Vitushkin (Russian Federation)*

Activities and publications during the period 2015-2019

New technologies

The preparation for the "Very long baseline atom interferometer" (VLBAI, 10 m atomic fountain) at the Hannover Institute for Technology (HITec) of the Leibniz Universität Hannover has progressed so far that the implementation of the VLBAI in the HITec building already started. The long-term geodetic objective is to perform stationary absolute measurements of gravity and its derivatives with resolutions exceeding the presently available possibilities of classical instruments by several orders of magnitude. In the future, this VLBAI fountain as an instrument with "higher order accuracy" should take a central role for the definition of gravimetric reference networks in central Europe and the gravimetric datum definition. It will serve for verification of transportable absolute meters w.r.t. their long-term stability. For more information go to https://www.geoq.uni-hannover.de/a02.html, and https://www.iqo.uni-hannover.de/vlbai.html.

Gravity applications

The gravity program at the United States Geological Survey (USGS) Arizona Water Science Center has become the "Southwest Gravity Program", as expanding into adjoining states. The primary product is network-adjusted relative- and absolute-gravity measurements of gravity change over time, as related to hydrologic processes. To facilitate rapid data analysis and network adjustment, GSadjust software has been developed, based on the PyGrav software

(Hector and Hinderer, 2016), but with additional GUI elements for drift correction and network adjustment. Current projects are in Albuquerque and Las Cruces, NM; Tucson, Prescott, and northwestern AZ; and Imperial Valley, CA. A website with software (both in-house and external), references, and a bibliography has been developed (http://go.usa.gov/xqBnQ). Efforts to publish data to the web (including integration with AGrav database) are ongoing.

Activities Reported by Members of the Study Group 2.1.1

Germany

Gravimetry activities at TU Darmstadt (PSG): Over the past four years, PSG took part in several airborne gravimetry campaigns. The focus of our research is the use of strapdown inertial measurement units (IMU's) for kinematic gravimetry in general, rather than using the classical, platform-stabilized spring-gravimeters. IMU's offer many operational advantages, as low power- and space consumption and an autonomous operation during the flights. Strapdown gravimetry supports the determination of 3-D gravity (i.e., including the deflection of the vertical).

Strapdown airborne gravimetry for geoid determination: With the focus of geoid determination, PSG took part in the following campaigns:

- 2013: Mid- and North-Chile
- 2014 and 2015: Two offshore-campaigns in the South Chinese Sea (Malaysia)
- 2015: Northwest Mozambique and Malawi
- 2015/2016: Antarctica: The PolarGap campaign

These campaigns were carried out in cooperation with the Technical University of Denmark (DTU Space). For all these campaigns, PSG's iMAR RQH-1003 strapdown IMU was flown side-by-side with a classical LaCoste and Romberg S-type sea/air gravimeter, allowing a direct comparison of the two sensors. It could be shown, that mainly thermal drifts of the Honeywell QA-2000 quartz accelerometers prevent the IMU from a gravity determination at the milligal level in the longer wavelengths (hours). The main research focus since 2014 was the design and evaluation of IMU calibration schemes, which are able to circumvent such drifts (Becker 2016; Becker et al. 2015a). This research was very successful: The cross-over precision could be reduced from several mGal down to 0.9 – 1.1 mGal for the four non-polar campaigns, thereby showing similar or even superior results compared to the LCR S-type gravimeter (Becker 2016; Becker et al. 2016). For the PolarGap campaign, the stand-alone IMU gravity reached a precision of 1.8 mGal after applying the correction. It is still an open question what was the limiting factor compared to the campaigns at lower latitudes, e.g. the stronger temperature changes, or the lower GNSS satellite elevation (leading to a significantly larger VDOP). For all of the abovementioned campaigns, it could be shown that the iMAR sensor was barely sensitive to even strong turbulence, being another important operational advantage compared to the classical systems: This can be cost-saving in production-oriented campaigns, as less lines (or even no lines!) need to be repeated any more due to strong turbulence.

Strapdown airborne gravimetry for geology and geophysics: In the Antarctic summer 2016/2017, PSG cooperated with British Antarctic Survey (BAS) in the scope of the Filchner Ice Shelf System project. For a total of 24 flights, the iMAR RQH sensor was the only gravity sensor on board the survey aircraft. Since the main focus of these survey flights was set on radar measurements for geophysical mapping and research, the flights had to be performed in drape-flyingmode, i.e. the aircraft altitude above ground was approximately maintained at a constant level. Such flights can be difficult for the classical spring-based gravity sensors, as strong gravity changes arising from altitude changes above sea level may exceed the sensor range for short-term gravity variations. There is no such limitation for the strapdown systems. The processing of this data is still in progress; first results however already indicate, that the drape-flying does not reduce the achievable accuracy of the strapdown gravity results. A cross-over precision of approximately 1.7 mGal could already be achieved, which is however again significantly lower compared to the non-polar campaigns listed above. It is again unclear if the precision is mainly limited by the VDOP in the standard PPP processing.

Future technologies: verification of absolute gravimeters, collaboration with metrology community for future sensors: The preparation for the "Very long baseline atom interferometer" (VLBAI, 10 m atomic fountain) at the Hannover Institute for Technology (HITec) of the Leibniz Universität Hannover has progressed so far that the implementation of the VLBAI in the HITec building can start in autumn of this year. The long-term geodetic objective is to perform stationary absolute measurements of gravity and its derivatives with resolutions exceeding the presently available possibilities of classical instruments by several orders of magnitude. In the future, this VLBAI fountain as an instrument with "higher order accuracy" should take a central role for the definition of gravimetric reference networks in central Europe and the gravimetric datum definition. It will serve for verification of transportable absolute meters w.r.t. their long-term stability. For more information go to https://www.geoq.uni-hannover.de/a02.html, and https://www.iqo.uni-hannover.de/vlbai.html.

Promotion and coordination in the establishment and measurements of regional gravity networks: new gravity reference in Mexico 2016: Within a joint project of the Instituto Nacional de Metrología en Méxicol (CENAM), the Gottfried Wilhelm Leibniz Universität Hannover (LUH), and the Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM), the measurement of nine first order gravity stations employing the reference FG5X-220 free-fall absolute gravity meter of the LUH were complete (Esparca et al. 2017). The field campaign took place from February 22th to March 14th of 2016, exactly 20 years after the last absolute gravity campaign was completed in Mexico. The measuring campaign started in the National Laboratory of micro-Gravimetry (LNG), with a mutual comparison between the LUH´s FG5X-220 and the CENAM´s FG5X-252, at the beginning and end of the field campaign, the later worked out as base station. Besides a successful instrumental comparison, we increased the existing network of gravity stations, four of which had been measured 20 years ago by NOAA in a tectonically active region of Mexico known as the Jalisco Block (JB).

Figure 5 Collaboration with metrology community: Gravity field measuring and modelling for optical clock comparisons

Collaboration with metrology community: Gravity field measuring and modelling for optical clock comparisons: A coordinated program of clock comparisons has been carried out within the EMRP-funded project "International Timescales with Optical Clocks" (ITOC, 2013-2016), aiming at a validation of the uncertainty budgets of the new optical clocks with regard to an optical redefinition of the SI second (Figure 5). As optical clocks are now targeting a relative accuracy of 10^{-18}, corresponding to a sensitivity of about 0.1 m^2/s^2 in terms of the geopotential or 0.01 m in height, precise knowledge of the gravity potential is required at the respective clock sites. Alternatively, optical clocks may also be employed for deriving the gravity potential (denoted as "chronometric levelling" or "relativistic geodesy") and hence offer completely new options for geodetic height determination. The ITOC project involves clock sites at the national metrological institutes (NMIs) in France (OBSPARIS, LNE-SYRTE), Germany (PTB), Italy (INRIM), the United Kingdom (NPL), and an underground laboratory in France near the Italian border (LSM, Laboratoire Souterrain de Modane). Absolute and relative gravity observations were carried out by the gravimetry group of LUH around the clock sites and then used to compute an updated quasigeoid model.

Finland

Marine gravity measurements: The Finnish Geodetic Institute (FGI) is participating in the FAMOS project 'Finalising Surveys for the Baltic Motorways of the Seas' (www.famosproject.eu). The project is a cooperation between 15 hydrographic and geodetic organizations of 7 Baltic Sea countries and it is co-funded by the European Union Connecting Europe Facility. In Activity 2 of the project marine gravity surveys are carried out in different parts of the Baltic Sea. A marine gravity survey took place in 2015 in the Bothnian Sea on a Finnish vessel (Bilker-Koivula et al. 2015).

Absolute gravity measurements: FGI continue doing repeated FG5X absolute gravity measurements in Finland for land uplift studies and monitoring. This year we will also do FG5X absolute gravity measurements in Lithuania and Estonia. The FGI will participate in the ICAG2017 that will take place in China in autumn.

In the Finnish Academy funded project GRAVLASER -'Improved absolute gravity measurements in the Antarctic' the aim is to deepen the knowledge of cryosphere-lithosphere interaction in Antarctica and to improve current and future scenarios of the Antarctic ice sheet contribution to global sea level rise. The project involves, among other things, measurements of absolute gravity change with the FG5X absolute gravimeter and development of novel laser scanning methods.

Superconducting gravity measurements: The iOSG022 superconducting gravimeter was successfully installed at the Metsähovi observatory and is now working well and producing high-quality data. In addition we the iGrav013 portable superconducting gravimeter was acquired. For now it is operating in Metsähovi alongside the iOSG022.

Russian Federation

A new prototype of a laser interferometric absolute ballistic gravimeter with the instrumental uncertainty of 2 microGal was developed and investigated at the D.I. Mendeleev Institute for Metrology (VNIIM), St Petersburg. Superconducting gravimeter "GWR iGrav" № 38 was installed and put into operation in November, 2018, on the gravimetric site "Lomonosov" in the Lomonosov branch of VNIIM (40 km from St Petersburg).

USA

The gravity program at the United States Geological Survey (USGS) Arizona Water Science Center has become the "Southwest Gravity Program", as we expand into adjoining states. The primary product is network-adjusted relative and absolute gravity measurements of gravity change over time, as related to hydrologic processes. To facilitate rapid data analysis and network adjustment, the GSadjust software was developed, based on the PyGrav software (Hector and Hinderer, 2016), but with additional GUI elements for drift correction and network adjustment. Current projects are in Albuquerque and Las Cruces, NM; Tucson, Prescott, and northwestern AZ; and Imperial Valley, CA. A website with software (both in-house and external), references, and a bibliography was launched at http://go.usa.gov/xqBnQ. Efforts to publish data to the web (including integration with AGrav database) are ongoing.

TAGS7 Gravimeter on "Optionally Piloted" Aircraft as a UAV test: In March 2017, the National Geodetic Survey (NGS) began its first operational survey using the Aurora Centaur Optionally Piloted Aircraft for its Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project. The survey operated for about a month, collecting data primarily over western North Carolina and eastern Tennessee. In the future, it is envisioned that operating such aircraft autonomously will reduce costs, increase efficiency, especially in difficult to reach areas.

Geoid Slope Validation Survey in Southern Colorado, Summer 2017: NGS conducted its third and final Geoid Slope Validation Survey in the mountains of southern Colorado in the summer of 2017. This multi-technique project consists of classic leveling, long-session GPS, astro-geodetic deflection of the vertical observations, absolute gravity measurements, and vertical gravity gradient determinations at over 200 bench marks, spaced at about 1.5 km east to west along highway US 160. The purpose is to compare geoid shape accuracies of various models, as well as quantify the contribution of the airborne gravity data acquired as part of the GRAV-D project. At each site, an A10 is used to determine the absolute gravity value, and a new Scintrex CG-6 is used to measure quadratic gradient.

Geopotential survey of NIST Optical Clock Laboratories, Summer 2015: NGS has established six new bench marks in and around various atomic clock laboratories at the NIST Boulder,Colorado campus. Classical leveling (<1 mm local, relative accuracy, and ~2 cm "global" accuracy) and absolute gravity measurements were used to determine heights, gravity values, and geopotential differences between the bench marks. The geopotential differences can be used directly – and immediately – to calculate the expected frequency shifts between the laboratories. After the GRAV-D airborne campaign is complete in 2022, NGS will define a new vertical datum for the United States. At that point it will be easy to provide geopotential numbers referenced to the geoid, accurate to the ~2 cm level. As continent-scale networks of linked optical clocks become feasible, these absolute geopotential values will be critical for direct clock comparisons.

France

Concerning atom sensor/gravimeter developments, there are currently about 10 institutes in the world and two companies (µQUANS and AOSENSE) developing such systems, but most are still under improvements in terms of accuracy and compactness (example: some sensors now use atom chips. There are also some studies into the development of gradiometers, and space programs (or studies) to use gradiometer in space (ESA, CNES, NASA). SYRTE is developing a new sensor, a demonstrator for space (https://syrte.obspm.fr/spip/science/iaci/projets/gradio/), Humboldt Univ Berlin is adapting its atom gravimeter to launch two clouds, Lens (Firenze) has developed one few years ago, and in China (Wuhan) gravimeters are used to make a gradiometer too.

Also, the MIGA project, whose ultimate goal is to detect gravitational waves with atom gradiometer, will have interest for geoscience (https://arxiv.org/pdf/1703.02490.pdf).

About the CAG, the accuracy is still 43 nm/s^2, sensitivity is 57nm/s^2 in 1s of measurement and 0.6nm/s^2 in 1/2 day. Current effort is now aimed at reducing the uncertainty to 10 or below 10nm/s^2.

It measured gravity continuously last month for the LNE Kibble balance (previously watt balance) to measure the Planck constant linked to kilogram to participate to the new definition of the kilogram which was adopted at the General conference on weights and measures (XXVI-th CGPM-2018) in November 2018.

Czech Republic

Long-term regional and local water storage changes (that cannot be captured by satellites) are interesting for many hydrologists. Superconducting gravimeters are used for supporting they research, but there might be also huge space for utilization of absolute gravimeters instead. In this respect, at VUGTK one tries to distinguish between the most critical components of error sources for FG5/FG5X gravimeters together with improvements in optics and electronics. In such a way one can contribute to contribute on the accuracy improvement of gravimeters based on laser interferometry.

Systematic errors of FG5/X absolute gravimeters are investigated. A new measurement system (Křen et al. 2016) has been developed that includes independent fringe signal detection system and zero-crossing determination based on FFT swept filtering (Křen et al. 2019). This system identified e.g. unaccounted distortion effect reaching up to 5 µGal in the original signal processing method used by FG5/X gravimeters. Further new methods and approaches have been developed to investigate systematic effects due to the verticality alignment, determination of Eötvös/Coriolis effect (Křen et al. 2018), coaxial cable effects (Křen et al. 2017). The most critical part is the determination of the diffraction effect (Křen nad Pálinkáš 2018). The Czech Republic has submitted CMCs for both absolute measurements and calibration of absolute gravimeters.

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Joint Working Groups of Sub-commission 2.1:

JWG 2.1.1: Establishment of a global absolute gravity reference system

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

Members

- *Jonas Ågren (Sweden)*
- *Henri Baumann (Switzerland)*
- *Mirjam Bilker Koivula (Finland)*
- *Jean-Paul Boy (France)*
- *Nicholas Dando (Australia)*
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- *Diethardt Ruess (Austria)*
- *Victoria Smith (UK)*
- *Ludger Timmen (Germany)*
- *Michel van Camp (Belgium)*
- *Derek van Westrum (USA)*
- *Leonid Vitushkin (Russia)*
- *Shuqing Wu (China)*

Activities and publications during the period 2015-2019

International gravity reference system and frame

Following the Resolution No. 2 of the IAG at the XXVI General Assembly of the IUGG in 2015, a concept of the International Gravity Reference System and Frame was developed. It should serve as a long-term basis to monitor the time variable gravity field as one of the keys to understanding the changing Earth and is a valuable tool observing crustal deformations and mass transports. In accordance with other geodetic reference systems and frames the acronyms IGRS/IGRF were fixed.

Definition of System and Frame

The definition of the reference system (IGRS) reflects the fundamental principles and must be stable over time. It is based on the momentary acceleration of free fall and on the traceability to the International System of Units (SI). It is completed by a set of conventional corrections for the time independent components of gravity effects: The tide system (zero tide), standard atmosphere[1] for the normal air pressure and the IERS reference pole.

[1] DIN5450 (ISO 2533:1975)

The reference frame (IGRF) as the realization of the system is based on observations with absolute gravimeters (AG) which are monitored at reference stations. The achieved uncertainty for measurement at reference stations should be better than 10 µGal, including systematic effects.

The frame describes the reduction of temporal gravity variations. To ensure a long term stable and common reference level and the compatibility of all observations, comparisons of AG need to be performed on a regular basis on different levels, following the CCM – IAG Strategy for Metrology in Absolute Gravimetry[2]. The basis are the key comparisons under the auspices of the International Committee for Weights and Measures (CIPM). The equivalence of each AG used for the IGRF must be documented by comparison results.

A set of conventional models for the correction of temporal gravity changes is selected, covering the Earth tides, ocean tide loading, atmospheric variations and polar motion. The recommended models are based on the Processing Standards of the International Absolute Gravimeter Base Network (IAGBN), which are widely used today. Vertical gravity gradients (VGG) are essential to transfer the measured value to the reference height and are part of the reference frame. The determination of the VGG is required for each IGRF station. An epoch needs to be assigned to each AG observation. Applied corrections for systematic effects, like self-attraction and diffraction need to be documented.

A regular re-observation of the reference frame is currently not planned but IGRF stations need to be maintained and kept accessible. Systematic long term gravity changes, e.g. due to post glacial rebound, are not part of the frame definition.

A common standard exchange format for AG observations and processing software are subject of JWG 2.1.2: Unified file formats and processing software for high-precision gravimetry which was initiated out of this JWG and established in December 2018.

Infrastructure

The main infrastructure of the IGRF is formed by gravity stations of three different types:

a) <u>Reference stations</u> are essential to ensure a long term stable reference level by monitoring AGs. A continuous gravity reference function should be provided by a superconducting (SG) and/or quantum gravimeter or by repeated AG observations. The reference function is represented by the residual gravity time series after reduction of site specific effects (Earth and ocean tides, atmosphere, polar motion). If a continuous monitoring is not possible, repeated AG observations every two months are recommended to capture seasonal variations. For stations operating a SG, it is recommended to perform AG observations every two years for the determination of the SG instrumental drift.

b) <u>Comparison stations</u> are reference stations as described in a) which allow for a simultaneous measurement of at least two AGs. The main purpose is to check the compatibility of instruments. Calibration of an AG serves as a tool to document significant systematic deviations in order to improve or restore the compatibility and should follow the CCM – IAG Strategy for Metrology in Absolute Gravimetry.

c) <u>Core stations</u> provide a link to the terrestrial reference frame (ITRF), where GGOS core sites play an important role. Core stations are reference stations described in a) where at least one

[2] https://www.bipm.org/wg/CCM/CCM-WGG/Allowed/2015-meeting/CCM_IAG_Strategy.pdf

space geodetic technique is established. It is therefore recommended to continuously monitor temporal gravity variations and to repeat absolute gravity observations at all GGOS core sites.

Potential IGRF stations are more than 20 active sites of the International Geodynamics and Earth Tide Service (IGETS), where superconducting gravimeters are operated. Further, about 60 stations of the proposed realization of the International Height Reference System (IHRS) were identified as potential collocation sites. A connection to the national levelling networks is recommended and GNNS should be collocated to monitor vertical displacements. The selection of a global set of stations to realize the IGRF based on updated site requirements should be subject of future efforts.

To make the IGRF accessible to users, an infrastructure of absolute gravity stations needs to be built up, forming a modern-day functional equivalent of the IGSN71. This requires the support and cooperation of National agencies, which are encouraged to establish compatible first order gravity networks, preferably based on AG observations, and to provide the relevant information.

Documentation and Data Inventory

All IGRF stations need be documented in the database AGrav which is jointly operated by BGI and BKG. At least one observation epoch should be available for each station. Repeated observations as required for reference stations should be made available in AGrav. Results of all AG comparisons will be documented in AGrav, extending the information available from the BIPM key comparison database KCDB.

Digital object identifier (DOI) will be assigned by BGI for AG observations stored in AGrav based on the prefix `10.18168/BGI.DB_AGrav` to data providers, network of stations and AG comparison epochs.

The International Database AGrav

The International Database on Absolute Gravity Measurements will serve as an inventory for the absolute gravity reference system (Figure 6). An extension of the database scheme to store comparison results was presented at the IAG symposium on Terrestrial gravimetry 12-15 April 2016, Saint Petersburg, Russia and published in the proceedings. A first impression on the realization of these updates were presented at the International Symposium on Gravity, Geoid and Height Systems (GGHS) 2016, Sept 19-23, 2016 Thessaloniki, Greece, and further progress at the EGU General Assembly 2017 in Vienna, Austria where a prototype was presented as live application.

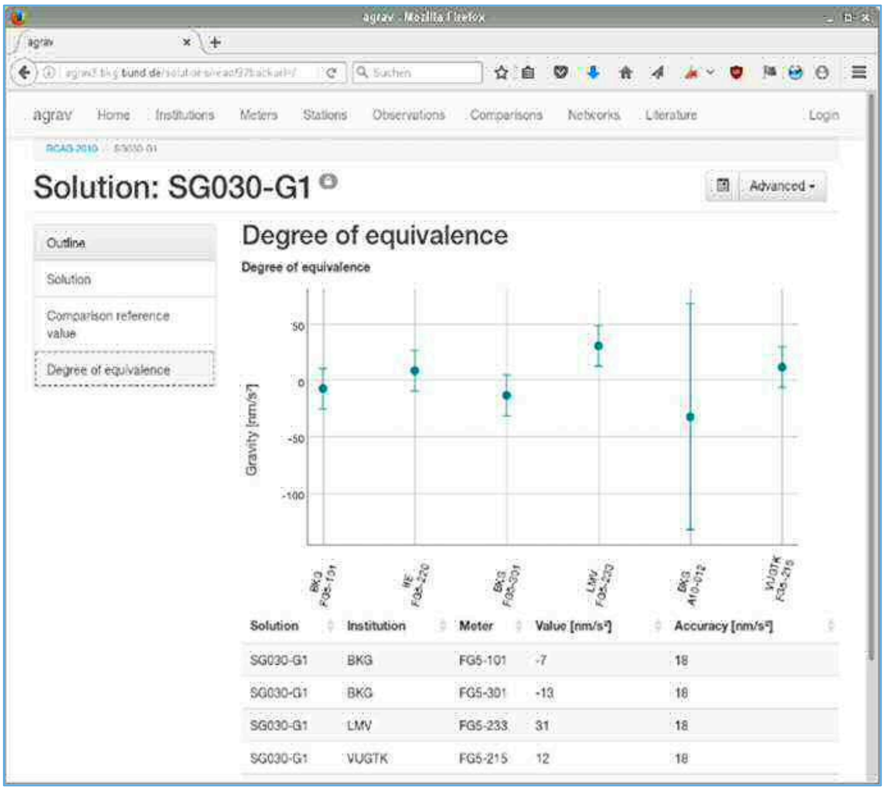

Figure 6 Presentation of the results from the Regional Comparison of Absolute Gravimeters at Wettzell, 2010 in the AGrav database. The degree of equivalence of the participating AGs relative to the reference function obtained from the superconducting gravimeter SG030 is shown.

Meetings of JWG 2.1.1

Working group meetings were held on Sept. 20th 2016 in Thessaloniki, Greece (GGHS), on Apr. 27th 2017, Apr. 11th 2018 and on Apr. 10th 2019 at the EGU General Assembly in Vienna, Austria, and on Sep. 20th 2018 in Copenhagen, Denmark (GGHS 2). At these meetings, the concept of the reference system and frame, the selection of reference sites and data processing were discussed. The results are summarized in minutes which were circulated among members and participants

Primary network of reference stations

A reference station should ideally provide an absolute gravity value at any time at the microgal level with an historical record of the local gravity changes and of the gravity measurement instrumentation in use. The gravity value should be obtained from repeated absolute gravity measurements with an accuracy at the microgal level with instruments that are linked to international comparisons of gravity meters. The reference station should then allow a comparison with another gravimeter at any time.

Temporal gravity variations should be monitored continuously by a superconducting gravimeter (SG), or in future, by an absolute cold atom gravimeter. Stations with repeated (conventional) absolute gravity measurements should be considered as well, e.g. station Matera/Italy, where FG5 observations are carried out on a weekly basis and which was discussed in particular. A recommendation on the minimum number of observations per year should at least cover seasonal variations, which would require e.g. 6 observations per year. Further, there is no need to maintain or occupy a reference station permanently, if easy access is granted. Complementary to the gravity observations, monitoring of height changes from GNSS measurements at the reference station would be necessary.

Reference stations with colocated gravity and geometric measurement instrumentation where several space geodetic measurements are performed (e.g. GNSS, VLBI, SLR…) might correspond to GGOS core sites. GGOS core sites should be linked to the GAGRS by continuous monitoring of gravity changes and repeated absolute gravity observations.

The data from all reference stations should be documented in the AGrav database.

To define a global set of reference stations, it is proposed to re-evaluate the positive response and update the results of the survey of 2011, addressed to the absolute gravity community and the Global Geodynamics Project (GGP, today IGETS). At this time, 36 stations were proposed. Some of these stations should also correspond to GGOS core sites.

International or regional comparisons stations

A comparison site is a reference station which provides extended facilities to allow the comparison of several absolute gravimeters. Monitoring of temporal gravity changes during the comparison is mandatory.

Secondary network: Infrastructure for an absolute gravity reference network

To replace IGSN71, an infrastructure must be established. It was a consensus among the participants, that it is not feasible and not necessary to comprehensively re-observe or evaluate the IGSN 71 network. As IGSN71 has served as a reference for a large number of relative gravity surveys, such evaluation may be very important for e.g. regional purposes, but is best performed by the pertinent national institutions.

Instead, new infrastructure based on absolute gravity observations performed worldwide by national institutions should be set up. It was recommended that all gravimeters take part in comparisons to ensure the best compatibility with the absolute gravity system and traceability to SI units. Absolute gravity stations should be divided into different levels depending on the uncertainty of the gravity observations, reaching from the field-level (e.g. A10 surveys) to the lab-level (FG5-type instruments).

National agencies should be encouraged to establish compatible first order networks, if necessary in international cooperation with institutions operating absolute gravimeters.

Generally all relevant data should centrally archived and documented in the AGrav database, which is currently extended and updated with a new web application. The data should be accessible to any user.

Standard models and corrections

Current practice on the correction of time variable gravity effects was discussed. A set of standard correction models should be proposed for less experienced users. In particular, for ocean tide loading, most recent models like FES 2014 should be used, the coefficients can be obtained from the ocean tide loading providers of M.S. Bos and H.-G. Scherneck. It was noted that this would result in an inconsistency with the current IERS conventions which recommends FES2004.

A homogenization of gravity corrections in post processing is only possible, if at least set-, better drop-files are provided and archived in the AGrav database. It should checked, if such functionality could be implemented into AGrav and if the users accepting to contribute these data.

Further activities of JWG 2.1.1

Recently, a first order gravity network in Mexico was newly established. For the latter, nine gravity stations employing the reference FG5X-220 free-fall absolute gravity meter of Leibniz Universität Hannover (LUH), Germany were measured from February 22th to March 14th of 2016 within a joint project of the Instituto Nacional de Metrología en Méxicol (CENAM) and Universidad Nacional Autónoma de México (UNAM).

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JWG 2.1.2 Unified file formats and processing software for high-precision gravimetry

Chair: Ilya Oshchepkov (Russia)
Vice chair: Vojtech Pálinkáš (Czech Republic)

Members

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- *Jacques Liard (Canada),*
- *Jeffrey Kennedy (USA),*
- *Jaakko Mäkinen (Finland),*
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- *Christian Ullrich (Austria),*
- *Axel Rülke (Germany),*
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- *Alessandro Germak (Italy),*
- *Shuqing WU (China),*
- *Derek Van Westrum (USA),*
- *Mirjam Bilker-Koivula (Finland)*

Acitivities and publications during the period 2015-2019

The joint working group was created in December 2018 from an open source software initiative in high-precision gravimetry within the JWG2.1.1. The following are the results achieved so far.

Meetings

The first and only meeting was held at EGU General Assembly in Vienna, Austria on April, 8 2019. There were presented two new projects that will, in the future, fulfill the main objectives of the working group. The first project is GINEF – Gravimeter Independent Exchange Format. The most important requirements for the format were discussed at the meeting. The second project is *gMeterPy*, a unified gravity processing software written in Python. The development environment were shown and details on how to use it were briefly discussed. The concept of raw data has also been discussed, as well as the necessity to reprocess them with independent software. The results of the questionnaire about gravimeters and their data formats, previously sent to members of the working group, were presented. It is noteworthy that among the participants of the working group there are all types of modern absolute gravimeters (free fall, rise and fall and quantum) of different manufacturers. The vast majority uses standard programs and processing methods. The responses of two commercial manufacturers, Micro-g LaCoste and MuQuans, have shown that they do not mind opening the raw data format.

Data levels

High – precision gravity data from gravimeters can usually be divided into several levels.

- Meta level: station, instrument, processing options and other details.
- Level 0: raw data, which can be reprocessed from scratch. These can be fringe signals or recordings from a feedback system.
- Level 1: time – series of gravity measurements. The drop data or readings from superconducting or relative gravimeters can always be represented as a time-series of measured values with different environmental or instrumental corrections. Corrections can be either time – dependent or independent. The different indexes, apart from time, should distinguish data from different gravimeters and stations or, for example, sets. Only corrections can be reprocessed at this level.
- Level 3: final gravity (small "g") value. Only some corrections can be reprocessed.

True reproducibility of the results is possible if and only if there is an access to level 0.

GINEF – Gravimeter Independent Exchange Format

The idea behind GINEF is exactly the same as for RINEX and/or SINEX for GNSS and space geodesy data. There are many different gravimeters, but they measure the same quantity of gravity (small "g"). There must be some way to present the data uniformly. This will be based on the data levels presented above. The GINEF format should be ASCII based set of files with meaningful and unique names. Archiving support is possible to save space. The time system is UTC without time zones support. The GINEF format should store raw data, time – series data, processing procedures and processing results, including normal equations for the network adjustment or individual time-series, like in SINEX file.

gMeterPy – Processing gravity measurements with Python

gMeterPy is an open source and free (MIT License) Python library/framework for processing measurement data from gravimeters, which are used for gravity field surveys in geodesy, geophysics and other branches of Earth and planetary sciences. The main intention is to go as deep as possible in processing **raw** data from scratch, as well as to support all types of instruments, corrections, common file formats and processing procedures. The project is hosted at GitHub (https://github.com/opengrav/gmeterpy) and the documentation is hosted at Read The Docs (https://gmeterpy.readthedocs.io). The gMeterPy processing software should realize standard models and corrections for the International Gravity Reference System/Frame (IGRS/IGRF) and should be able to process gravity measurements from the most widely used gravimeters, but with possible extension to any other instrument. No GUI interface is planned for now. The first test version 0.0.1 is already out.

Sub-commission 2.2: Methodology for Geoid and Physical Height Systems

Chair: *Jonas Ågren (Sweden)*
Vice Chair: *Artu Ellmann (Estonia)*

Overview

The IAG Sub-Commission 2.2 (SC 2.2) promotes and supports scientific research related to methodological questions in geoid determination and physical height systems, both from the theoretical and practical perspectives, concentrating particularly on methodological questions contributing to the realisation of the International Height Reference System (IHRS) with the required sub-centimetre accuracy. SC 2.2 is the only SC of Commission 2 that deals with physical height systems. It differs from SC 2.4 ("Regional geoid determination") and its subcomponents in that it concentrates on methodological questions for geoid determination in the context of the realisation of physical height systems, particularly on the now on-going realisation of IHRS (Sánchez et al. 2016; Ihde et al. 2017).

A first SC 2.2 constituting splinter meeting was organized at the 1st Joint Commission 2 and IGFS International Symposium on Gravity, Geoid and Height Systems 2016 in Thessaloniki, Greece.

An early activity was to start up the Joint Working Group 2.2.2 (JWG 2.2.2), "The 1-cm Geoid experiment", together with the International Service for the Geoid (ISG) and the Inter-commission Committee on Theory (ICCT). This working group primarily aims at developing geoid determination methodology by benchmarking different regional geoid determination methods (developed by different groups or so-called "schools") through computations on common test datasets, most notably in a test area in Colorado covering the US Geoid Slope Validation Survey 2017 (GSVS17). The latter comparison is called the Colorado 1 cm geoid experiment below; cf. the JWG 2.2.2 report below.

The most crucial activity of SC 2.2 has been to support the JWG 0.1.2 with the "Strategy for the Realisation of the International Height Reference System (IHRS)". The main task has been to contribute to dealing with the question of how far regional gravity field determination should be standardized for the realization of IHRS. This was made by first contributing to discussions of standardization with mainly JWG 0.1.2 and ICCT JSG 0.15, which finally resulted in that the Colorado 1 cm geoid experiment became more tightly linked to realization of IHRS. SC 2.2 has then contributed to the Colorado 1 cm geoid experiment in different ways, for instance by writing the specification of the experiment (Sánchez et al. 2018a) and by contributing with regional gravity field solutions. More details can be found below and in the reports of JWG 0.1.2 and JWG 2.2.2.

Another related issue of SC 2.2 has been to investigate how to merge and validate existing local (or regional) geoid models. This has been the main topic of the JWG 2.2.1 "Integration and validation of local geoid estimates". See the JWG 2.2.1 report below.

The members of the SC 2.2 are deeply involved in many aspects of the development of regional gravity field determination methods and the realisation of physical height systems. The SC has been active in arranging scientific conferences, most notably the GGHS2016 conference in Thessaloniki, September 2016, the upcoming IAG-IASPEI Joint Scientific Assembly in Kobe, Japan, August 2017, and the GGHS2018 conference in Copenhagen, September 2018.

It is recommended that SC 2.2 continues in the next 4-year period. It is important that the Colorado 1 cm experiment is properly finalized and that the question of standardization is taken up again in view of the results of this experiment.

Below the challenges of regional gravity field determination for realisation of IHRS are first discussed. After that, the contribution of SC 2.2 is elaborated on in some more detail. This is followed by the reports of JWG 2.2.1 and JWG 2.2.2.

On the challenge of regional gravity field determination for realisation of IHRS

A global height reference frame with high accuracy and stability is fundamental to determine the global change of the Earth. A major step towards the goal of a globally unified height frame was taken by the IAG resolution (No. 1) for the definition and realisation of an International Height Reference System (IHRS), which was officially adopted at the IUGG 2015 meeting in Prague (Drewes et al. 2016; Sánchez et al. 2016; Ihde et al. 2017). Much work is now being made to realize IHRS, which will result in the first International Height Reference Frame (IHRF). The realisation will primarily be achieved by geometric satellite methods (like GNSS, SLR and VLBI) in combination with gravimetrically determined geopotential values (e.g. Ihde et al. 2017). The latter can be derived using a Global Geopotential Model (GGM) originating from the dedicated satellite gravity missions, complemented with terrestrial gravity, satellite altimetry and other information to reduce the omission error. In case highest accuracy is to be reached, regional geoid determination is an integral part of the realisation of the IHRS (*regional* here means combining the GGM with *regional* terrestrial gravity and other data, like a DEM). It is the intention that IHRS will be realized using a global network of reference stations in a similar way as ITRS is realised by ITRF. The realisation of IHRS (which is the main goal of JWG 0.1.2) will be specified in a document similar to the IERS conventions for the three-dimensional case (ITRS/ITRF).

An important question for SC 2.2 is to what extent geoid (or geopotential) determination for realisation of IHRS can (or should) be *standardised*. It is for instance proposed in Ihde et al. (2017) that a certain long wavelength satellite-only GGM be singled out as a matter of convention, which is then to be modified using regional/local gravity data, satellite altimetry and other data (like a topographic and bathymetric models). This is an example of what could be standardised, but also other aspects need to be specified. One problem in this context concerns the above-mentioned fact that several regional geoid determination methods (and software) are available, which to some extent give different numerical results (e.g. Ågren et al. 2016 and the JWG 2.2.1 report below). Different groups (or schools) tend to prefer their own method, which might be an obstacle to standardisation and which might lead to inconsistent realization of IHRS.

It is the ultimate goal that the determined potential values at the IHRF stations shall be determined with an accuracy of 10^{-2} m^2s^{-2} (Ihde et al. 2017), which corresponds to 1 mm in the geoid height or height anomaly. IAG thus aims at extremely high accuracy in the long run. It will be a major challenge to determine the potential with anywhere near this accuracy. In order to reach the sub-centimetre geoid, both theoretical and data improvements are required. The theoretical framework for sub-centimetre accuracy are dealt with by the IAG JSG 0.15 "Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre", but it should be emphasized that gravity data (and other types of data) also need to be updated to reach the goal. Recommendations regarding how to update the gravity data around the IHRF stations will be much needed in the future. Today the gravity data situation around the world is very diverse (cf. Sánchez and Sideris 2017). This is complicated by the fact that many of the gravity datasets are classified, or are available only for some groups under special permissions, etc. Even in the parts of the world with good gravity data, the above-mentioned goal is still far away in for instance the methodologically most demanding mountain areas.

To illustrate the challenge to compute a sub-centimetre geoid model in such a difficult area, a few results are presented from the Nordic NKG2015 geoid modelling project (Ågren et al. 2016). A particularly demanding area is southern Norway, with extremely rough topography with high mountains intersected by deep fjords. Comparatively good gravity data are available on land. In many of the fjords, however, gravity has been missing for a long time, at the same time as sufficiently dense bathymetry has been unavailable (or classified). Recently, however, new marine gravity data were observed in some of the largest fjords. These new observations were included for the computation of the NKG2015 quasigeoid model, but were neither available for the combined GGM EIGEN-6C4 with maximum degree 2190 (Förste et al. 2015) nor for the updated European regional EGG2015 model (Denker 2015). The relative quasigeoid difference (after subtraction of the mean) between NKG2015 and EIGEN-6C4 are presented in Figure 7, while difference between NKG2015 and EGG2015 can be found in Figure 8. Statistics for the GNSS/levelling residuals after a 1-parameter fit/transformation are given in Table 1.

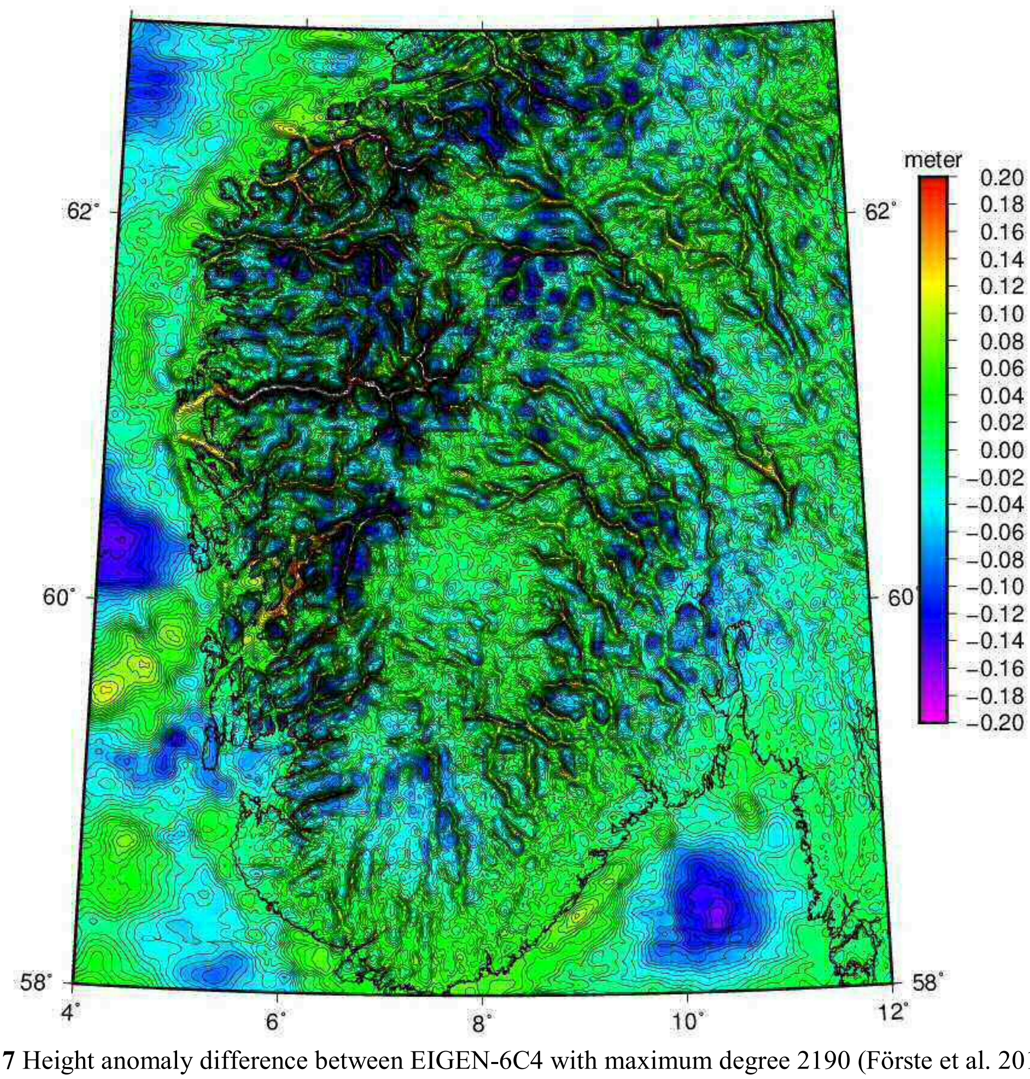

Figure 7 Height anomaly difference between EIGEN-6C4 with maximum degree 2190 (Förste et al. 2014) and NKG2015 in southern Norway. The mean has been subtracted. The same permanent tide system is used for both models. The contour interval is 1 cm. Note the frequent sign changes for the discrepancies over adjacent areas.

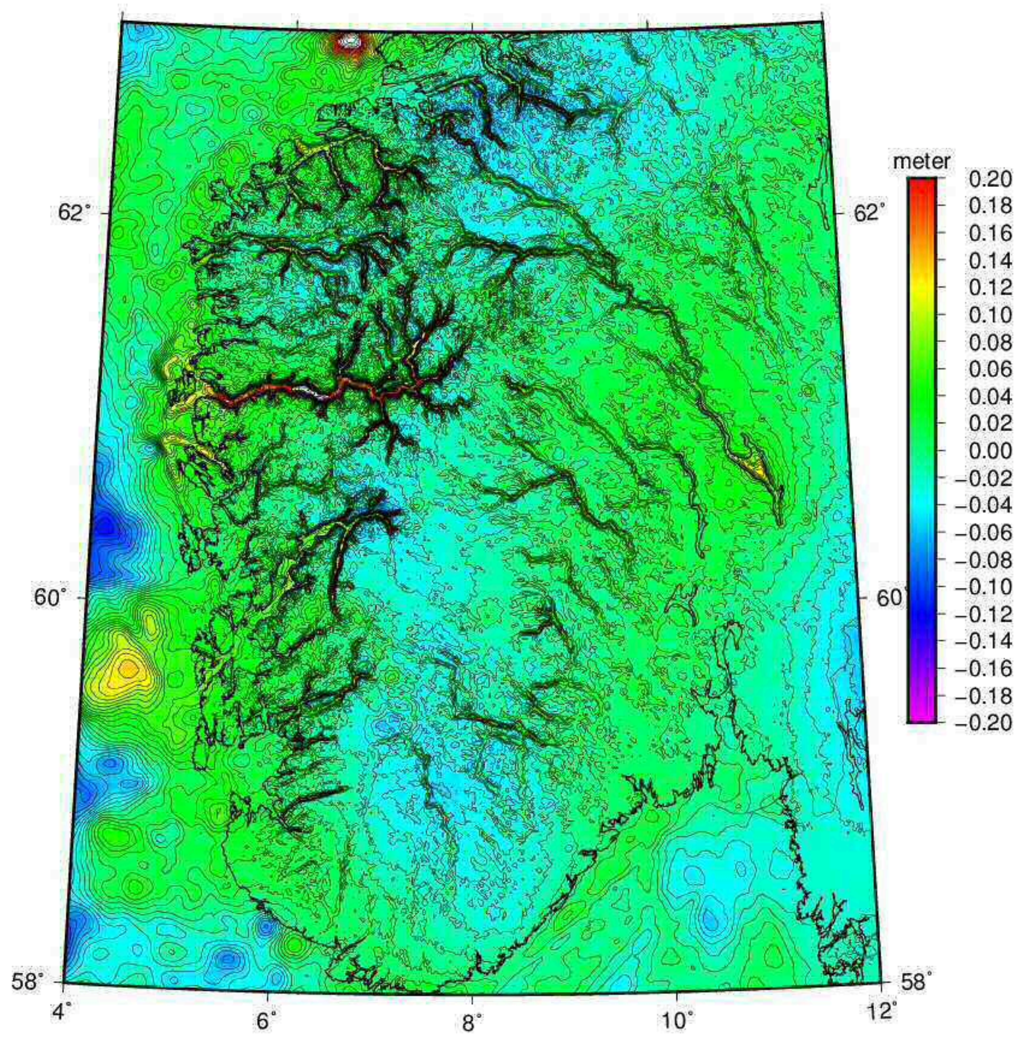

Figure 8 Height anomaly difference between the European EGG2015 (Denker 2015) and NKG2015 in southern Norway. The mean has been subtracted. The same permanent tide system is used for both models. The contour interval is 1 cm.

Table 1 Statistics for the GNSS/levelling residuals after a 1-parameter fit/transformation in Southern Norway. Consistent permanent tide systems and postglacial land uplift epochs. Unit: meter.

Model	#	Min	Max	Mean	StdDev
NKG2015	583	-0.129	0.080	0.000	0.027
EIGEN-6C4	583	-0.219	0.119	0.000	0.054
EGG2015	583	-0.142	0.084	0.000	0.041

The above results illustrate the challenge to compute a sub-centimetre geoid in a rough area. It is clear that the omission error is the major limitation for the combined EIGEN-6C4 GGM. Since it is very large, it is difficult to see the effect of the missing fjord data. The omission error is, on the other hand, not a problem for the regional EGG2015 model. In this case the large effect of missing fjord data becomes more visible. Most (but not all) of these fjord differences are due to that the new fjord marine gravity data were used for NKG2015 only. Besides these two factors (omission error and missing fjord data), there are still unexplained discrepancies between the models, which most likely depend on methodological differences (the methods differ significantly). It should be pointed out that it is difficult to separate what depends on the method and what on gravity data. The above results are presented mainly as a future challenge for the realisation of IHRS and for SC 2.2.

Contribution of SC 2.2 to the realization of IHRS

In 2016, L. Sánchez (chair JWG 0.1.2) initiated a discussion with J. Ågren (chair of SC2.2), and J. L. Huang (chair ICCT ISG 0.15) of the question of how far regional gravity field determination can be standardized for the realization of IHRS. This was followed up by a splinter meeting at IAG-IASPEI Joint Scientific Assembly in Kobe, Japan in August 2017, at which it was concluded that it is presently not possible to single out a certain "IHRS method" for regional gravity field determination. This would require that the active geoid modellers agree on all aspects of this method, which the participants of the meeting agreed is not realistic at the moment. The different methods differ in too many ways and the reasons behind this are not always understood or agreed upon. The meeting recommended instead that we should aim for setting up a selection of *basic requirements* (or minimum requirements), which a regional method must fulfil to count as providing a realization of IHRS. Within these limits, the choice of method should be left open to the modeller. We should, on the other hand, work towards a more far reaching standardization in the long run. It was especially noted that international comparisons are important here, both in the long and short term, to quantify how much the methods differ, to learn more about the reasons behind this and provoke interaction between different groups.

Based on the discussions at the above-mentioned splinter meeting, J. Ågren of SC2.2 and J. L. Huang of ICCT JSG 0.15 recommended that the JWG 2.2.2 ("The 1-cm geoid experiment") should be more tightly linked to the JWG 0.1.2 (on the realization of IHRS). The two JWGs agreed, and it was decided to extend the Colorado 1 cm geoid experiment in such a way that all groups should also compute potential values along the GSVS17 profile. It was further agreed to design the experiment so that it becomes as meaningful as possible for the task to realize IHRS, meaning for instance that absolute height anomalies and geoid heights are to be computed and compared (corresponding to the conventional W_0 value of IHRS, see Sánchez et al., 2016). SC 2.2 has contributed to the writing if two versions of the specification document for the Colorado experiment. The current version is Sánchez et al. (2018a). It might be said that the specification contains a first rough sketch of an IHRS list of basic (minimum) requirements for regional gravity field determination (even though it is not complete and even though parts of it are special for the Colorado experiment, for instance that the non-tidal permanent tide system is used, which is due to practical reasons).

The Colorado experiment is still on-going. The first preliminary results were presented at the GGHS2018 conference in September 2018, where a splinter meeting was also organized together with JWG 0.1.2, JWG 2.2.2 and ICCT JSG 0.1.15; see Wang et al. (2018) and Sánchez et al. (2018b) for first, very preliminary, results. Until May 2019, 14 groups have submitted more thoroughly checked solutions, among them most of the leading groups in the field of regional gravity field determination. See the reports of JWG 2.2.2 and JWG 0.1.2 for more details. The results are promising. The different solutions will be presented and compared at the IUGG General Assembly in July 2019, and it is then the intention to publish this work in a special issue of Journal of Geodesy. Based on the results of the Colorado 1 cm geoid experiment, a next step should be to return to the original question of how regional gravity field determination should be standardized for realization of IHRS and agree internationally on this.

Other parts of the realisation of IHRS also concern SC 2.2, for instance vertical datum unification and the role of traditional precise levelling. An important reference regarding vertical datum unification is Sánchez and Sideris (2017), which focus particularly on the unification of the South American height systems.

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Joint Working Groups of Sub-commission 2.2:

JWG 2.2.1: Integration and validation of local geoid estimates

Chair: *Mirko Reguzzoni (Italy)*
Vice Chair: *Georgios Vergos (Greece)*

Members

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- *R. Barzaghi (Italy)*
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- *N. Kuhtreiber (Austria)*
- *H. Abd-Elmotaal (Egypt)*
- *W. Featherstone (Australia)*
- *Jianliang Huang (Canada)*
- *Cheinway Hwang (Taiwan)*
- *Shuanggen Jin (China)*
- *G. Guimaraes (Brazil)*

Activities and publications during the period 2015-2019

Rationale

Regional geoid estimates (in areas having e.g. extension of some degrees) can give a detailed description of the high frequency geoid features. They are based on local gravity databases and high resolution DTMs that allow to reconstruct the high frequency spectrum of the gravity field, thus improving the global geopotential model representation. Local geoid estimates are computed following well-defined estimation methods that can give reliable results. These estimates are frequently used in engineering applications to transform GPS/GNSS derived ellipsoidal heights into normal or orthometric heights. Despite the fact that methodologies in geoid estimation have a sound basis, there are still some related issues that are to be addressed.

When comparing local geoid estimates of two adjacent areas inconsistencies can occur. They can be caused by the different global geopotential models used in representing the low frequency part of the gravity field spectrum and/or the method that has been adopted in the geoid estimation procedure. Biases due to a different height datum can also be present. Thus proper procedures should be proposed and assessed to homogenize local solutions. The main activity of the JWG 2.2.1 was devoted to the establishment of a methodology for merging local gravimetric geoid solutions, i.e. removing biases and other systematic effects by exploiting some information coming from satellite-only global gravity models.

Since the differences between local solutions can also originate from different geoid estimation methods, a comparison among these methods is an interesting issue for the JWG 2.2.1. In the framework of the GEOMED2 project, some of the currently used methods have been compared in estimating the geoid model of the Mediterranean Sea and surrounding areas, underlying their differences and evaluating their results on the basis of GNSS/levelling data.

The last issue that has been addressed in the JWG 2.2.1 concerns the procedures to be applied for local geoid estimates in areas with sparse or bad quality gravity data. In this respect, some tests have been performed in the framework of the GEOMED2 project to show that simulated data can positively contribute in improving the estimates by minimizing edge effects.

Local geoid collection

For the purposes of the working group activities, and in particular for the task of merging different local solutions, it is necessary to have a dataset of geoid models available at ISG. This required a first activity of collection of local geoid models on a worldwide scale, and in particular for Europe that is the selected test area. In the future, the proposed merging procedure could be applied to all models available in the ISG archive. Currently this archive is composed as reported in Table 2 (last update of the statistics was on May 1, 2019). More than 80% of the models are classified as gravimetric, since the merging involved this kind of solution only. Collecting models included the activities of contacting authors, asking for model publication at ISG, converting the models into a unique ASCII format and publishing dedicated webpages in the ISG website (containing a short model description, a model figure, bibliographic references, the contact person, etc.).

Table 2 Number of models per continent in the ISG archive

Europe	70
North America	36
Africa	20
Asia	19
Oceania	14
South America	13
Antarctica	4
Arctic	3
Total	179

Table 3 Number of models per policy-rule in the ISG archive

Public	123
On-Demand	20
Private	36
Total	179

Local geoid patching methodology

The proposed unification strategy consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining geoid distortions along the national borders by a proper interpolation. The advantage of this approach is that the resulting unified geoid includes both the low frequencies of the satellite-only geoid model and the high frequencies of the local ones. These high frequencies are expected to be more accurate in the definition of the equipotential than those coming from a "terrestrial" global geopotential model combined with the residual terrain effect. Moreover, this procedure allows for a fast update of the unified model when a new geoid is available.

The procedure, which should be as automatized as possible, is summarized in the following steps:

- Acquisition of the local geoid/quasigeoid model from the ISG archive (if more than one model is available for the same area, the most accurate or the most recent one is selected).
- Detection of the national borders and extraction of a subset of uniformly distributed points.

- Evaluation of the point elevations from the Shuttle Radar Topography Mission (SRTM) at each selected knot of the geoid/quasigeoid model.
- Synthesis of the geoid/quasigeoid from a satellite-only model from the International Center for Global Gravity Field Models (ICGEM) archive.
- Synthesis of the geoid/quasigeoid from EGM2008 or EIGEN6C4 for degrees higher than the maximum degree of the used satellite-only model, with a smooth transition between the two models in the spherical harmonic domain (the use of this information is optional).
- Computation of Residual Terrain Correction (RTC) on elevation residuals with respect to a properly averaged Digital Terrain Model (DTM).
- Computation of geoid/quasigeoid residuals by subtracting the global model and the RTC contributions from the original ISG model.
- Empirical modelling of the error covariance matrix of the geoid/quasigeoid residuals, also considering the available information on the satellite-only global model error covariances.
- Estimation of a bias and other systematic effects $S(\varphi,\lambda)$ by least-squares adjustment, according to the general formula (Heiskanen and Moritz, 1967):

  $$S(\varphi,\lambda) = a_1 + a_2\cos\varphi\cos\lambda + a_3\cos\varphi\sin\lambda + a_4\sin\varphi$$

  or to an approximate one, such as:

  $$\widetilde{S}(\varphi,\lambda) = b_1 + b_2(\varphi-\varphi_0) + b_3\cos\varphi(\lambda-\lambda_0)$$

  to be iteratively applied by revising the empirical error covariance modelling.
- Application of the estimated biases and systematic effects to all the considered local models.
- Refinement of the geoid/quasigeoid conjunction at national borders by a moving average or stochastic interpolation.
- Production of a new file in ISG format containing the merged geoid/quasigeoid model.

Note that a conversion from quasigeoid to geoid or vice versa has to be preliminarily implemented, at least in an approximate way, in order to merge the same type of models.

Numerical tests of geoid patching

First of all, some results regarding the Italian quasigeoid model ITALGEO05 (gravimetric solution) are reported to illustrate how the algorithm works; see Figure 9 to Figure 17 and

Table 4. Then, the procedure is applied to a subset of European models and the solution is compared with the existing continental model EGG2015, which is available at ISG too; see Figure 18 to Figure 24 and Table 5. The final target of this numerical test is to show that, if the used gravity data were not preliminary reduced for biases, the geoid patching is less affected by distortions due to the different national reference systems than continental geoid models.

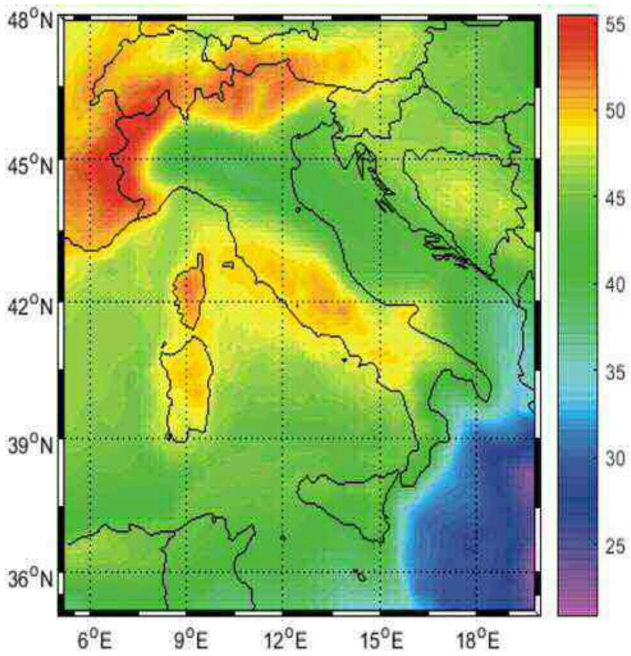

Figure 9 ITALGEO05 quasigeoid model (units in m); this model is in the ISG archive but is not publicly available from the ISG website.

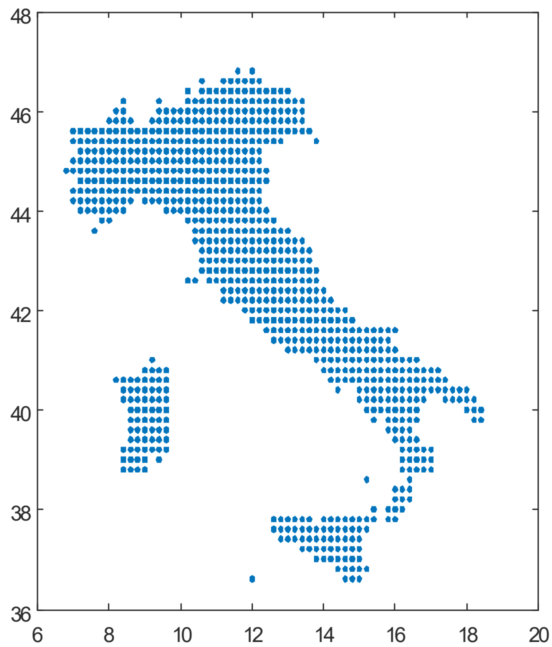

Figure 10 The selected 835 points among the ITALGEO05 grid, inside the Italian borders; these points will be used for estimating a bias and other systematic effects.

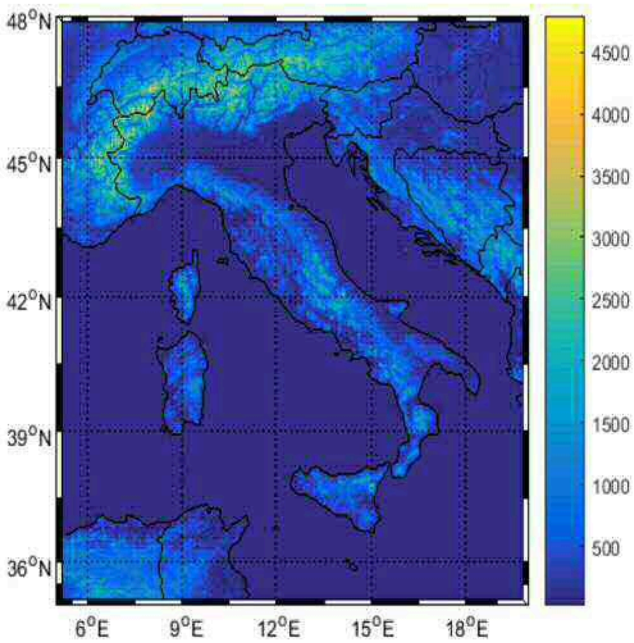

Figure 11 Italian DTM as derived from SRTM (units in m).

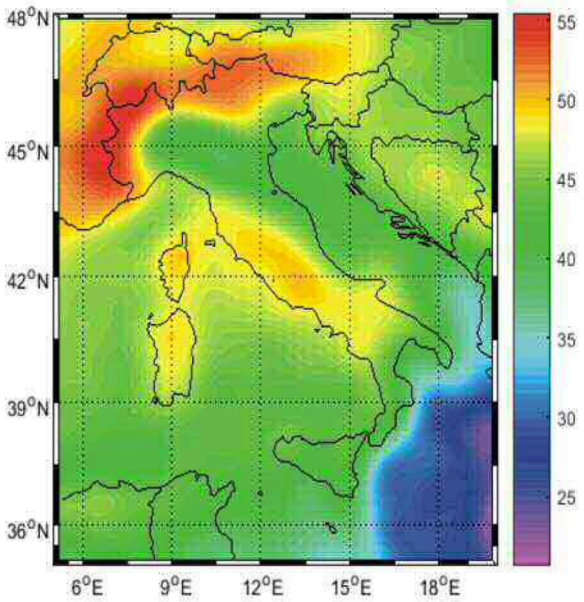

Figure 12 Synthesis of the Italian quasigeoid from GOCO-05S satellite only model up to degree and order 280 (units in m).

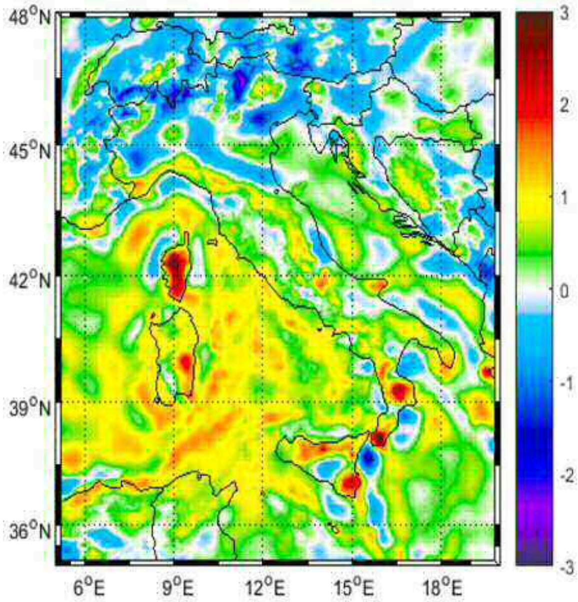

Figure 13 Residuals between ITALGEO05 and GOCO-05S up to degree and order 280 (units in m).

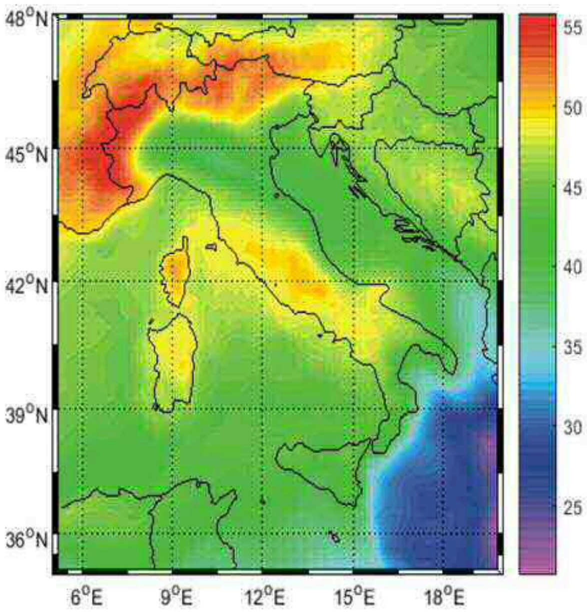

Figure 14 Synthesis of the Italian quasigeoid from GOCO-05S up to degree and order 280, and EGM2008 above degree 280, with a smooth transition down to degree 210 (units in m). This additional information should not degrade the bias estimate (see e.g. Gatti et al., 2013; Gerlach and Rummel, 2013), but could be useful to further reduce the residuals between global and local models.

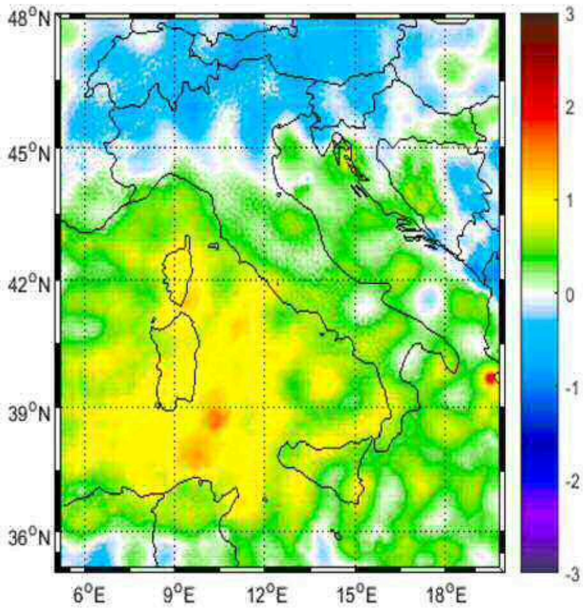

Figure 15 Residuals between ITALGEO05 and GOCO-05S up to degree 280 complemented with EGM2008 up to degree 2190 (units in m). In the presented examples, biases and systematic effects are estimated from residuals in Fig. 5, only using information from satellite-only global models.

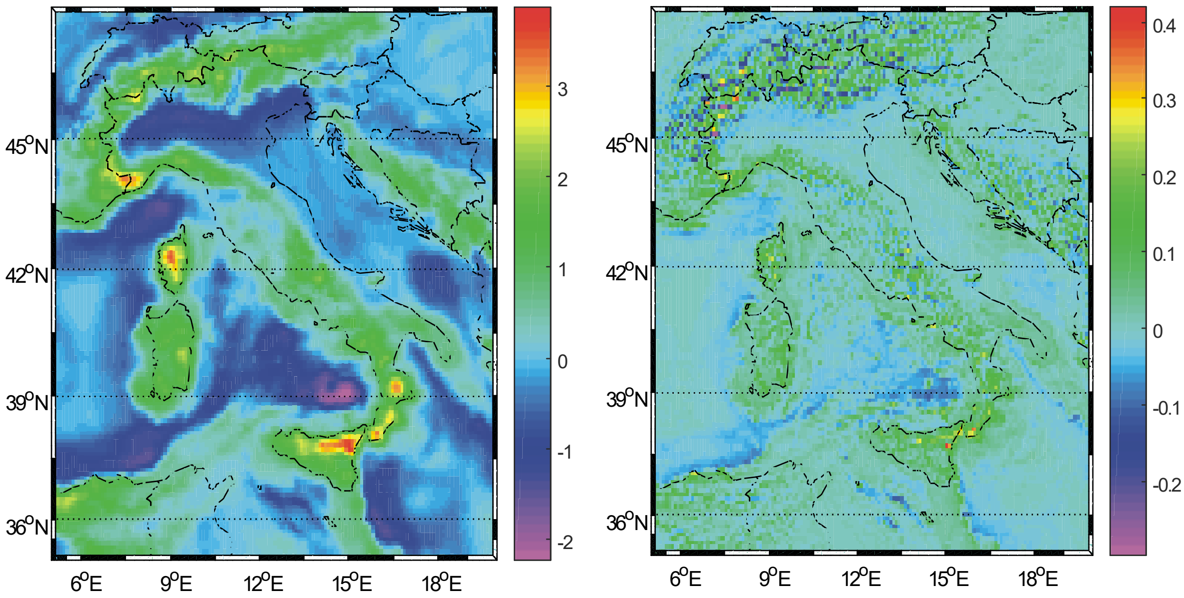

Figure 16 Residual Terrain Correction (RTC) from residual elevations with respect to an averaged DTM (units in m). On the left, SRTM is averaged over windows of 30’ 30’, which is compatible with the subtraction of a satellite-only global model from the local quasigeoid. On the right, SRTM is averaged over windows of 5’ 5’, which is compatible with the subtraction of EGM2008 too. The use of RTC to further reduce quasigeoid residuals for the bias estimation is still under investigation and is not applied in the presented examples.

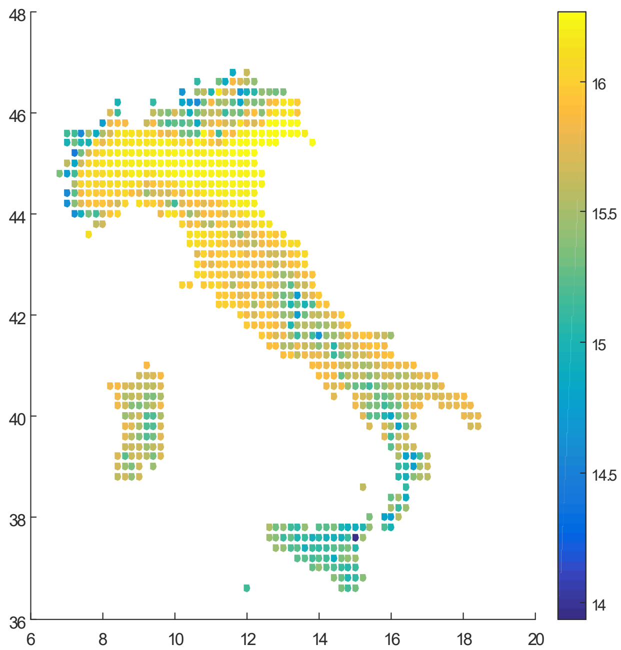

Figure 17 Error variance obtained by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients, taking also into account the point elevations (units in cm).

Table 4 Estimated bias and systematic effects of ITALGEO05 (units in m) when using a stochastic model coming from the GOCO-05S error covariance matrix plus a global omission error covariance matrix from EGM2008 degree variances plus a diagonal covariance matrix for the local quasigeoid model error (standard deviation of 5 cm).

$\hat{b}_1 = 0.265$	$\hat{\sigma}_{b_1} = 0.041$
$\hat{b}_2 = -8.731$	$\hat{\sigma}_{b_2} = 0.787$
$\hat{b}_3 = -1.632$	$\hat{\sigma}_{b_3} = 0.332$

As for the test on a subset of European models, it has been performed by considering the following countries (the name of the used model in brackets):

- France (QGF98)
- Corsica (QGC02)
- Italy (ITALGEO05)
- Iberian Peninsula (IBERGEO2006)
- Belgium (BG03)
- Switzerland (CHGEO2004Q)
- Greece (GreekGeoid2010).

For each model, a subset of about 1000 points on land and inside the national borders has been selected for the bias and trend estimation. The digital terrain model (DTM) for each country has been derived from SRTM.

The reference geoid has been synthesized from a combination of the GOCO-05S satellite-only global model up to degree and order 280 and the EGM2008 model from degrees 200 to 2190, with a smooth transition from degrees 200 to 280, and then subtracted from the local solutions. No residual terrain correction (RTC) has been further removed from the resulting geoid residuals. The patching of these residuals, before applying any bias or trend estimation, is shown in Fig. 10. The overall standard deviation of these residuals is equal to 0.46 m and discontinuities between neighbor countries are well visible.

The geoid error of the reference model has been computed by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients and from EGM2008 degree variances, also considering the smooth transition in the combination of the two models. A white noise with a standard deviation of 5 cm has been attributed to each local geoid model. The resulting error variances are shown in Fig. 11. If the EGM2008 contribution was not subtracted from the data, instead of modelling the omitted signal from the global EGM2008 degree variances and using an a-priori standard deviation for the local geoid model error, one could estimate a covariance function for each model by fitting the empirical covariance of the residuals with respect to GOCO-05S, see Fig. 12. This alternative has not been implemented in the presented test, since residual cross-covariances have to be adapted too, and this introduces complications in guaranteeing that the resulting error covariance matrix is positive definite.

By using the computed geoid residuals and the discussed stochastic modelling, a bias and a trend for each local geoid have been estimated by least-squares adjustment, as reported in Table 5. The estimated biases and trends are shown in Figure 21, while the residuals after the de-trending procedure are displayed in Figure 22. The overall standard deviation of the residuals is now equal to 0.13 m and discontinuities between neighbor countries are not really visible by using this color scale. However, a refinement of the patching result to better join the geoid models at national borders is required and has been implemented by a moving weighted average. Some example of this refinement are shown in Figure 23. A more refined interpolation with a varying window and based on some stochastic modelling will be investigated in the future.

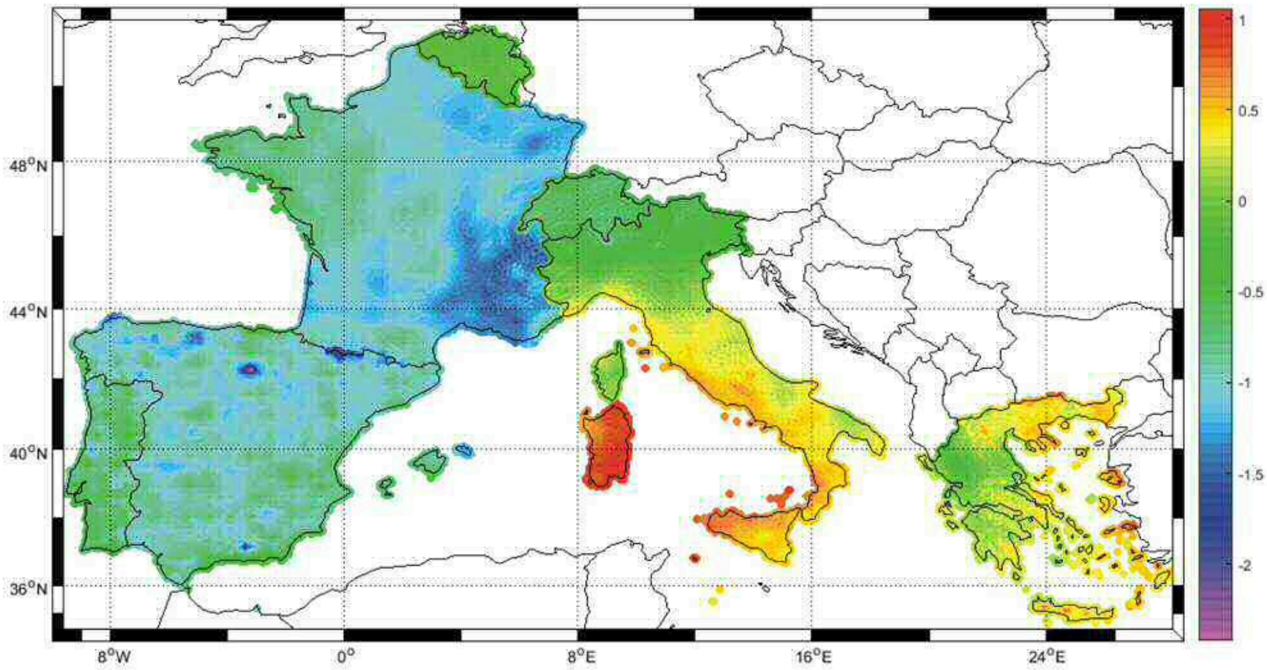

Figure 18 Model residuals with respect to a GOCO-05S/EGM2008 combination of GOCO-05S before applying the de-trending procedure, i.e. as they are stored in the ISG archive (units in m).

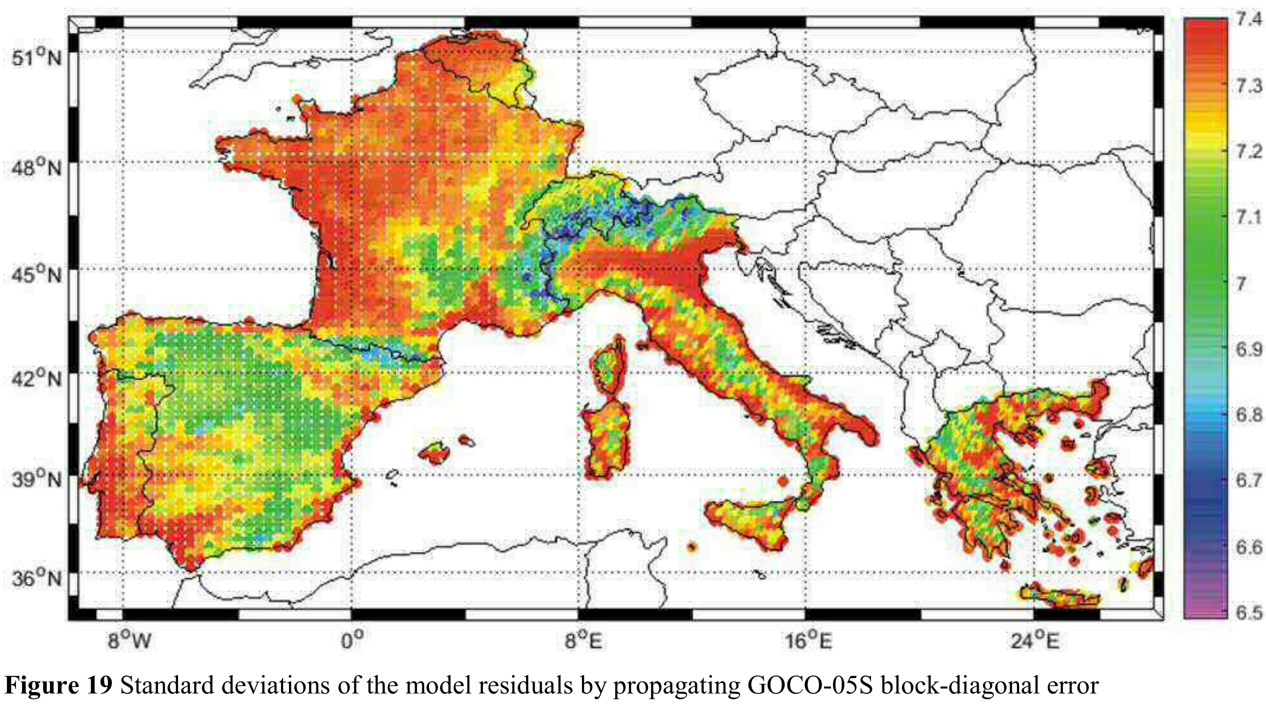

Figure 19 Standard deviations of the model residuals by propagating GOCO-05S block-diagonal error covariance matrix and EGM2008 error degree variances, and by adding 5 cm white noise (units in cm). Note that cross-covariances have been computed too. The resulting full covariance matrix of the model residuals has been used to jointly estimate all biases and trends by least-squares adjustment.

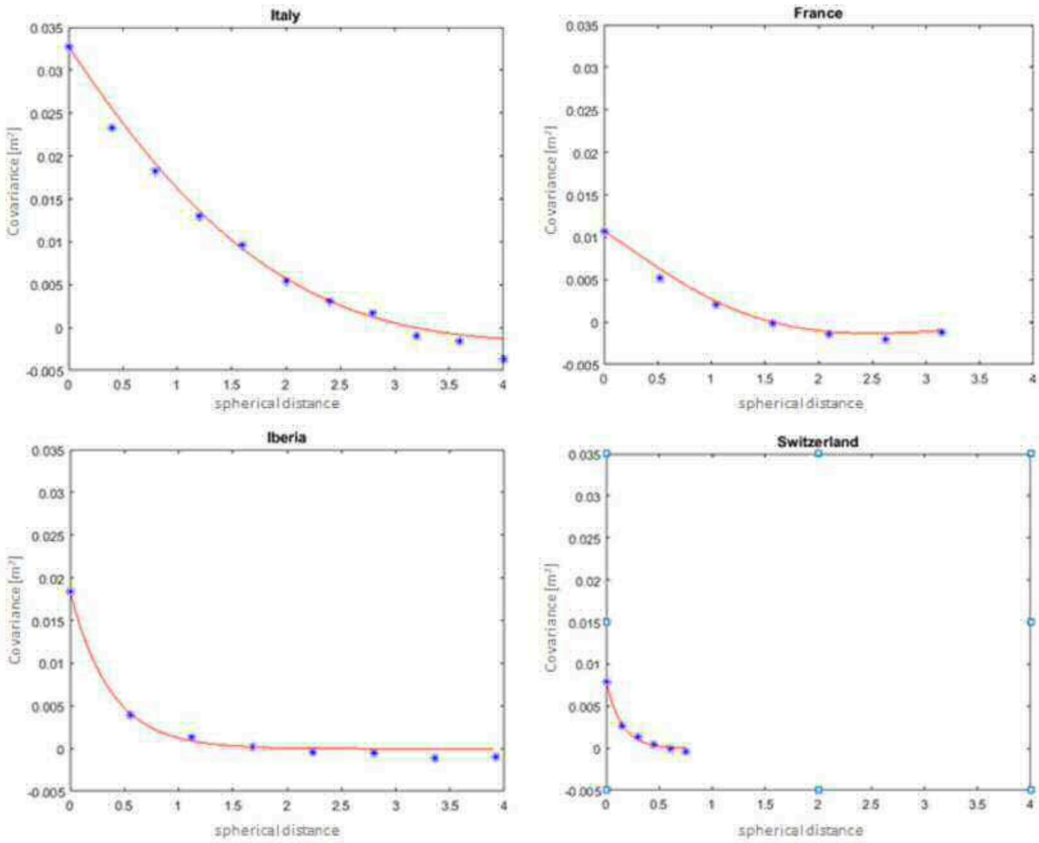

Figure 20 Examples of estimated covariance functions (red lines) by fitting the empirical covariance values (blue dots) of the residuals with respect to GOCO-05S, separately computed for each model.

Table 5 Estimated biases and trends with the corresponding error estimates (units in m). Recall that b_1 represents the bias, while b_2 and b_3 the trend in latitude and longitude, respectively. All the estimated parameters are statistically significant, apart from Corsica (there is no bias) and Belgium (there is no trend in longitude).

	France	*Corsica*	*Italy*	*Iberia*	*Switzerland*	*Belgium*	*Greece*
$\hat{b}_1$	-1.065	0.015	0.203	-0.921	-0.613	-0.126	0.221
$\hat{b}_2$	1.360	-8.735	-8.431	-1.797	3.569	2.899	0.610
$\hat{b}_3$	-4.399	-10.104	-1.703	-0.701	-1.209	1.133	6.228
$\hat{\sigma}_{b_1}$	0.002	0.015	0.002	0.002	0.003	0.004	0.003
$\hat{\sigma}_{b_2}$	0.050	1.884	0.067	0.059	0.540	0.828	0.105
$\hat{\sigma}_{b_3}$	0.058	3.675	0.086	0.051	0.298	0.727	0.142

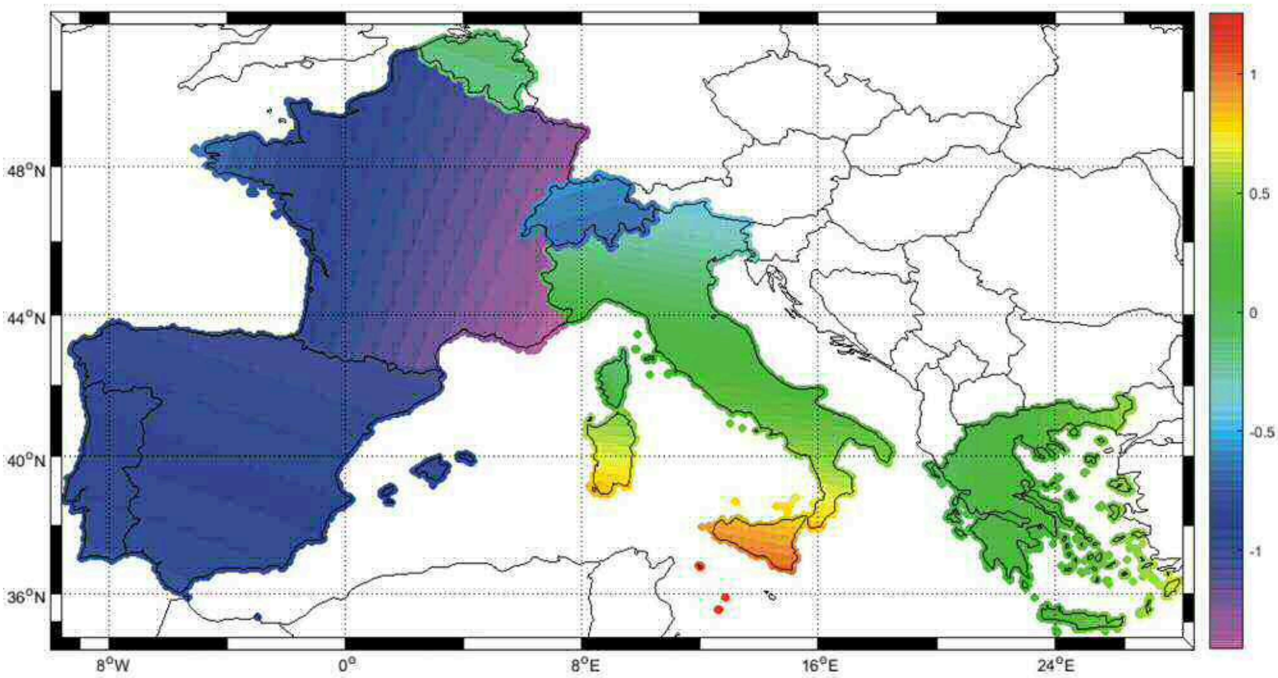

Figure 21 Estimated biases and trends (units in m).

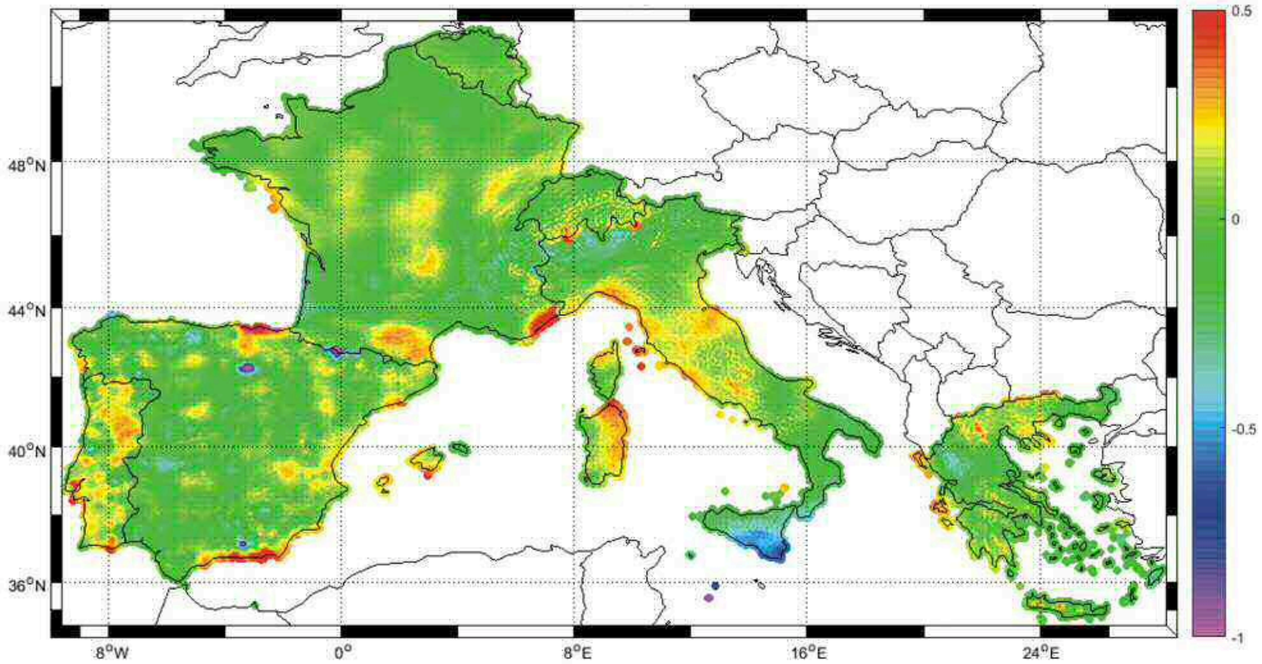

Figure 22 Model residuals with respect to a GOCO-05S/EGM2008 combination of GOCO-05S after applying the de-trending procedure (units in m); compare with Figure 18.

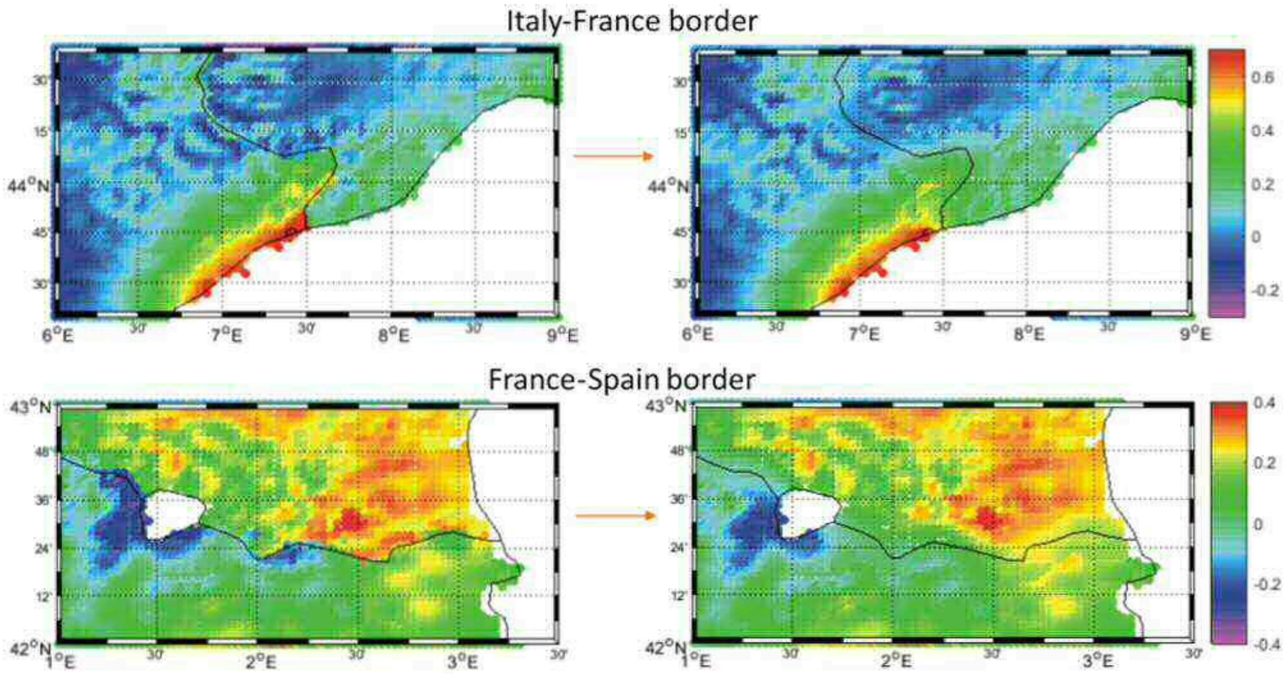

Figure 23 Examples of border refinement by moving average interpolation in order to better join the local models after the de-trending procedure (units in m).

Finally, a comparison with the EGG2015 European model has been performed. The differences are shown in Figure 24. They have a mean of 53.7 cm and a standard deviation of 11 cm. By comparing both the patched model and EGG2015 with the synthesis from GOCO-05S, the resulting statistics are the following:

$$\text{mean(patched\_model - GOCO05S)} = 0.2 \text{ cm (globally)}$$

$$\text{mean(patched\_model - GOCO05S)} \in (-1.6 \text{ cm}, 0.6 \text{ cm}) \text{ (for all countries)}$$

$$\text{mean(EGG2015 - GOCO05S)} = -53.6 \text{ cm (globally)}$$

$$\text{mean(EGG2015 - GOCO05S)} = \begin{cases} -55.2 \text{ cm (France)} \\ \ \ 25.6 \text{ cm (Corsica)} \\ -46.4 \text{ cm (Italy)} \\ -51.5 \text{ cm (Iberia)} \\ -60.3 \text{ cm (Switzerland)} \\ -55.6 \text{ cm (Belgium)} \\ -44.0 \text{ cm (Greece)} \end{cases}$$

Other activities on height datum unification

Although based on sparse GPS/levelling data, instead of gridded geoid/quasigeoid national models, similar activities have been performed for the height datum unification of continental Italy with Sicily and Sardinia (Barzaghi et al., 2015) and continental Spain with Balearic and Canary Islands (Reguzzoni et al., 2017). Other investigations concerning height datum unification have been performed over Greece and Turkey (Vergos et al. 2015; 2018). All these preliminary studies were useful to better tune the proposed procedure in the framework of the JWG 2.2.1.

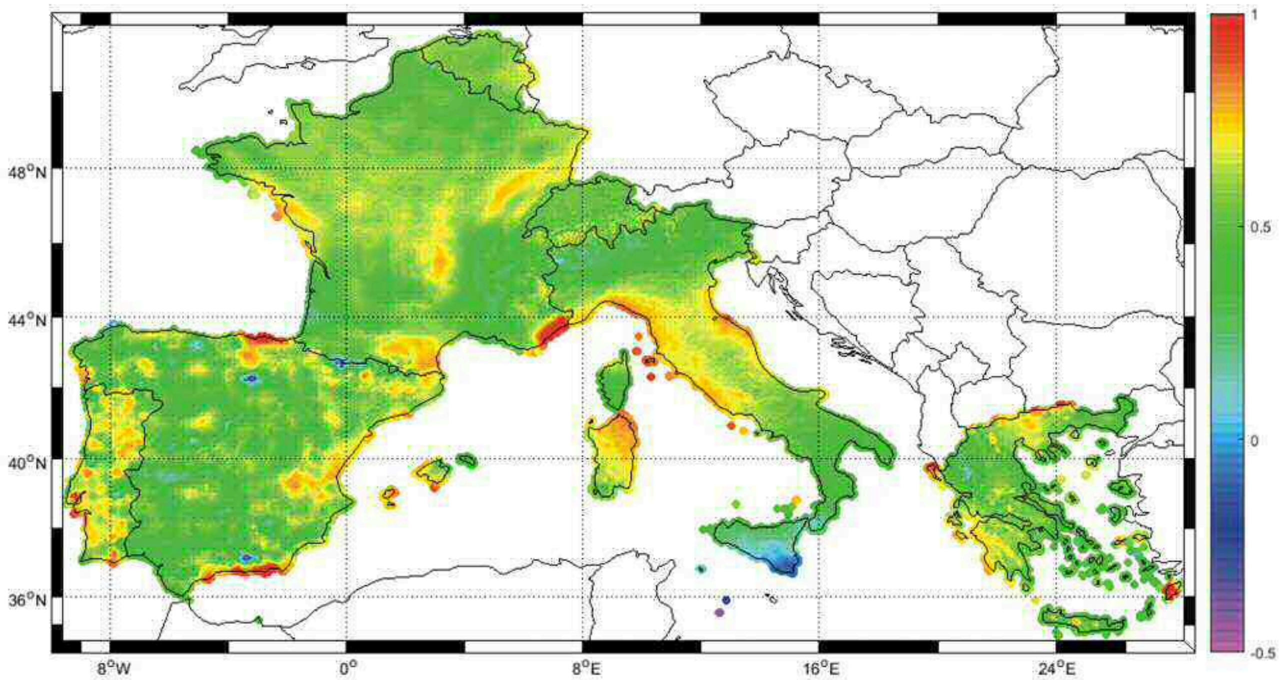

Figure 24 Differences between the patched model and EGG2015 (units in m). In order to compute these differences, the EGG2015 model (full resolution) has been previously interpolated at points of the national models.

Comparison of geoid estimation methods

One topic of the JWG 2.2.1 is the analysis of different geoid estimation methods. This topic has been developed in the framework of the GEOMED2 project, which aims at estimating the geoid over the Mediterranean area. To this purpose, the collocation approach, the Stokes formula with Wong-Gore (WG) kernel modification, and the Least Squares Modification of Stokes formula with Additive corrections (LSMSA, also known as KTH method) have been applied to the available dataset and their results have been compared to each other.

The research groups involved in these computations are:

- International Gravimetric Bureau (BGI) for data reduction and gridding;
- French Naval Hydrographic and Oceanographic Service (SHOM) for marine gravity data analysis;
- Politecnico di Milano (POLIMI) for data reduction and geoid computation by collocation;
- Aristotle University of Thessaloniki (AUTH) for data reduction and geoid computation by Stokes-WG;
- Turkish General Command and Mapping (GCM) for geoid computation by KTH method;
- University of Zagreb (UZG) for geoid computation by KTH method.

Gravity data over the computation area have been reduced for the long wavelength components by means of the EIGEN6C4 global geopotential model up to degree and order 1000. High frequency features have been computed and removed from the gravity data using the methodology designed by Hirt and Khun (2014). All computations related to the terrain effect have been based on SRTM3.

Then, the residual gravity values have been gridded by kriging on a 2'×2' grid over the computation area ($29° \leq \varphi \leq 48°$, $-10° \leq \lambda \leq 40°$). Besides this grid, a free-air gravity grid has been computed by restoring the contributions of the global gravity model (GGM) and the residual terrain correction (RTC) at the Earth surface. The heights of points at the Earth surface have been evaluated by interpolating SRTM3 over the grid knots.

The residual gravity grid has been used for computing the residual geoid grid by applying the Fast Collocation and Stokes-WG approaches. Then, the final geoid estimates have been obtained by restoring the EIGEN6C4 GGM and the RTC components. On the contrary, the LSMSA-KTH method has been applied on the second grid, namely the free-air gravity grid. The accuracy of these geoid estimates has been assessed on GPS/levelling points available in Italy and Greece. The results of this comparison are summarized in Table 6 and Table 7.

Table 6 Statistics on the differences between geoid estimates and GPS/levelling over Italy (after bias and tilt removal).

	Collocation (POLIMI)	**Stokes-WG (AUTH)**	**KTH (GCM)**	**KTH (UZG)**
#	977	977	977	977
Mean (m)	0.000	0.000	0.000	0.000
St. Dev. (m)	0.090	0.097	0.093	0.096
Min (m)	-0.229	-0.217	-0.462	-0.409
Max (m)	0.382	0.463	0.282	0.325

Table 7 Statistics on the differences between geoid estimates and GPS/levelling over Greece.

	Collocation (POLIMI)	**Stokes-WG (AUTH)**	**KTH (GCM)**	**KTH (UZG)**
#	1542	1542	1542	1542
Mean (m)	0.057	0.068	-0.838	0.166
St. Dev. (m)	0.128	0.128	0.127	0.135
Min (m)	-0.497	-0.448	-1.286	-0.326
Max (m)	0.574	0.507	-0.365	0.560
RMS (m)	0.140	0.145	0.838	0.214

Based on these outcomes, one can state that the different methods are substantially equivalent, but for the bias components that are quite different. This is a point to be investigated in more details, particularly in view of the application of geoid estimation methods to the definition of $W(P)$ in the framework of the International Height Reference System.

Moreover, the differences among the three solutions are displayed in Figure 25, Figure 26 and Figure 27, after subtracting a bias from the KTH solution by GCM. Even though the standard deviations of the differences with respect to the GPS/levelling data are basically equivalent, see Table 6 and Table 7, the three approaches show different behaviours over sea. This will be further investigated by comparing the results with models based on radar altimeter data.

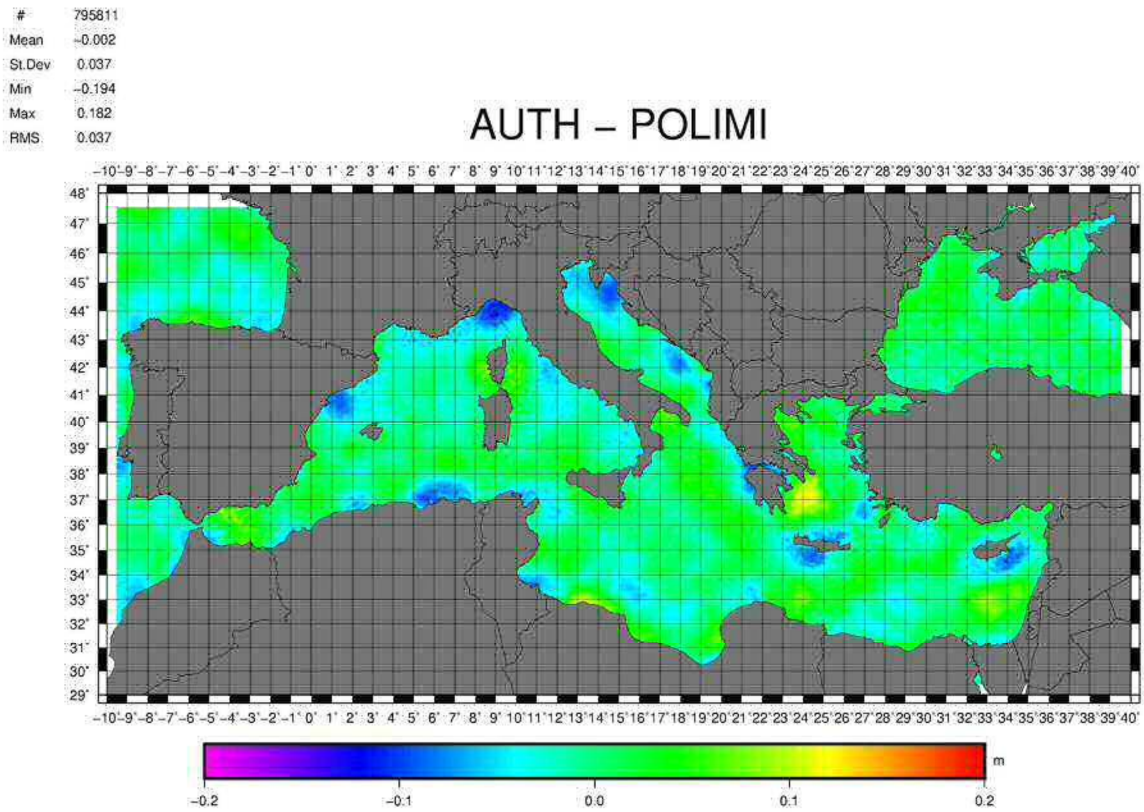

Figure 25 Differences between Stokes-WG (AUTH) and Fast Collocation (POLIMI) solutions. Statistics on the differences are shown in the upper left corner (units in m).

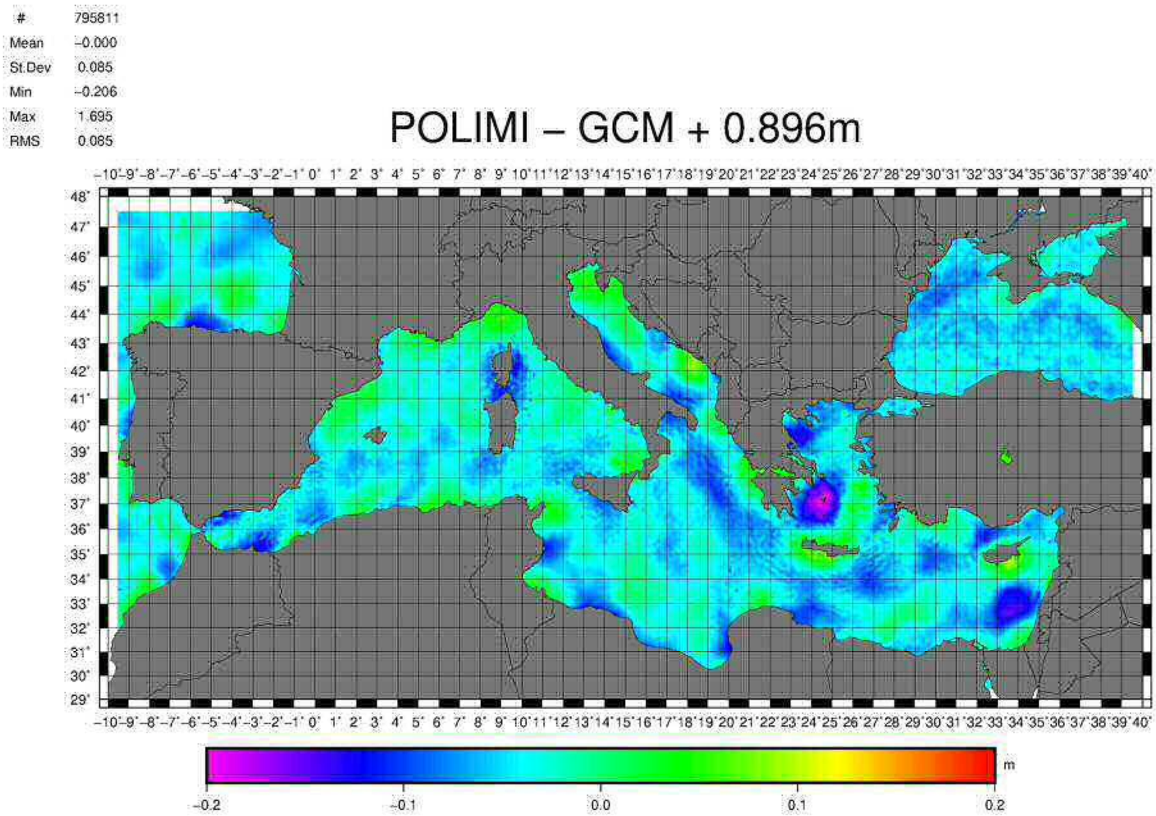

Figure 26 Differences between Fast Collocation (POLIMI) and KTH (GCM) solutions. Statistics on the differences are shown in the upper left corner (units in m).

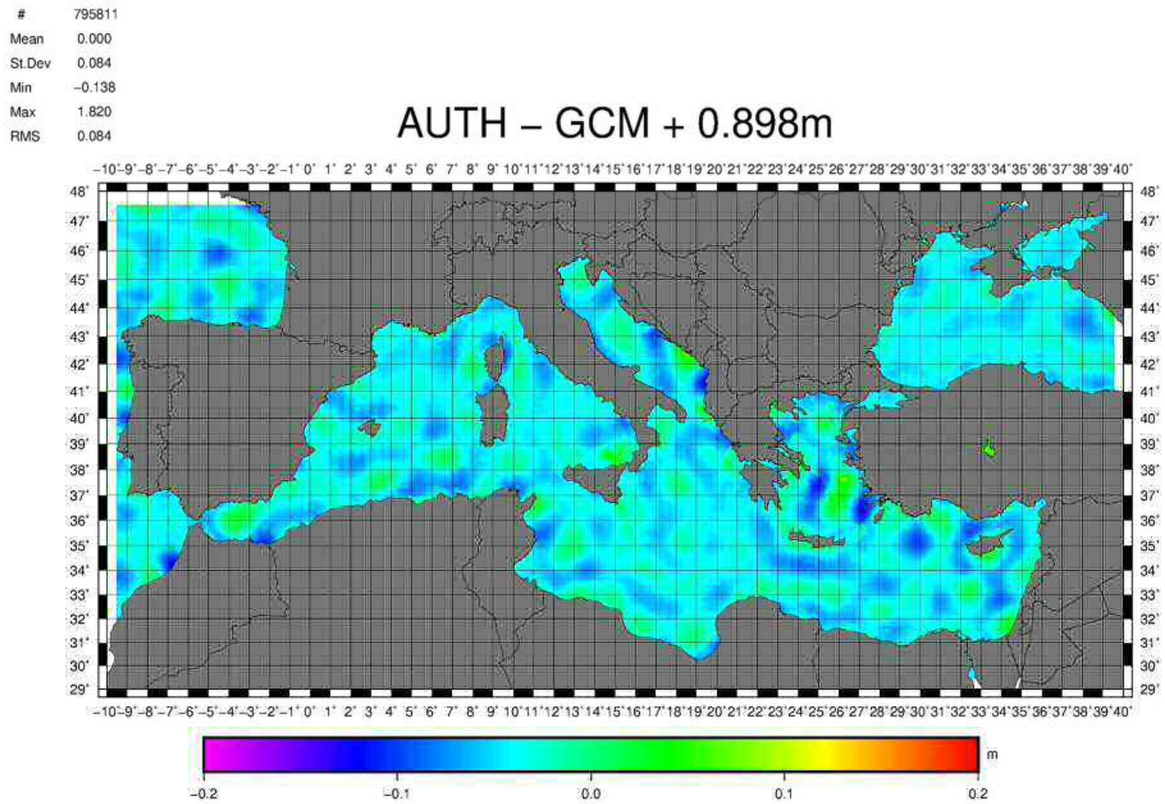

Figure 27 Differences between Stokes-WG (AUTH) and KTH (GCM) solutions. Statistics on the differences are shown in the upper left corner (units in m).

Geoid estimation in areas with sparse gravity data

Another topic of the JWG 2.2.1 is the definition of rules for geoid estimation in areas where data are sparse. This problem can be further extended to the topic of void areas that can cause edge effects on the geoid solutions. In this respect, a possible solution is to simulate data having a covariance signature equivalent to the one of the actual data. The simulated residual data can be derived as:

$$\Delta g_r^s(P) = T^+ \nu$$

where T is a triangular matrix, ν is a zero mean white noise

$$C_{\nu\nu} = \sigma_\nu^2 I \qquad E(\upsilon) = 0 \; E[\nu] = 0$$

and

$$C_{\Delta g \Delta g} = T^+ T$$

being $C_{\Delta g \Delta g}$ $C_{\Delta g \Delta g}$ the covariance of the actual residual gravity data. It can be proved that the $\Delta g_r^s(P)$ values computed in this way have the covariance structure of the real data. These simulated values can be used to fill in data gaps, thus minimizing edge effects. Several tests of this procedure, performed in the context of the GEOMED2 project, proved that the procedure is effective and can be used when necessary.

In the following, one of these tests is presented. It has been performed over Sardinia, one of the main Italian islands. In this case, the residual gravity data over land have been substituted with simulated ones, and then the Fast Collocation is applied to obtain the geoid residuals. In Table 8 and Figure 28, the statistics and the map of the differences between the geoid residuals (over sea) obtained starting from measured gravity residuals and from simulated data (over land) are shown.

Table 8 Statistics of the differences over sea of the geoid residuals obtained by using measured or simulated gravity residuals over land (Sardinia).

	Geoid residual differences
#	2797
Mean (m)	0.002
St. Dev. (m)	0.015
Min (m)	-0.102
Max (m)	0.072
RMS (m)	0.016

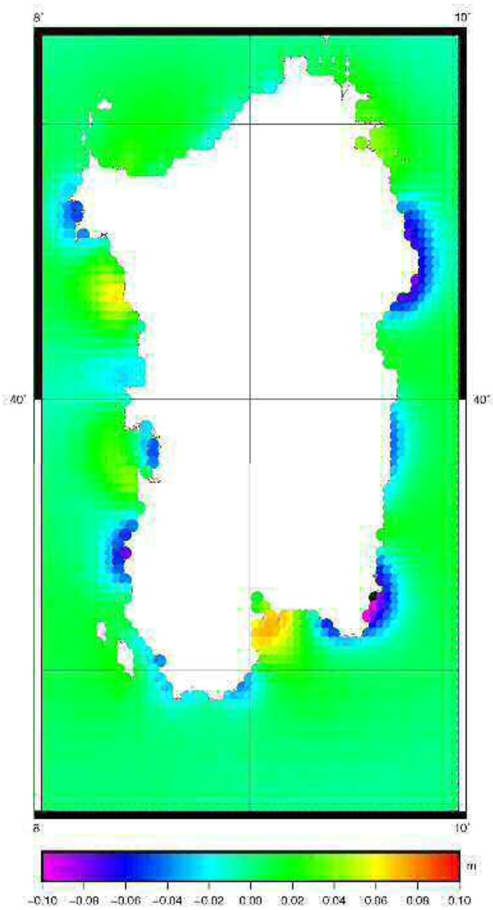

Figure 28 Map of the differences over sea of the geoid residuals obtained by using measured or simulated gravity residuals over land (Sardinia).

The statistics, particularly the RMS, support the reliability of the procedure. Figure 28 shows that the effect over sea (far from the coasts) is not significant. On the contrary, the lack of data or the presence of not reliable data over land could more largely affect the solution over sea.

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JWG 2.2.2: The 1 cm geoid experiment

Chair: Yan Ming Wang (USA)
Vice Chair: Rene Forsberg (Denmark)

Members

- *Ågren Jonas (Sweden)*
- *Barzaghi Ricardo (Italy)*
- *Blitzkow Denizar (Brazil)*
- *Claessens Sten (Australia)*
- *Erol Bihter (Turkey)*
- *Grigoriadis Vasilios (Greece)*
- *Huang Jianliang (Canada)*
- *Jiang Tao (China)*
- *Liu Qing (Germany)*
- *Matej Varga (Croatia)*
- *Matsuo Koji (Japan)*
- *Willberg Martin (Germany)*
- *Sanchez Laura (Germany)*

Corresponding Members

- *Abd-Elmotaal Hussein (Egypt)*
- *Ahlgren Kevin (USA)*
- *Avalos David (Mexico)*
- *Bašić Tomislav(Croatia)*
- *Carrion Daniela (Itali)*
- *Dalyot Sagi (Israel)*
- *Denker Heiner (Germany)*
- *Ellmann Artu (Estonia)*
- *Erol Serdar (Turkey)*
- *Featherstone Will (Australia)*
- *Filmer Mick (Australia)*
- *Hwang Cheinway (Taiwan)*
- *Isik Mustafa Serkan (Turkey)*
- *Krcmaric Jordan (U.S.A.)*
- *Li Jiancheng (China)*
- *Li Xiaopeng (USA)*
- *Natsiopoulos Dimitrios (Greece)*
- *Novák Pavel (Czech)*
- *Pangastuti Dyah (Indonesia)*
- *Pitoňák Martin (Czech)*
- *Sarid Hezi (Israel)*
- *Sjöberg Lars (Sweden)*
- *Vergos Georgios (Greece)*
- *Veronneau Marc (Canada)*

Activities and publications during the period 2015-2019

Overview

The 1 cm geoid experiment working group (WG) has been collaborating closely with the following groups and sub-commissions (SC):

1. GGOS JWG: Strategy for the Realization of the IHRS (chair L. Sánchez)
2. IAG SC 2.2: Methodology for geoid and physical height systems (chair J. Ågren)
3. ICCT JSG 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy (chair J. L. Huang)

Currently, 14 groups are actively participating in the experiment. Since the maximum number of members is limited to 20 according to the IAG by-laws, the leading author of each group is listed as the WG member (15), and the co-authors are listed as corresponding members (24).

This WG coordinates international cooperation on determining the best ways to combine satellite gravity models and terrestrial/airborne gravity data in geoid modelling and work towards a 1 cm accuracy goal. The lessons learned from this study will be greatly important for future geoid modelling in the geodetic community.

Within the geodetic community, there are various methods of geoid computation based on different philosophies and theories. While they all aim to achieve a cm-level accurate geoid model, numerical differences exist because each method has a different way of dealing with gravity data and topography, as well as handling the errors in the satellite models, terrestrial data and airborne data. It is of great scientific interest to know how well these methods agree numerically, and to know at the same time the accuracy that can be achieved in geoid modelling.

In this experiment, the WG has been focused on the geoid/height anomaly and geopotential values computed at selected points in Colorado, U.S.A., where the elevation ranges from 940 to 4400 meters. In the study area, the U. S. National Geodetic Survey has conducted airborne gravity surveys for geoid computation (https://www.ngs.noaa.gov/GRAV-D/) and the Geoid Slope Validation Survey of 2017 that provides GPS, levelling, gravity, and deflection of vertical data over a traverse about 320 km in length for geoid model validation (https://www.ngs.noaa.gov/GEOID/GSVS11/index.shtml).

Comparison Results

The WG presented the first comparison results at the International Symposium on Gravity, Geoid and Heights Systems 2 (GGHS) on September 17-21, 2018 in Copenhagen, Denmark. At the time, there were 8 groups who contributed their models to the comparison.

A splinter meeting was held jointly with JSG0.15, SC2.2 and ICCT JSG 0.15 at GGHS. It was agreed that multiple iterations of geoid computations are necessary, and that the results should be published in a special issue of Journal of Geodesy. The first iteration has models from 14 groups, a more than 70% increase in the number of participating groups. The analysis of the model comparisons will be shown at the IUGG 2019 meeting in July in Montreal, Canada. The description of methods and results of each group will be peer reviewed and published in the JG special issue.

Sub-commission 2.3: Satellite Gravity Missions

Chair: *Adrian Jäggi (Switzerland)*
Vice Chair: *Frank Flechtner (Germany)*

Overview

Sub-commission 2.3 promotes scientific investigations concerning the dedicated past CHAMP, GOCE, GRACE (e.g., Tapley et al., 2019), and the ongoing GRACE-FO (Follow-On) satellite gravity field missions, the development of alternative methods and new approaches for global gravity field processing also including complementary gravity field data types, as well as interfacing to user communities and relevant organizations. The sub-commission is accompanied by a steering committee consisting of the members Srinivas Bettadpur, Sean Bruinsma, Thomas Gruber, Roland Pail, Torsten Mayer-Gürr, Ulrich Meyer, Cheinway Hwan, Shuanggen Jin, Federica Migliaccio, and Gerhard Heinzel. At its splinter meeting at the International Symposium on Gravity, Geoid and Height Systems (GGHS) 2016 the steering committee was further enlarged by Annette Eicker and Carmen Böning. The members of the steering committee cover all relevant aspects from the generation, analysis and use of static and temporal global gravity field models based on data from dedicated gravity field missions, the combination of different satellite and terrestrial data types, and the study of future gravity mission concepts. Based on discussions at the GGHS 2016 splinter meeting and among the steering committee members, the focus of SC 2.3 during the reporting period was put on the following activities:

COST-G: a new IAG component to provide time-variable gravity field solutions

The chair and vice chair of SC 2.3 were leading the activities of the European Gravity Service for Improved Emergency Management (EGSIEM), a project of the Horizon 2020 Framework Program for Research and Innovation of the European Commission aiming to unify the knowledge of the GRACE/GRACE-FO community to pave the way for a long awaited standardisation of time-variable gravity-derived products and to explore new and innovative approaches for gravity-based flood and drought forecasting (Jäggi et al., 2019). To achieve these objectives, different prototype services were established in the frame of the EGSIEM project. Based on this, a proposal has been submitted by SC 2.3 to the IAG Executive Board to continue one of the EGSIEM prototype services, the so-called Scientific Combination Service, beyond the EGSIEM project under the umbrella of IAG's International Gravity Field Service (IGFS). The new IAG component was proposed to be called International Combination Service for Time-variable Gravity Fields (COST-G) and shall deliver consolidated time-variable global gravity field models by combining solutions from several individual analysis centers (ACs, see Figure 29). The contributing ACs shall base their analyses on different methods but apply agreed-upon consistent processing standards to deliver consistent time-variable gravity field models. The combination of the individual solutions shall be performed both on the level of the individual gravity field solutions (Jean et al., 2018) and on the level of normal equations exchanged via SINEX files (Meyer et al., 2019). This concept shall mainly be adopted to data from the past GRACE and the current GRACE-FO missions, but combinations from non-dedicated missions such as from ESA's magnetic field mission Swarm or from spherical SLR satellites may also be performed. A first draft of the COST-G terms of references (ToR) has been submitted to IAG and subsequently been discussed at the IAG Executive Board meeting during the EGU General Assembly 2017 in Vienna, Austria. Based on this discussion further iterations about structural elements of COST-G and its role under the umbrella of IGFS were performed by involving the IGFS President, Riccardo Barzaghi, IAG's Commission-2 President, Roland Pail, and IAG's Secretary General, Herman Drewes. Eventually COST-G was formally approved at the IAG Executive Committee meeting during the EGU General Assembly 2018 in Vienna, Austria. The agreed-upon structure is currently already being reflected on the IGFS website (see Figure 30), where COST-G may be found as a new Product Center of the IGFS.

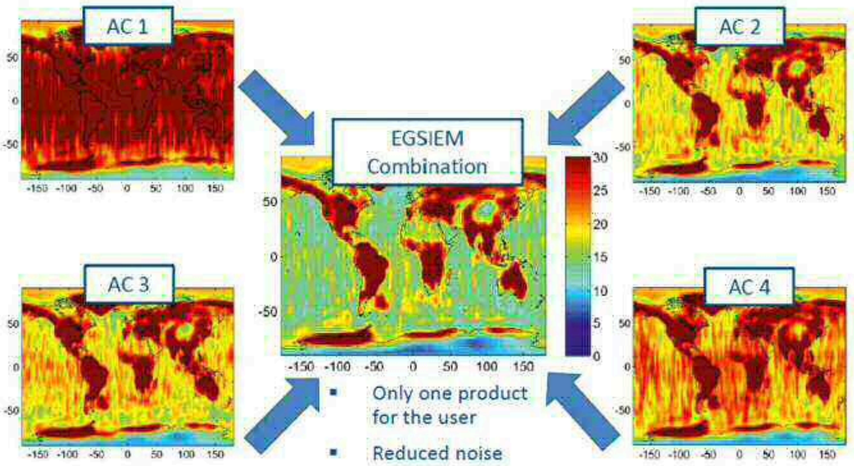

Figure 29 Principle of the COST-G service to generate one consolidated time-variable gravity field product for the user community as a combination of several solutions produced at different analysis centers (ACs).

The IGFS coordinates the following "Level-1" IAG services and service centres

- BGI (Bureau Gravimetrique International), Toulouse, France
- ISG (International Service for the Geoid), Milano, Italy
- ICGEM (International Center for Global Earth Models), Potsdam, Germany
- COST-G (International Center for Global Earth Models), Bern, Switzerland
- IDEMS (International Digital Elevation Model Service), Leicester, UK
- ICET (International Center for Earth Tides), Faaa, Tahiti, French Polynesia
- Technical Support Centre of IGFS, NGA, Saint Louis, USA

Figure 30 COST-G under the umbrella of IGFS as product center for time-variable gravity fields, see http://igfs.topo.auth.gr/igfs-presentation/.

In order to optimally coordinate the preparational phase of COST-G, Richard Biancale (unfortunately passed away on Feb 4, 2019) and the chair of SC 2.3 submitted a proposal to the International Space Science Institute (ISSI) to set-up an international team devoted to support the set-up of COST-G. The submitted proposal was favourably evaluated by the ISSI science committee and the first COST-G International Team Meeting took eventually place at the ISSI premises in Bern, Switzerland, during the week of 14-18 January 2019. Participants from the Astronomical Institute of the University of Bern (AIUB), Centre National d'Etudes Spatiales (CNES), German Research Center for Geosciences (GFZ), Graz University of Technology (TUG), University of Hanover (LUH), Stellar Space Studies (SSS), and DGFI-TUM discussed both technical and programmatic issues of COST-G. A major outcome of the ISSI team is the finalization of the COST-G ToR, which may be found in the appendix of the SC 2.3 report. It is worth mentioning that besides the original EGSIEM ACs also the Center for Space Research (CSR) agreed to contribute to COST-G. The Jet Propulsion Laboratory (JPL) is still considering to contribute, but did not yet give their formal consent at the time of writing this report.

COST-G is currently planned to go officially online at the 2019 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Montréal, Canada. At this occasion a first release of a combined GRACE monthly gravity field series covering the entire GRACE period will be made available by COST-G. Already now COST-G provides an operational combination of monthly gravity field solutions from the non-dedicated Swarm mission in the frame of an ESA project led by the Technical University of Delft (Visser et al., 2019). At the EGU General Assembly 2019 in Vienna, Austria, COST-G also started a further initiative led by DGFI-TUM to study combinations of monthly gravity field solutions as derived from a multitude of spherical SLR satellites (Bloßfeld et al., 2019).

By May 28, 2019 the COST-G ACs will eventually get access to the GRACE-FO Level-1B data, which so far were only available to the members of the GRACE-FO Science Data System (SDS) for verification and validation purposes. It is expected that at least half a year of time will be needed for the COST-G ACs to get acquainted with the GRACE-FO data. A second meeting of the ISSI COST-G International team is thus planned for January 2020 in Bern, Switzerland, where COST-G will eventually decide on the strategy for an operational provision of combined GRACE-FO monthly gravity fields.

Recommendations of the Geodetic Missions Workshop 2017 in Banff, Canada

Members of the of the steering committee of SC2.3 were actively involved in the formulation of recommendations from the Geodetic Missions Workshop 2017 in Banff, Canada, towards the ESA directorate of Earth observation. In view of the fact that presently no operational gravity mission is planned and recognizing the need for better water management, disaster preparedness as well as climatological time series and considering the increasing lack of ground-based and up-to-date observations, a sustained gravity observation space infrastructure with higher spatial and temporal resolutions and reduced latency in comparison to present demonstrator missions such as GRACE and GRACE-FO was recommended to be implemented as a future Sentinel mission of the European Copernicus Programme.

Increase the visibility towards the European Copernicus Programme

In order to promote the needs of the gravity field community towards the European Copernicus Programme, several lobby events have been organized in Brussels. A first so-called "Tea Time Event" was organized on March 2, 2017 at the Helmholtz Office in Brussels with the support of GFZ's EU project office and the Swiss Contact Office for European Research, Innovation and Education (SwissCore) to inform representatives of the European Commission on achievements of satellite gravimetry and future perspectives. A second and larger event, entitled "Observing water transport from space – a vision for the evolution of Copernicus", was organized by GFZ's EU project office on May 31, 2017 at the Radisson Red Hotel in Brussels to inform representatives of ESA and the European Commission that gravity missions are now ready to be integrated in the European space infrastructure and that continuous gravity measurements are essential for numerous crucial questions regarding changes and dynamic processes in land, freshwater hydrology, cryosphere, ocean, atmosphere and solid Earth. Besides teaser talks given at both events by Annette Eicker and Carmen Böning, the distribution of flyers and position papers, the President of IAG's Commission-2, Roland Pail, additionally informed at the second event on the science and user needs for a sustained observation of global mass transport from space as they were established by more than 80 international experts under the umbrella of the IUGG (Pail et al. 2015).

Due to the limited response of the European Commission on these events, the focus on increasing the visibility towards Copernicus was slightly adapted afterwards. As a member of the National Support Group on H2020-Space in Switzerland, the chair of SC 2.3 had since 2018 direct access to early versions of the H2020 Work Programmes of the Earth Observation Calls. Suggestions for input to the Work Programmes and changes of specific wording were therefore submitted via the national delegates of the members of SC 2.3, in particular for the DT-SPACE-24-EO-2020 Call "Copernicus evolution - Mission exploitation concepts". In parallel the chair and vice chair of SC 2.3 were suggesting to set up a new H2020 proposal to promote and ingest satellite gravimetry data into the existing Copernicus services. Based on their initiative a proposal entitled "Global Gravity-based Groundwater product (G3P)" led by GFZ Potsdam has been submitted in response to the Earth Observation Call LC-SPACE-04-EO-2019-2020: Copernicus evolution – Research activities in support of cross-cutting applications between Copernicus services. The evaluation results of this effort are expected to be communicated in summer 2019.

Support of current and fostering of new gravity field missions

Members of the SC 2.3 initiated, managed and significantly contributed to the satellite gravity mission proposal "Mass variation observing system by high-low inter-satellite links (MOBILE)" in response to ESA's call for ideas on Earth Explorer (EE) 10 missions. It was based on the innovative idea of high-precision inter-satellite distance measurements between Medium Earth Orbiters (MEOs) and at least one Low Earth Orbiter (LEO) with micrometer accuracy (Pail et al. 2019). A scheme of the constellation set-up is shown in Figure 31. The main advantage of this mission concept is the close to radial measurement geometry and the associated isotropic error structure, in contrast to the typical striping artefacts resulting from GRACE/GRACE-FO-type along-track inter-satellite ranging (Hauk et al. 2019). Additionally, the modularity of the concept as well as the option to integrate it in already existing space infrastructure makes this mission concept a valuable option for realizing a sustained long-term gravity monitoring system from space. Unfortunately, the mission proposal was not selected among the three EE10 candidate missions by ESA.

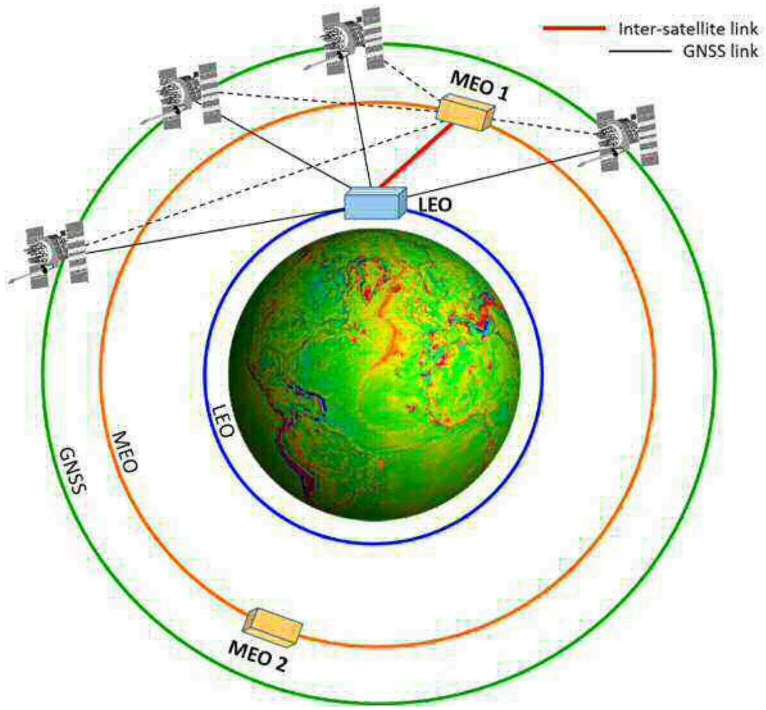

Figure 31 MOBILE mission concept.

Members of the SC 2.3 were also heavily involved in the development and implementation of the GRACE Follow-On mission (Flechtner et al. 2016), as well as the potential implementation of a mass transport mission in the frame of NASA's Earth Science Decadal Survey 2018.

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Sub-commission 2.4: Regional Geoid Determination

Chair: Maria Cristina Pacino (Argentina)
Vice Chair: Hussein Abd-Elmotaal (Egypt)

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 M.C. Pacino, Argentina)
- SC 2.4c: Gravity and Geoid in North and Central America (chair Marc Véronneau, Canada)
- SC 2.4d: Gravity and Geoid in Africa (chair H. Abd-Elmotaal, Egypt)
- SC 2.4e: Gravity and Geoid in the Asia-Pacific (chair Jay Hyoun Kwon, Korea)
- 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
A complete re-computation of the European quasigeoid (EGG2015) based on a 5th generation GOCE geopotential model was presented at the 26th IUGG General Assembly in Prague, Czech Republic, 2015 (Denker 2015). A further complete update was done in 2016 (EGG2016) in preparation for a new national quasigeoid model for Germany. The EGG2015 model served for deriving gravity potential estimates and the associated relativistic redshift corrections for optical clock comparisons (Denker et al. 2018, Voigt et al. 2016).

SC 2.4b: Gravity and Geoid in South America
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 971.413 stations gravity data are available for geoid determination. A new South America geoid model has been computed on a 5' x 5' grid, by the remove-compute-restore technique using 971.413 point gravity data (free-air gravity anomalies), the SAM3s_v2 DTM for the computation of terrain correction and other topographic and atmospheric effects. An A-10 gravity meter, under the responsibility of the University of São Paulo, was involved in various activities in São Paulo and in Brazil, out of Argentina, Venezuela, Costa Rica and Ecuador.

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 focus on the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA’s National Geodetic Survey (NGS). This modernisation, to be released in 2022, 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).

SC 2.4d: Gravity and Geoid in Africa

Abd-Elmotaal et al. (2017a) have computed the most detailed 3" × 3" DTM for Africa to date using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). Abd-Elmotaal et al. (2018d and 2018c) have established two new gravity databases for Africa, AFRGDB_V2.0 and AFRGDB_V2.2 using the new sub-data set, available by BGI, together with the old data set after correcting the gravity values in many places, especially at Morocco. From this data, several local geoid models have been developed.

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

The activity of SC 2.4e was rather low in the reporting period 2015-2019. It focussed on activities in Korea and Taiwan, where additional gravity observations and improved geoid modelling were performed. In Taiwan, absolute gravity changes were interpreted by geodynamic processes, and in Korea a calibration site for relative gravimeters has been established.

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

Further progress has been made to include new data and to open access to already existing data. Here, especially the PolarGap campaign, an international effort of Denmark, the UK and Norway improved the data situation in the region very close to the South pole, which is not covered by GOCE measurements. As a highlight the publication of the first Antarctic-wide gravity anomaly dataset has to be mentioned (Scheinert et al., 2016).

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. SC 2.4a has cooperated with national delegates from nearly all European countries, whereby existing contacts have been continued and extended.

European Quasigeoid

A complete re-computation of the European quasigeoid (EGG2015) based on a 5th generation GOCE geopotential model was presented at the 26th IUGG General Assembly in Prague, Czech Republic, 2015 (Denker 2015). A further complete update was done in 2016 (EGG2016) in preparation for a new national quasigeoid model for Germany. Besides that, the terrestrial gravity and terrain data base was continuously improved, with significant updates performed, e.g., for Germany and Bulgaria. In addition, some new contacts to countries in Eastern Europe developed and possibly some further data updates may occur in this region. A major re-computation of the European quasigeoid is foreseen for 2020. The developed quasigeoid models were evaluated by different national and European GPS and levelling data sets, where emphasis was put on the effect of the data updates and the modelling refinements. Furthermore, applications of the quasigeoid model, such as vertical datum connections and the delivery of ground truth data for high-precision optical clock comparisons, were investigated. In this context, the EGG2015 model served for deriving gravity potential estimates and the associated relativistic redshift corrections for optical clock comparisons (Denker et al. 2018, Voigt et al. 2016). For instance, such a comparison of optical clocks was carried out between Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and Laboratoire national de métrologie et d'essais – Système de Références Temps-Espace (LNE-SYRTE) in Paris, representing the first optical frequency comparison across national borders; the fully independent clocks agreed with an unrivalled fractional uncertainty of 5×10^{-17}, which corresponds to a height uncertainty of about 0.5 m (Lisdat et al. 2016). Further clock comparisons were supported in Italy (Grotti et al. 2018) and in Germany (between PTB and Max-Planck-Institut für Quantenoptik, MPQ, in Garching near Munich), approaching the 1 – 2 decimetre level. Further improvements of the transportable optical clocks are expected soon, aiming at a performance level of 10^{-18}, which corresponds to a height uncertainty of about 1 cm. Hence, the optical clocks may offer in the near future completely new options to independently observe and verify geopotential differences over large distances, with the perspective to overcome some of the limitations inherent in the classical geodetic approaches (Mehlstäubler et al. 2018, Delva et al. 2019). For example, clocks could be used to interconnect tide gauges on different coasts without direct geodetic connection and help to unify various national height networks, even in remote areas.

Besides the work related to the optical clocks, a new official German quasigeoid model GCG2016 (German Combined QuasiGeoid 2016) was developed on the basis of gravimetric (EGG2016) and GNSS/levelling data; this work was done in cooperation with Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany (for further details see BKG 2016). Furthermore, regional gravity field modelling based on point masses (Lin et al. 2019) and the computation of topographic and atmospheric effects with tesseroids was investigated (Lin and Denker 2019). In addition to this, contributions were made to IAG Joint Working Group (JWG) 0.1.2. “Strategy for the Realization of the International Height Reference System (IHRS)” and Sub-Commission SC 1.3a: Europe (EUREF – Regional reference frames).

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

Chair: *Maria Cristina Pacino (Argentina)*
Vice Chair: *Denizar Blitzkow (Brazil)*

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 by different organizations, universities and research institutes.

Improvements of gravity data bases

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 971.413 stations gravity data are available for geoid determination. Figure 32 shows the new and old gravity data. The new gravity observations have been carried out with LaCoste&Romberg and/or CG5 gravity meters. GPS double frequency receivers have been used to derive the geodetic coordinates of the stations. The orthometric height for the recent surveys was derived from geodetic height using EGM2008 restricted to degree and order 150.

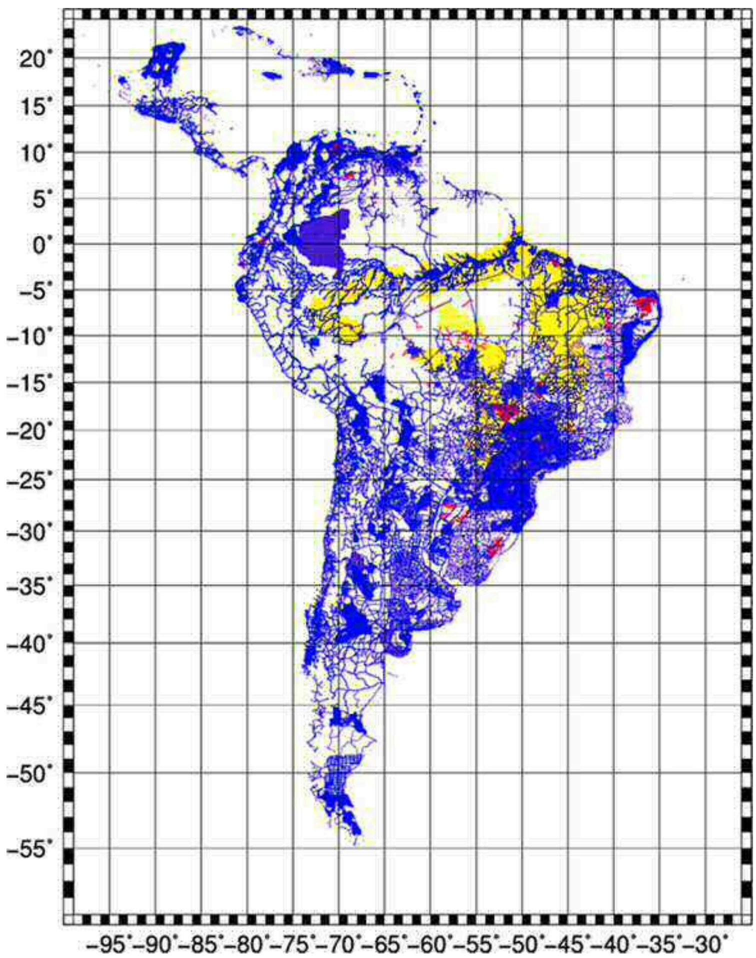

Figure 32 South America gravity data

Argentina

The last four years, 1070 new gravity stations have been measured in Corrientes and Missiones provinces in Argentina (green and red points in Figure 33, respectively).

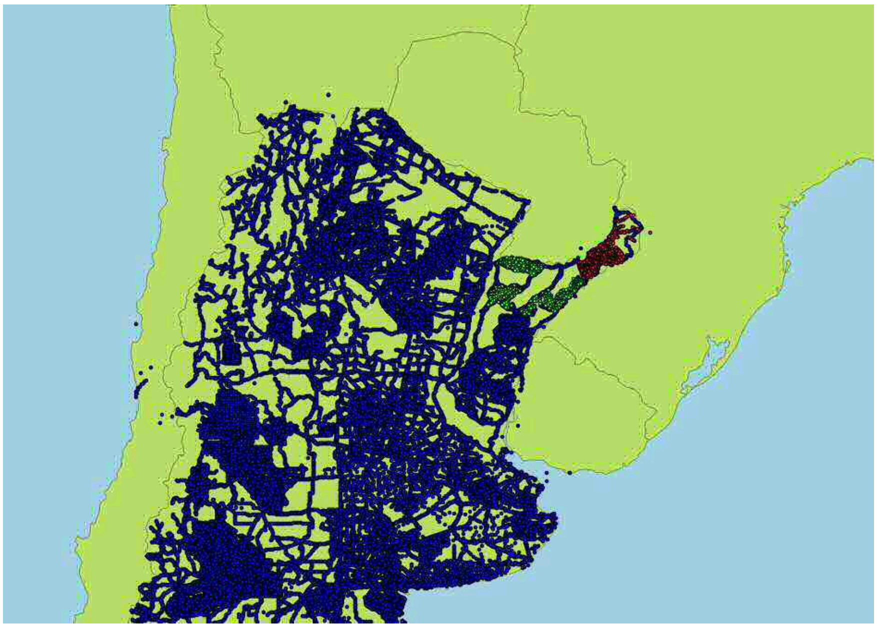

Figure 33 *Gravity data in Argentina*

Brazil

In the last five years, IBGE (CGED), Polytechnic School of the University of São Paulo, Laboratory of Surveying and Geodesy (EPUSP-LTG), SAGS project (GETECH/NGA) and the Thematic Project (FAPESP, Brazilian research foundation) a total of 18.186 new gravity stations have been measured (Figure 34 and Figure 35).

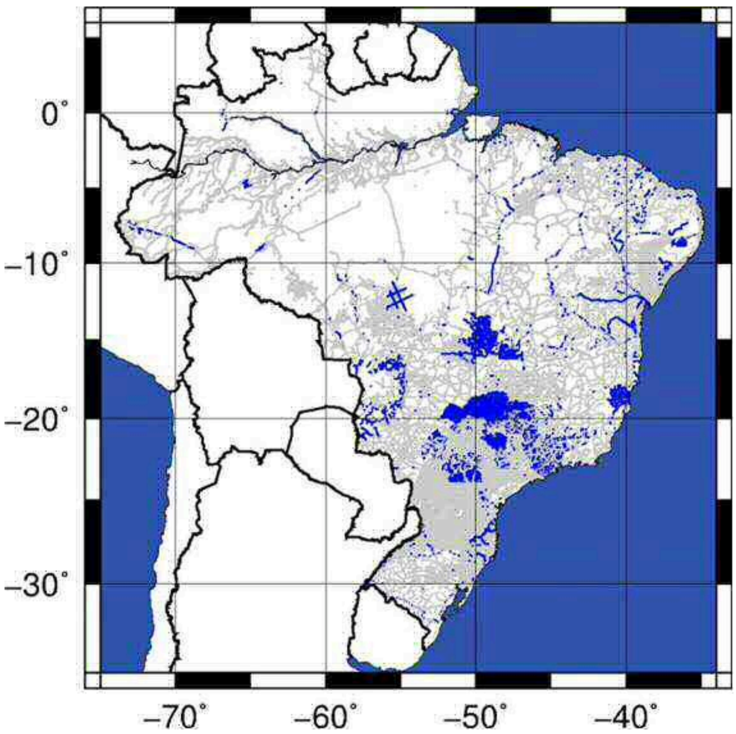

Figure 34 Brazil new gravity data.

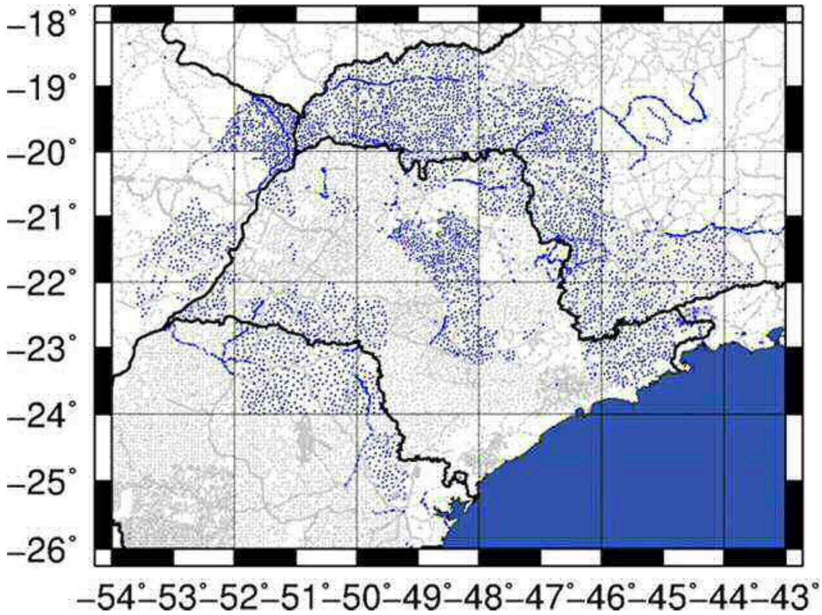

Figure 35 Thematic Project and EPUSP-LTG survey.

Ecuador

From 2013 up to 2016, gravimetric surveys in Ecuador obtained 1194 new points. SAGS gravity data were surveyed by IGM, IBGE and EPUSP. The gravity values of the densification surveys were connected to the existing FGN (Fundamental Gravity Network) in the country. Figure 36 shows the surveys of the 2013, 2014, 2015, and 2016 with pink, green, yellow and red points, respectively.

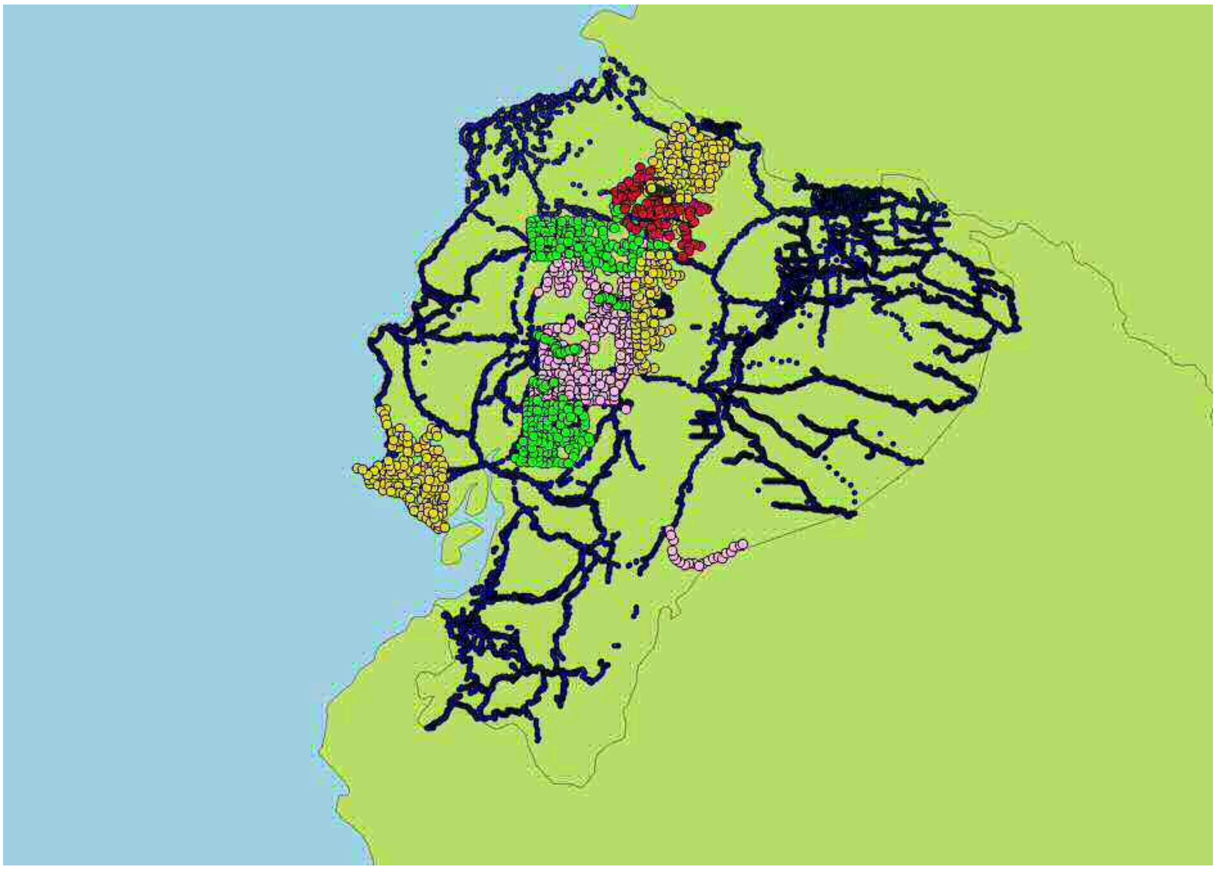

Figure 36 Ecuador surveys.

Venezuela

A total of 591 new gravity stations have been recently measured. They were observed by *Instituto Geográfico Venezuelano Simon Bolivar* (IGVSB), IBGE and EPUSP, densification network on roads (brown, pink and green points in Figure 37) and rivers in the South (orange and yellow points in Figure 37) in Venezuela.

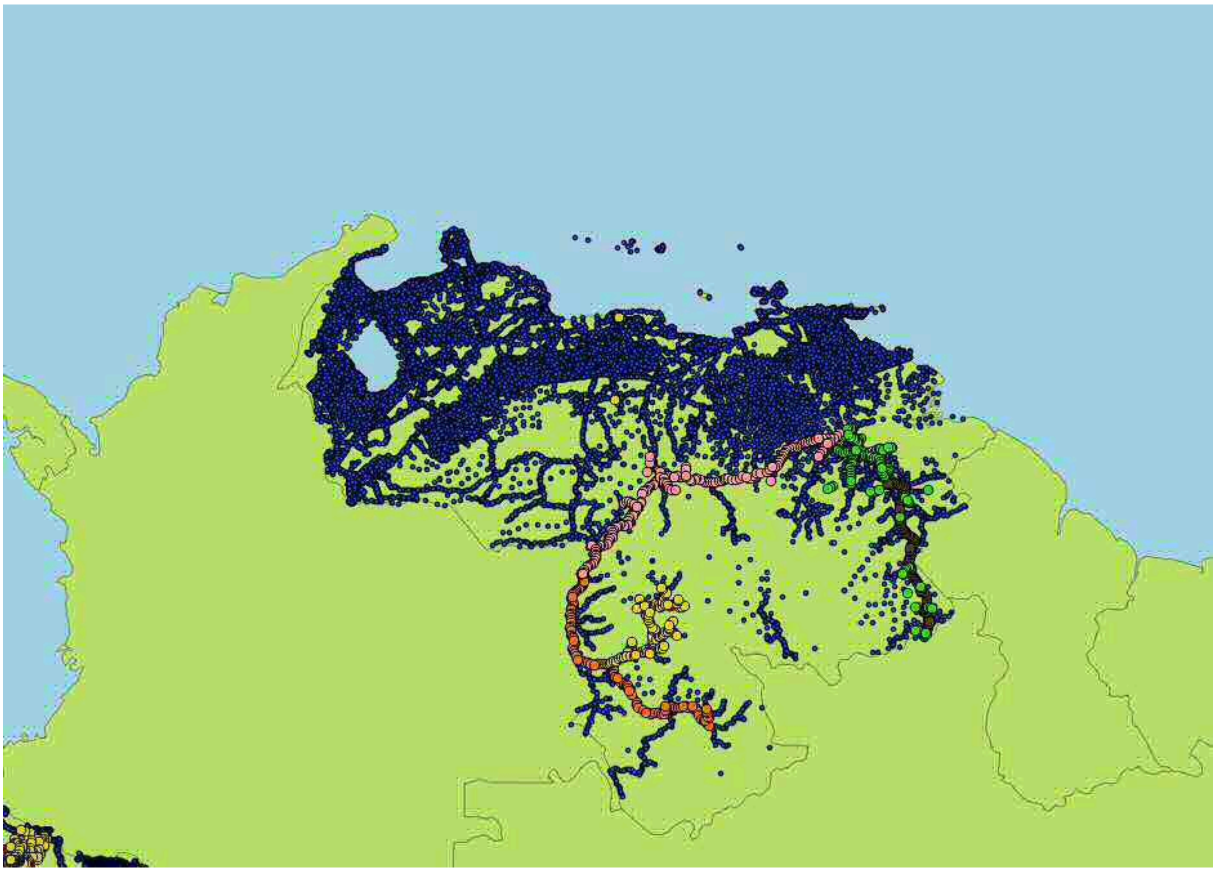

Figure 37 Gravity survey in Venezuela.

Earth tide model

University of São Paulo, supported by a few organizations, is involved in a project for Earth Tide model for Brazil. The idea is to occupy a sequence of 13 stations around the country for one year in each station. The cities planned for occupation are: Cananeia, Valinhos, São Paulo, Presidente Prudente, Porto Velho, already observed, Manaus and Brasilia, under observation at the moment; 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 gPhone gravity meters are available. Figure 38 shows the distribution of the stations.

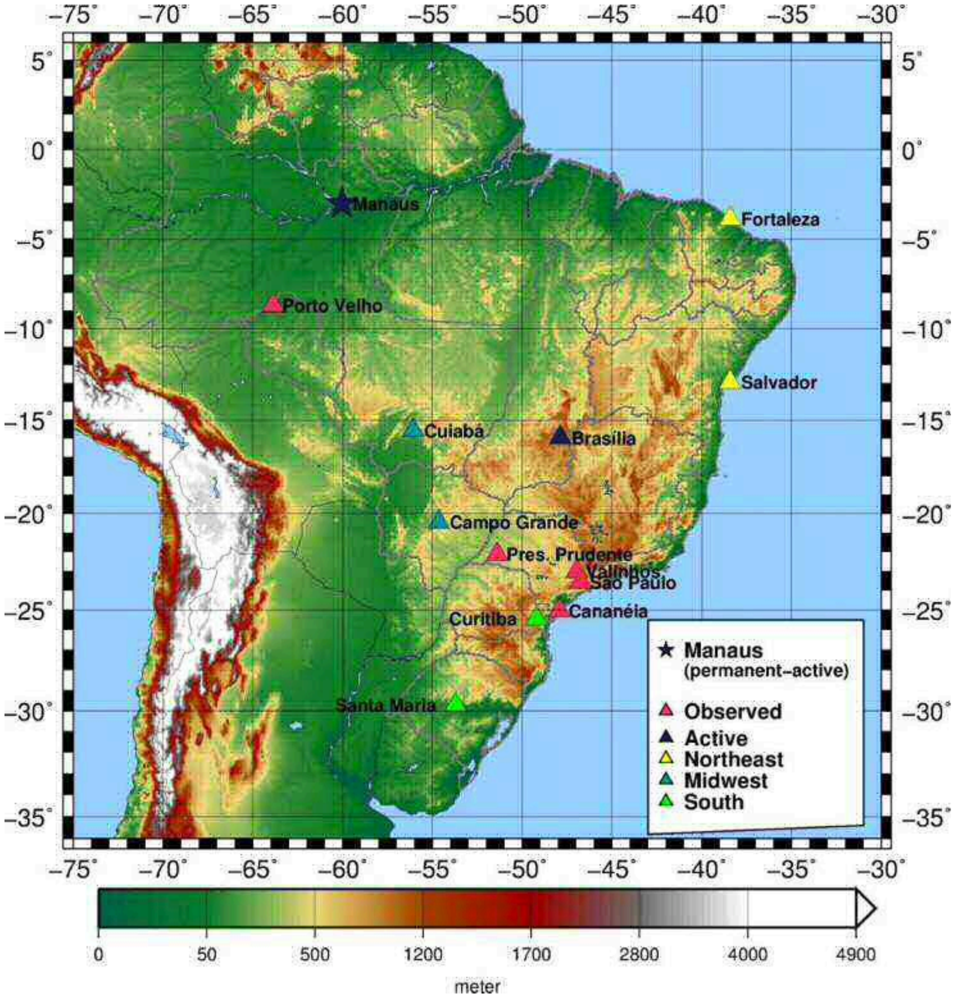

Figure 38 Distribution of sites to be observed for Earth tides.

Absolute gravity measurements

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 39). The gravity meter is involved in various activities in São Paulo and in Brazil, out of Argentina, Venezuela and Ecuador. Figure 40 shows the establishment of new (blue point) and reoccupied (red points) absolute stations in São Paulo State. From north to south of Brazil a set of absolute stations have also been established (Figure 41). The idea is to establish an absolute gravity network in Brazil and in South America.

Figure 39 Absolute gravity meter A10-32.

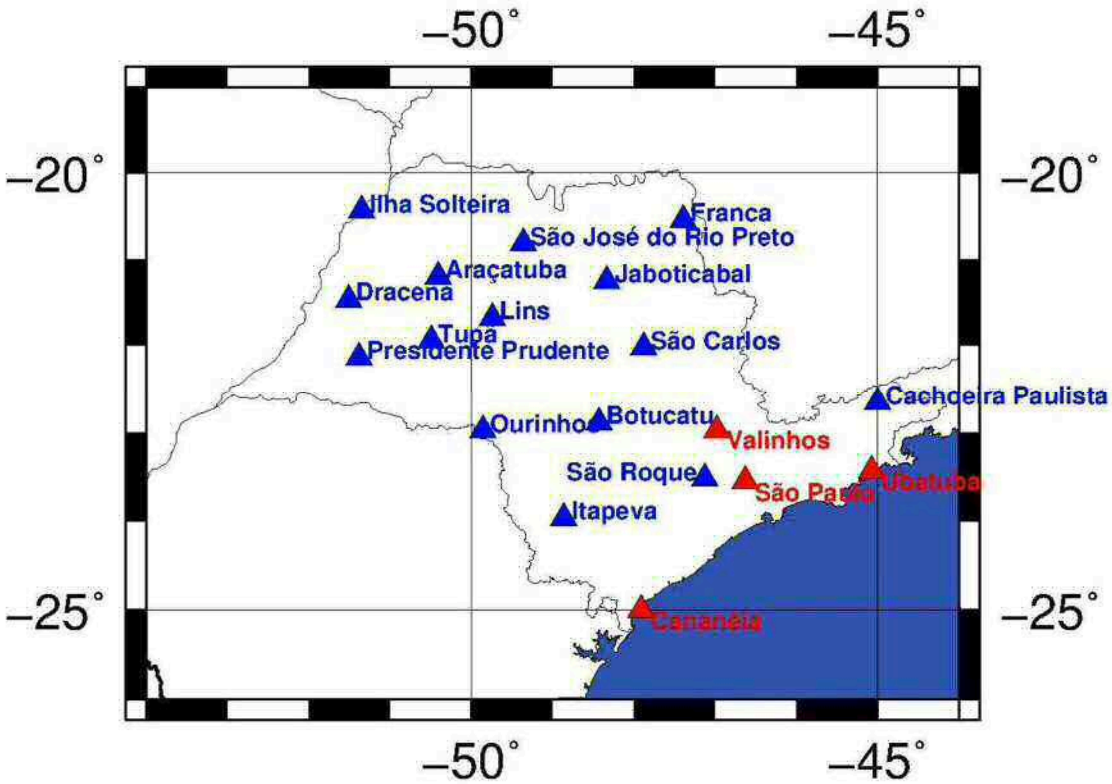

Figure 40 Absolute gravimetric stations in São Paulo State.

Figure 41: Absolute gravity stations in Brazil.

Absolute Gravity Network - Argentina

University of São Paulo, Polythecnic School, Department of Engineering Transportation (EPUSP-PTR) supported by Institute of Geography and Cartography (IGC) of São Paulo and Centro de Estudos de Geodesia (CENEGEO), National Geographic Institute of Argentina, National Universities of Rosario and San Juan and the Institute of Research for Development IRD (France), cooperated for the establishment of the Absolute Gravity Network in the country The network was developed in three stages of measurement: “North”, “South” and “Seismic zone”, taking out a total of 43 measurements of absolute gravity with 36 final points, 4 of them with double measurement, 2 with triple measurement, and one with 4 measurements (Figure 42). The National Geographic Institute officially adopted RAGA as the National Zero Order Gravimetric Network for Argentina.
In order to consolidate and improve the network, the measurements will continue in order to:

- Initiate a systematic re-measurement of the points already measured to detect possible changes and analyzing their causes and effects.
- Network densify to progressively improve the fit of existing points.
- Measure at least one point of absolute gravity at the Isla Grande de Tierra del Fuego.

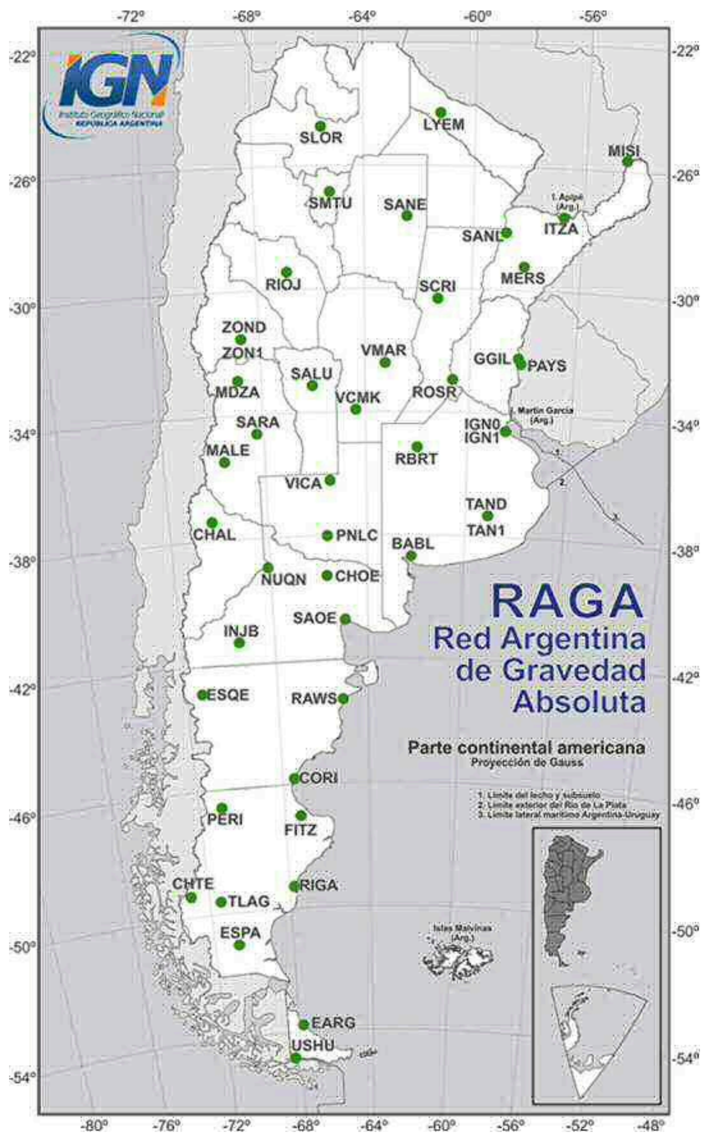

Figure 42 Absolute Gravity Network in Argentina

Absolute Gravity Network – Costa Rica

University of São Paulo, Polythecnic School, Department of Engineering Transportation (EPUSP-PTR) supported by Institute of Geography and Cartography (IGC) of São Paulo and Centro de Estudos de Geodesia (CENEGEO) and the University of Costa Rica, Faculty of Surveying Engineering and Instituto Geográfico Nacional (IGN), Costa Rica, cooperated for the establishment of the Absolute Gravity Network in the country. A total of 18 stations have been observed (Figure 43). The measurements have been undertaken with A-10 Micro-g LaCoste absolute gravitymeter, number 032. The stations are identified by the name of the city as follow: San José (UCR), Pavas (TOBI), San José (EITL), Heredia (GTCG), Cerro Buenavista (CDMT), Buenos Aires (BURE), Golfito (UCRG), Quepos (QUEP), Esparza (ESPA), Nicoya (UNAN), Liberia (LIBE), Santa Rosa (PNSR), Tilarán (TILA), Los Chiles (CHIL), Turialba (UCRT), Limon (UCRL), Sarapiqui (SARA), Gandoca (RGMO). Figure 43 shows the distribution of the stations in the country. The final results are under analysis and they will be published very soon. But, it is already known that the Standard Deviation (S.D.) of the network, in most of the stations, are between 10 to 12 μGal. This network will be a contribution for the International Global Absolute Reference Frame (IAGRF). The following people participated to the efforts for the measurements: Denizar Blitzkow and Ana Cristina O. Cancoro de Matos from CENEGEO; Iuri Bjorkstrom and Valéria Cristina Silva, from University of São Paulo; Oscar H. Lucke, Juan Antonio Picado Salvatierra, Jaime Garbanzo Leon, Alonso Vega Fernandez from University of Costa Rica, Álvaro Álvarez Calderón from the National Geographical Institute of Costa Rica.

In the past two important efforts have been experienced in Costa Rica. In the first case, IGSN71 efforts set up two gravity reference stations. One of the sites was located in the Central Park of the capital city of San José. The other site was placed in the coastal city of Puntarenas. This last one is important since it is near the site of the tide gauge used to establish the mean sea level, which was a height reference for the original geodetic network of Costa Rica.

After IGSN71, the geophysics commission of the Pan-American Institute for Geography and History formed a group called the Latin-American Gravity Informative System (known as SILAG for its initials in Spanish) with support of the Inter-American Geodetic Survey (IAGS), at that time. This group, with support of the individual geographical institutes of the nations involved, implemented a project called Latin-American Network for the Normalization of Gravity 1977 (known as RELANG77 for its initials in Spanish). This project created a network of gravity reference stations through relative gravity observations based on the IGSN71 values. For Costa Rica, RELANG created eight gravity reference stations.

Moreover, Costa Rica is located within a highly dynamic region regarding tectonics and volcanism. This means that the gravity value might change over time due to vertical deformation of the surface caused by crustal faults and subduction processes and due to changes in the internal mass distribution caused by magmatic processes. So, the present absolute network will be very important for gravity changes monitoring, between other applications.

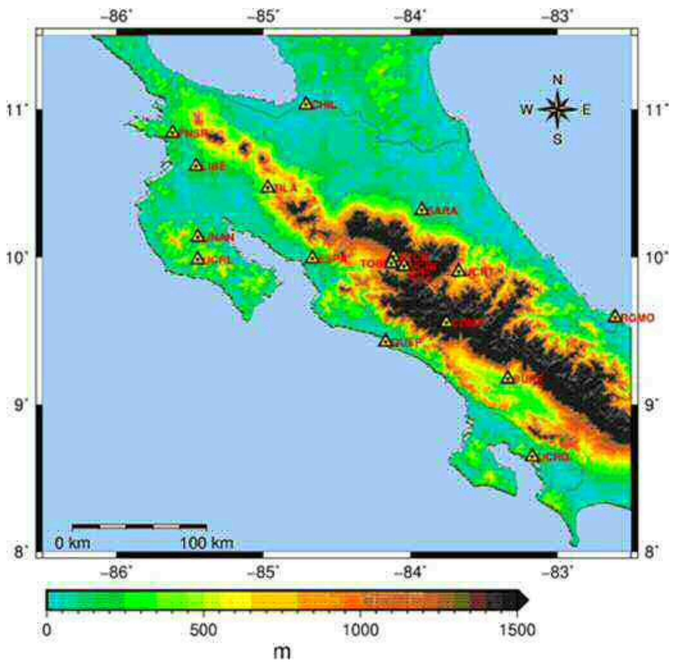

Figure 43 Absolute Gravity Network in Costa Rica

Absolute Gravity Network – Venezuela

USP (Universidade de São Paulo) and IGC (Instituto Geográfico e Cartográfico de São Paulo) are cooperating in the establishment of Absolute Gravity Network in Venezuela. The observations had the collaboration of IBGE (Instituto Brasileiro de Geografia e Estatística), CENEGEO (Centro de Estudos de Geodesia), IGVSB (Instituto Geográfico Venezolano Simón Bolívar) and PEDVESA (Petróleo Venezolano SA). In two campaigns a total of 13 stations have been established with three re-observations (R) (Figure 44). The measurements have been undertaken with A-10 Micro-g LaCoste gravimeter, number 032. The stations are identified by the name of the city as follow: CAGIGAL, MARACAIBO, SANTA INÉS, CARACAS, CIUDAD BOLIVAR, EL CALVARIO, ELORZA, JUNQUITO, LA GUAIRA, MATURIN, MERIDA, PUERTO AYACHUCO, SANTA ELENA DE UAIREN. The final results are available on request.

Figure 44 Distribution of the Absolute Gravity Stations in the Venezuela

South America geoid model (GEOID2015)

The new South America geoid model has been computed on a 5' x 5' grid, by the remove-compute-restore technique using 971.413 point gravity data (free-air gravity anomalies), the SAM3s_v2 DTM for the computation of terrain correction and other topographic and atmospheric effects. The mean free-air gravity anomaly (FA) in a 5' grid over continent was derived from the complete BA (FA over the ocean obtained from satellite altimetry model DTU10). The short wavelength component was estimated with FFT technique using the modified Stokes integral through spheroidal Molodenskii-Meissl kernel modification. The reference field used was EIGEN-6C4 up to degree and order 200. The computed points are in a grid of 5' x 5' covering the area from 56.9583333° S to 14.9583333° N in latitude, and from 94.9583333° W to 30.0416667° W in longitude. The geoidal heights are referred to WGS84 (Figure 45). The model is available in ISG site (http://www.isgeoid.polimi.it/).

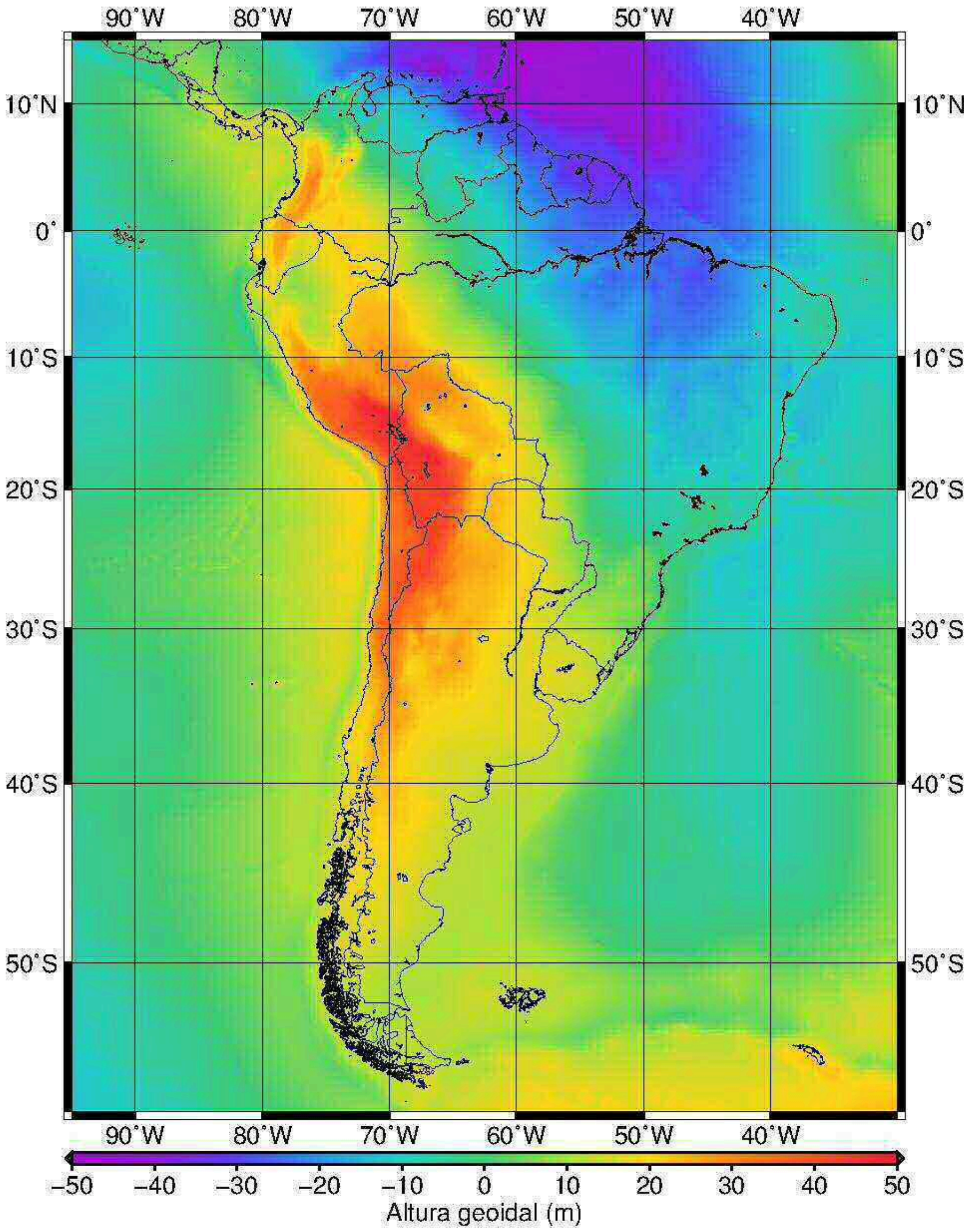

Figure 45 The new South American geoid model GEOID2015

IHRF Brazil and Sao Paulo state

In order to implement the International Height Reference Frame (IHRF) in Brazil, the Instituto Brasileiro de Geografia e Estatística (IBGE) selected 6 stations from 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). Recently in CUIB, BRAZ and PPTE absolute gravity observations have been undertaken with A-10/032 gravitymeter; similar measurements should be obtained in the near future in the remaining stations. The actual gravity data distribution around a 210 km (~2°) radius is shown. In order to reach IHRF requirements, a terrestrial gravity densification around IHRF stations has been carried out since 2017 by IBGE. Another future issue is to connect IHRF stations to the levelling network. The disturbing potential was computed by Hotine method using the numerical integration procedure. 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.

Sub-commission 2.4c: Gravity and Geoid in North and Central America

Chair: *Marc Véronneau (Canada)*
Vice Chair: *David Avalos (Mexico)*

Overview

The activities of the sub-commission 2.4c (Gravity and Geoid in North and Central America) is principally focus on the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA's National Geodetic Survey (NGS). This modernisation, to be released in 2022, 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, the sub-commission 2.4c contributes to the vertical component of the modernisation. (https://www.ngs.noaa.gov/datums/newdatums/)

As Canada already adopted a geoid-realised height reference system back in 2013 (Véronneau and Huang, 2016), one of the activities of the sub-commission 2.4c is to assure the alignment of the North American-Pacific Geopotential Datum of 2022 (NAPGD2022) with the Canadian Geodetic Vertical Datum of 2013 (CGVD2013). Already, US NGS and the Canadian Geodetic Survey (CGS) agreed on a common equipotential surface (W_0 = 62,6366,856.0 m^2s^{-2}); however, other parameters and concepts remain to be discussed in order to maintain a common height reference frame over the years. Current standards are described in a NOAA technical report (https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf).

Even though Mexico's INEGI and geodetic agencies for the Caribbean and Central America are not ready in adopting a geoid-based datum for their respective countries, they agreed informally in 2014 in using the same definition adopted at NGS and CGS. It is currently the same value as adopted in the IERS convention.

Under INEGI's leadership, a new regional gravimetric geoid model (Avalos et al., 2016) was determined for Mexico, Central America and the Caribbean (GGM-CA-2015; W_0 = 62,636,856 m^2s^{-2}). The realization of this model represents enhanced technical geodetic capabilities for eight national geographic institutions in the region: Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Mexico and the Dominican Republic. This activity was supported primarily by the Pan-American Institute of Geography and History (PAIGH), but as well by NGS, University of New Brunswick and the Mexican Agency for International Development and Cooperation (AMEXCID). Representatives from CGS and NGS travelled for geoid workshops at INEGI in Aguascalientes, Mexico at different occasions.

In order to assure good communication within the sub-commission 2.4c in the development of a geoid model for North America, Central America and the Caribbean, INEGI, NGS and CGS are holding monthly teleconferences since late 2015. NGS is hosting the teleconferences. At the same time, INEGI is taking a leadership role for communication with Central America and several Caribbean countries.

The sections below show some of the activities that the sub-commission is working on. The list is not necessarily exhaustive.

International Height Reference System

In 2015, the IAG introduced a resolution for the International Height Reference System (IHRS) and selected W_0 = 62,636,853.4 m^2s^{-2} (mean tide), which differs by 2.6 m^2s^{-2} with the valued agreed (tide free) between NGS and CGS in 2012. The IHRS datum is higher than the North American datum by about 26 cm. At mid-continent, the North American definition of the vertical datum has the mean sea level of the Atlantic Ocean near Halifax about 38 cm below the datum while the mean sea level of the Pacific Ocean near Vancouver about 17 cm above the datum.

INEGI, NGS and CGS contributed sites and terrestrial gravity data at these sites (50-km radius) for the IHRF reference stations.

In addition, NGS is coordinating geoid work with SIRGAS (sub-commission for South America).

Geospatial Summit

US NGS organized successful Geospatial Summits in 2015, 2017 and 2019 to provide information to their clients about the planned modernisation of National Spatial Reference System. These summits provide an opportunity to NGS to share updates and discuss the progress in their activities. In addition, they allow NGS to receive feedback and collect requirements from their stakeholder across the federal, public and privates sectors. CGS attended the first two summits in person, but remotely for the third summit. (https://www.ngs.noaa.gov/geospatial-summit/index.shtml)

IGLD (2020)

With the modernisation of the height reference systems in the USA and Canada, it also implicates impact to the International Great Lakes Datum of 1985 (IGLD (1985)). This vertical datum used for the management of the Great Lakes and the St-Lawrence Seaway was determined from the national adjustment of the North American levelling network (NAVD 88). However, the height are dynamic (H^d) and include hydraulic correctors to assure each lake is level. Members of the sub-communication 2.4c participate to the twice-yearly meetings of the Coordinating Committee to provide expertise in developing the new IGLD (2020), which will be based on NAPGD2022. Heights for the new IGLD (2020) will remain dynamic with hydraulic correctors. Though, the hydraulic correctors will be smaller in magnitude than for the current IGLD (1985).

CGS and NGS studied together quality of the geoid models over the Great Lakes using altimetry data and GNSS measurements at water gauges. Furthermore, the analysis demonstrated the usefulness of the airborne gravity data from the GRAV-D project in improving the geoid model, in particular over Lake Michigan where the shipboard gravity data are problematic. Results demonstrate that a 1.5 cm precision is achievable (Li et al., 2016).

In addition, CGS and NGS studied precision of the geoid models using water gauges data on the Great Lakes. Each agency made use of the gauges in their respective country. Preliminary results indicate that the geoid models can reduce the magnitude of the hydraulic correctors by a factor of two with respect to IGLD(1985). CGS and NGS presented their finding of the improvement to the IGLD at the AGU 2018 and EGU 2019, respectively.

Gravity

The GRAV-D project is progressing on schedule. As of April 2019, the project was 75.8% completed. Current progress of the GRAV-D project can be viewed on the NGS web site (https://www.ngs.noaa.gov/GRAV-D/).

As a highlight, GRAV-D successfully completed the first full airborne gravity survey on an optionally piloted aircraft, the Centaur operated by Aurora Flight Sciences. The survey was conducted out of North Carolina from mid-March to mid-April 2017 and collected high quality gravity data over the Appalachian Mountains.

Since 2014, NGS is releasing annually new experimental gravimetric geoid models (xGEOID*YY*) that incorporate new satellite gravity models (GRACE/GOCE), airborne gravity data under the GRAV-D project and all available terrestrial gravity data (https://beta.ngs.noaa.gov/GEOID/xGEOID/). For each new model, a similar model is calculated without using the GRAV-D data to study the contribution coming from the GRAV-D project. GRAV-D data are integrated to the geoid model by spherical harmonic expansion. The xGEOID19 geoid model, which is presently under construction, is a collaborative effort between CGS and NGS in anticipation of NAPGD2022. The model is developed using a common dataset (gravity and DEM).

These models are validated against the Geoid Slope Validation Surveys (GSVS) of 2011 and 2014 in Texas and Iowa, respectively. These surveys incorporate multi-techniques on a 325-km baseline: absolute gravity, relative gravity, GNSS, levelling and digital-camera deflections of the vertical. Wang et al. (2016, 2017) includes analysis of the Iowa line (high plateau going through the mid-continent gravity high). A third GSVS survey was completed in 2017 in the rough topography of the State of Colorado.

In 2016, CGS started experimenting with GRAV-D following a different approach, which consists in embedding them, with the proper frequency, to the terrestrial gravity data. Thus, it incorporates the GRAV-D data to the geoid model by the Stokes integration with a modified kernel. This work is still under development.

NGS hosted a successful five-day airborne gravimetry workshop for Geodesy Summer School in May 2016 in Silver Spring, MD. The session touches many topics: theory, collection, processing, instrumentation, etc. Renowned experts gave the lectures. The school was well attended with participants from USA, Canada and Europe.

NGS hosted the North American Comparison of Absolute Gravimeters in 2016 (NACAG16) at TMGO, near Boulder CO. NACAG16 included the participation of 14 institutions from nine countries across North America (Canada, Mexico, USA), Europe (Germany, Italy, Luxembourg, Russia) and South America (Brazil). The USA had four FG5 (NIST, NGS, Micro-g, NGA), Canada had two FG5 (NRC, CGS) and Mexico had one FG5 (CENAM). Results from NACAG16 are presented in a report available from NGS (van Westrum et al., 2016).

CGS finalized the realization of its Canadian Absolute Gravity Network. The 64 gravity sites are collocated with continuously-tracking GNSS stations or GNSS stations forming the Canadian Base network (force-centering concrete pillars anchored to the bedrock observed every ~five years). In addition, CGS maintains additional absolute sites for Geosciences (e.g., groundwater, GIA, seismic study). These sites are not only used for gravity standard in Canada, but also as a ground-infrastructure for the determination of g-dot and the relation between gdot and h-dot for geoid monitoring as a validation approach for GRACE. (http://webapp.geod.nrcan.gc.ca/geod/data-donnees/cgsn-rncg.php?locale=en)

In 2018, INEGI established 19 new absolute gravity sites in support to the national reference frame, which is linked to the standards of the International Absolute Gravity Base Network (IAGBN). The project was conducted in collaboration with NOAA. Additionally, the University of Hannover, in collaboration with CENAM (Mexico), established one new gravity site and re-observed 8 existing sites (originally observed in 2016) in southern Mexico for the purpose of monitoring temporal gravity variation. Mexico has now 28 absolute gravity sites allowing calibration of relative gravimeters and support to the establishment of IHRS stations.

Since 2019, Costa Rica has now 17 new absolute gravity sites to support the improvement of the national gravity network and the future establishment of one IHRS station.

INEGI is resuming the fieldwork of relative gravity data collection across Mexico. This activity falls under the project called National Gravity Densification, intended to produce a gravity dataset with a coverage as continuous and homogeneous as possible. The main goal is to achieve a minimum of five observations per cell of 5'x5' across Mexico. INEGI is observing about 5000 new stations (approximately 81,000 km^2) per year.

In El Salvador, the National Records Center of the National Institute of Geography (IGN/CNR) has measured gravity at 1,119 benchmarks, which represents 90% of the national levelling network. In addition, there is progress in the planning a project to conduct a national airborne gravity survey, which is expected to take place in 2020 or 2021.

As part of the realization of a unique geoid model for North America, NGS and CGS received a set of 9 million gravity points across North America from the US National Geospatial-Intelligence Agency (NGA). In addition, INEGI provided a gravity dataset of some 91,000 points across Mexico to NGS and CGS. The next activity is to clean these new datasets with respect to data already existing in the databases at CGS, NGS and INEGI and to build a unique dataset that the three agencies can used to develop geoid models. This would eliminate the discrepancies observed between the different geoid models due to inconsistent datasets. The same process will be done for the Digital Elevation models.

As of early 2019, a first version of a common dataset is now available between IBEGI, NGS and CGS, but more work is required to improve the dataset further.

Geoid Monitoring

NGS put in place a team to focus on geoid monitoring allowing study variability of the geoid in time using space technique (GRACE/GRACE-FO) and ground technique in support to the modernisation of the NSRS. The name of the team is Geoid Monitoring Service (GeMS).

CGS is processing the monthly GRACE solutions available from different agencies (GFZ, CRS, and JPL) to calculate the linear trend from the effect of Glacial Isostatic Adjustment and melting of glaciers. In addition, CGS is investigating monthly variation of the geoid due to hydrological cycle. Some effort is also done in using the time series at the absolute gravity stations.

Miscellaneous

- CGS assessed GRACE and GOCE Release 5 Global Geopotential Models over Canada (Huang and Véronneau, 2015).
- NGS and CGS, with contribution from UofC and China's mapping office, wrote the Section of Local Geoid Determination in the Encyclopedia of geodesy (Wang et al., 2016).
- CGS is investigating glaciers effect on the geoid (Huang et al., in preparation).

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Sub-commission 2.4d: Gravity and Geoid in Africa

Chair: Hussein Abd-Elmotaal (Egypt)

Overview

The African Gravity and Geoid sub-commission (AGG) belongs to the Commission 2 of the International Association of Geodesy (IAG). The main goal of the African Gravity and Geoid sub-commission is to determine the most complete and precise geoid model for Africa that can be obtained from the available data sets. Secondary goals are to foster cooperation between African geodesists and to provide high-level training in geoid computation to African geodesists. Details on the African geoid initiative can be found at the webpage http://www.minia.edu.eg/Geodesy/AFRgeo/.

Creation of Detailed DTM's

Abdalla and Elmahal (2016) employed local levelling data to assess the global digital elevation model from Shuttle Radar Topography Mission (SRTM3) over Khartoum State area in Sudan. A linear convolution low-pass Gaussian filter has been employed to reduce noise inherited in the DEMs. The systematic errors in the differences between the DEM-based and levelling heights are removed by using third order polynomial model.

Abd-Elmotaal et al. (2017a) have computed the most detailed 3" × 3" DTM for Africa to date using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). The ASTER-GDEM model, which is available only on land, has been smoothed from its original 1" × 1" resolution to the used 3" × 3" resolution using the block average operator technique employing special characteristics at coastal boarders. The 30" × 30" SRTM30+ has been used, after being interpolated to 3" × 3" grid size, to fill-in the missing sea regions of the ASTER-GDEM model. The created 3" × 3" DTM (see Figure 46) has an accuracy of 25 m and 4 m on land and sea, respectively.

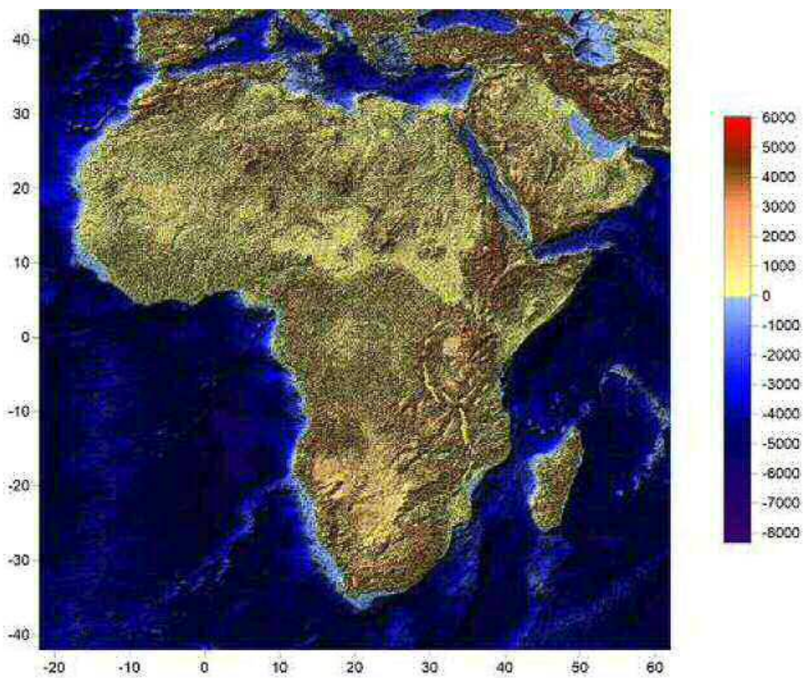

Figure 46 The 3" × 3" AFH16S03 DTM for Africa, after Abd-Elmotaal et al (2017a)

Local Geoid Determination in Africa

Abdalla and Green (2016) have utilized the Fast Fourier Transform and the Least-squares modification of Stokes formula to determine a gravimetric geoid model over Khartoum state in Sudan. The FFT and LSM solutions were evaluated against EGM08 and the local GPS-levelling data. Both comparisons reveal that the LSM solution is more consistent in terms of systematic errors and it is highly correlated with EGM08, the mean values of the geoid differences with respect to EGM08 and GPS-levelling data is found to be 0.14 m and 0.11 m, respectively.

Godah and Krynski (2015a) have computed a new gravimetric geoid model for Sudan using the least-squares collocation and a GOCE-based GGM. The computed geoid for Sudan has a precision of about 30 cm.

Sjöberg et al. (2015) have computed gravimetric geoid for Uganda using the least- squares modification of Stokes formula with additive corrections and the GOCE model TIM_R5 filled with surface gravity anomalies extracted from the World Gravity Map 2012. Using 10 GNSS/levelling data points distributed over Uganda, the RMS fit of the gravimetric geoid model before and after a 4-parameter fit is 11 cm and 7 cm, respectively.

Abdalla et al. (2018a) have computed a new geoid model for Sudan by optimizing the local and global gravimetric data to improve geoid modeling, due to the lack of the gravity data in Sudan. The accuracy of the new geoid model of Sudan is 18 cm after using a 7-parameters fitting model. An improvement of 4 cm is achieved compared to the geoid model of Sudan computed in 2014.

Godah et al. (2019) have extended the determination of the geoid model to the region of East Africa. In this study, the contribution of dedicated gravity satellite missions to the modelling of the earth's gravity field for East Africa has been studied.

Kühtreiber and Abd-Elmotaal (2015) have proposed an alternative geoid fitting technique that employs the least-squares collocation technique aiming to use the minimum number of GNSS/levelling stations in the geoid fitting process based on minimum range and standard deviation criteria, leaving the rest of the GNSS/levelling stations for the use of the external check of the geoid quality. Abd-Elmotaal et al. (2015a) studied the comparison among three methods on the best combination of the gravity field wavelengths in the geoid determination in Egypt. Abd-Elmotaal (2015a) has computed a geoid model for Egypt using the best estimated response of the earth's crust due to the topographic loads. In 2017, the most precise geoid for Egypt to date has been computed by Abd-Elmotaal implementing Moho depths and optimal geoid fitting approach. The external accuracy of that geoid attains 16 cm.

Establishing Gravity Databases

Abd-Elmotaal et al. (2015b) have established the first gravity database for Africa (AFRGDB_V1.0). The AFRGDB_V1.0 has been established employing a weighted least-squares prediction technique. As the used data set suffers from very large gaps, especially on land, and in order not to let the solution be free on those gaps, an underlying grid has been used to fill in these gaps with a resolution of 30' × 30'. This underlying grid has been created using a high-degree tailored geopotential model for Africa employing similar technique as that developed in (Abd-Elmotaal et al, 2015c).

Abd-Elmotaal et al. (2017b) have evaluated the AFRGDB_V1.0 gravity database for Africa using a new gravity data set, consisting of around 34,000 stations, that has been made available by the Bureau Gravimétrique International (BGI). Most of the points of the new data set are located on the large gaps of the data set used to establish the AFRGDB_V1.0 gravity database. This enables an external check of the AFRGDB_V1.0 gravity database at those new data points. The results show that the AFRGDB_V1.0 has an internal precision of about 9 mgal and external accuracy of about 16 mgal.

Abd-Elmotaal and Kühtreiber (2016) have studied the effect of the curvature parameter on the least-squares prediction within poor data coverage and developed a powerful technique to optimally fit the empirical covariance function. Abd-Elmotaal and Kühtreiber (2017) have proposed an optimum gravity interpolation technique for large data gaps to be used for creating the next version of the gravity database for Africa.

Abd-Elmotaal et al. (2018d and 2018c) have established the two new gravity databases for Africa, AFRGDB_V2.0 and AFRGDB_V2.2 using the new sub-data set which has been made available by BGI (thanks Sylvain Bonvalot) with the old data set after correcting the gravity values in many places, especially at Morocco. A grid filtering of the gravity data on sea took place to decrease the dominant effect of the ocean data. The two gravity databases have been established using the same source data with different stratigies varing from using ultra high-degree reference models to satellite only low-degree reference model. The two gravity databases agree to a greate extent, especially in the areas where gravity data were available. Both gravity databases have approximately 5.5 mgal as an internal precision and 7 mgal as an external accuracy.

Regional Geoid Determination for Africa

In 2015, Abd-Elmotaal et al. have computed the first model for the regional geoid for the whole continent of Africa (cf. Figure 47). This geoid model has utilized the AFRGDB_V1.0 gravity database of Africa (Abd-Elmotaal et al., 2015b). The first geoid model of Africa faces two main problems: the wrong gravity data at Morocco and the complete lack of data in a very large gap in the middle region of the African continent. Accordingly, the geoid at these two places is doubtful.

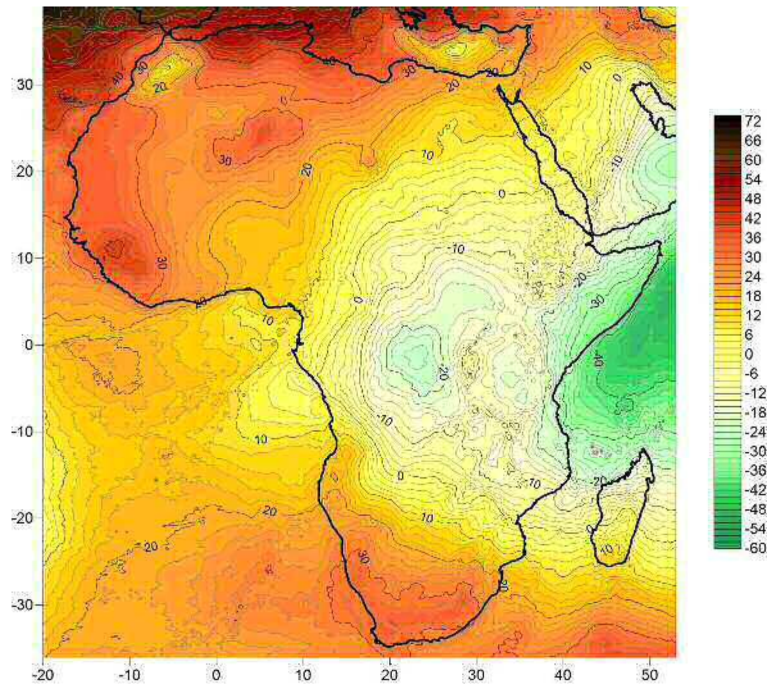

Figure 47 The African geoid model AFRgeo2015 (after Abd-Elmotaal et al., 2015d)

Important Complementary Studies in Africa

Godah and Krynski (2015b) carried out a comparative study of GGMs based on one year GOCE observations with the EGM08 and terrestrial data over the area of Sudan. The results reveal that geoid heights and free-air gravity anomalies obtained from the GOCE-based GGMs agree with the corresponding ones from the EGM08 truncated to d/o 200 with standard deviation of 18–20 cm, and 3.4–4.2 mgal, respectively. Their agreement with the terrestrial free-air gravity anomalies and the GNSS/levelling geoid heights, in terms of standard deviation is about 5.5 mgal, and about 50 cm, respectively. Abd-Elmotaal (2015b) performed an assessment study of the GOCE models over Africa. This study showed that the DIR-R5 solution of GOCE gives the best results for Africa.

Benahmed Daho and Meslem (2018) have studied the external assessment of GRACE/GOCE based geopotential models over Algeria by using collocated GPS/Levelling observations and new gravity anomalies data. Mammar et al. (2019) have prepared a study towards the validation of the new data to determine a geoid model in Algeria. This study proved that the acquired gravity data by BGI for Algeria are precise enough for a geoid determination in Algeria, However, due to the large gaps there, an airborne gravity compaign is highly recommended for precise geoid determination in Algeria.

Abdalla and Ali (2018) have carried out a study of a combined refinement for DEM using low-pass filters and a fitting model in Sudan. This study revealed that this combination and fitting have improved the quality of the produced DEM signifinactly.

Abd-Elmotaal et al. (2016, 2018a) have studied the effect of Victoria and Nasser Lakes on the gravity reduction and on the geoid determination. These studies reveal that these lakes (especially Victoria Lake) have significant effect on both the gravity reduction and the geoid determination. Consequently their effect should be taken into account in precise geoid determination.

Abd-Elmotaal and Ashry (2016) studied the effect of the digital height model resolution on the gravity reduction and geoid determination for Egypt. The results showed that using very fine DHM with a very coarse DHM will take long CPU time and give worst results. This study reveals that the best combination with minimum required CPU time is 3" × 3" with 30" × 30". Accordingly, there is no need for going to 1" × 1" DHM for Africa as 3" × 3" can save CPU time and efforts and gives good results.

Abd-Elmotaal and Hassan (2016, 2017) and Abd-Elmotaal (2018) have proposed a GRACE-like model that can be efficiently used to estimate the total water storage. These studies showed that the proposed algorithm gives comparable results to those of GRACE without stripes. Agutu et al. (2019) have performed groundwater estimation from GRACE over Ghana. Abdalla et al. (2018b) have carried out similar study in Sudan. Abd-Elmotaal et al. (2018b) have estimated the underground water in Africa using GRACE and hydrological models. This study gives reasonably acceptable results for the underground water in Africa. Anyah et al. (2018) carried out a study aiming to understand the linkages between global climate indices and terrestrial water storage changes over Africa using GRACE products.

Abd-Elmotaal and Kühtreiber (2018) have studied the effect of land depressions on the gravity and geoid using unclassified DTMs. The study proved that the effect is local for the gravity and regional for the geoid, and consequently have to be taken into account for precise geoid determination.

Future Activities

A new geoid model for Africa is going to be presented during the forthcoming IUGG2019, Montreal, Canada, July 8–18, 2019 by Abd-Elmotaal et al. The new geoid model utilizes the new adopted gravity data set for Africa. A significant improving of the geoid model at Morocco as well as at the middle region of the African continent is quite remarkable. The new geoid model for Africa is shown in Figure 48.

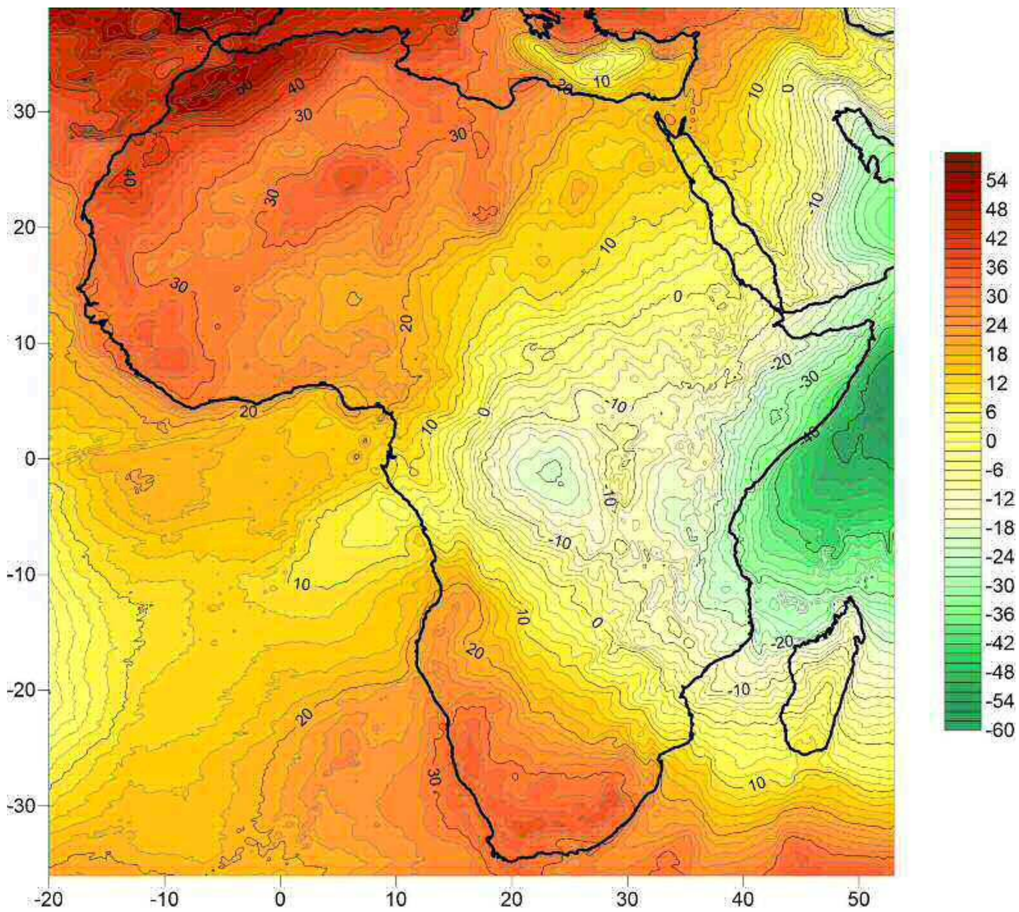

Figure 48 The new African geoid model AFRgeo2019 (after Abd-Elmotaal et al., 2019).

Ulotu is going to use the CRUST 1.0 and LITHO 1.0 models to compute better reduced gravity anomalies and geoid for Tanzania.

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.

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Sub-commission 2.4e: Gravity and Geoid in Asia-Pacific

Chair: *Jay Hyoun Kwon (Korea)*
Vice Chair: *Cheinway Hwang (Taiwan)*

Overview

In the period of 2015-2019, not many activities related to the gravity and geoid are reported in the Asia-Pacific area. Korea continuously measures the gravity on top of mountains to upgrade the geoids, and Taiwan also renews the geoid. In terms of research, the geodynamic processes are related to the changes in absolute gravity in Taiwan, while Korea established a calibration site for the relative gravimeter to find out the characteristics of the relative gravimeter with respect to the height and distance differences between the sites. Taiwan agrees to share absolute gravity data as well as the new grid of geoid. Korea is establishing the criteria for the gravity data sharing mainly in terms of resolution and precision.

Gravity and Related Data

The National Geographic Information Institute (NGII) of Korea has been obtained the new land gravity data from 2008. Recently, NGII measured the gravity at triangulation points, which are mostly located at the top of the mountains, to upgrade the local geoid model. Gravity data at a total of 964 triangulation points were measured from 2015-2016. Furthermore, the gravity at 2,620 2nd order unified control points were measured from 2017-2018. The sum of the new land gravity data obtained from 2008 to 2018 is about 13,500 points and their resolution is about 3~5km. This dataset includes the gravity data measured at 48 sites of continuously operating reference station (CORS). Also, the absolute gravity data at 23 sites have been measured periodically and the one located in the NGII is being continuously measured. A total of 27,343 points of airborne gravity data were obtained from the end of 2009 to early 2010 in cooperation with the DTU, and about 1,950,000 points of shipborne gravity data were measured by the Korea Hydrographic and Oceanographic Agency (KHOA) from 1996-2010.

NGII is also considering the gravity data sharing via IGB and the level of the precision and resolution for data sharing will be determined soon. Figure 49 shows the distribution of gravity data in Korea.

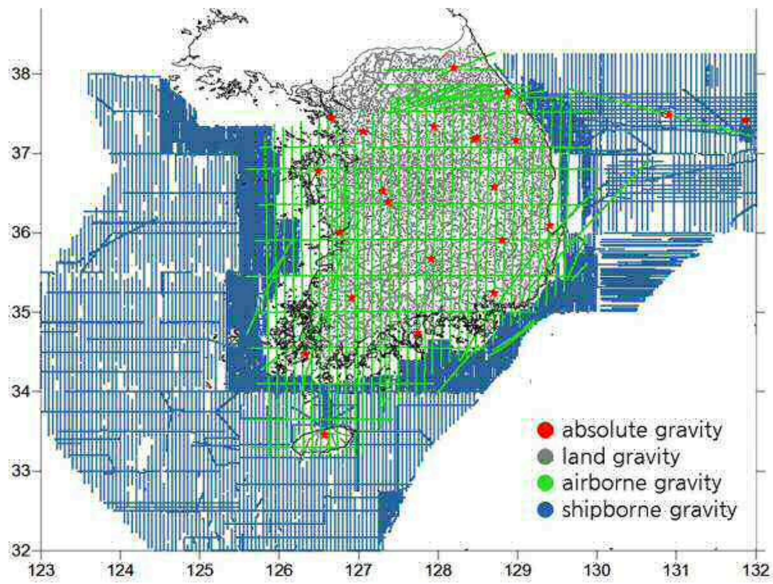

Figure 49 Distributions of gravity data, 23 absolute gravity (red circle), land gravity (gray circle), airborne gravity (green circle), shipborne gravity (navy circle)

In Taiwan, the absolute gravity values at 24 sites have been continuously measured to study the geodynamic processes (Figure 50). Around Taiwan, gravity data from land, airborne and shipborne gravity measurements have been compiled, augmented with altimeter gravity at sea. The study on the new geoid grid and the geodynamic processes are described in the sections below.

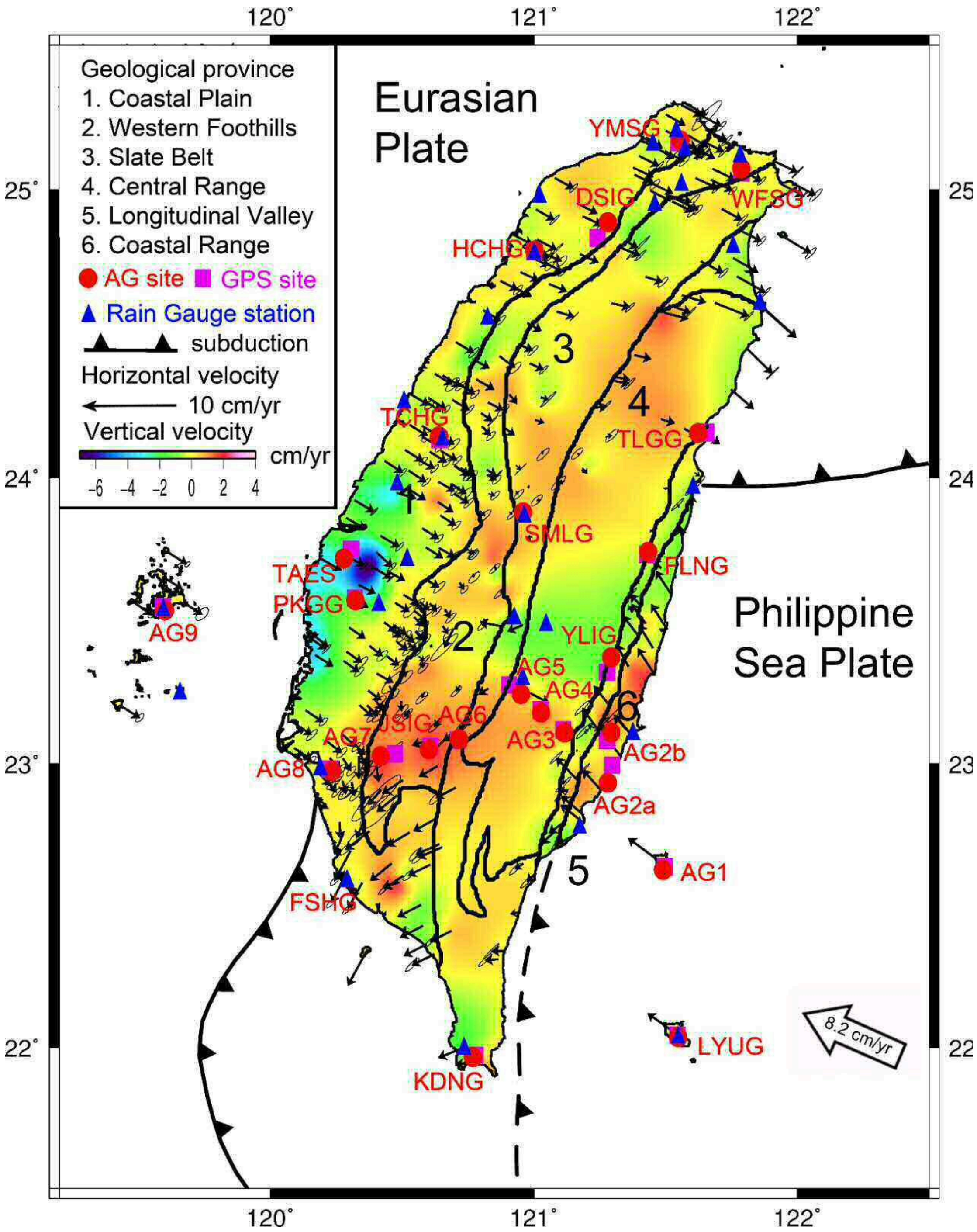

Figure 50 Distributions of 24 absolute gravity (AG) sites (circles), along with their nearest GPS sites (squares), over six geological settings of Taiwan. Also shown are the GPS-derived horizontal rates (arrows, with error ellipses) at 317 sites. The vertical displacement rates from GPS are interpolated into an areal rate (color-shaded) to show the pattern of uplift (positive rate) and subsidence (negative rate) across Taiwan. The mean horizontal displacement rate of the Philippine Sea Plate relative to the Eurasian Plate is 8.2 cm/yr (Ching et al., 2011).

Quasi/Geoid Control

The Korean NGII re-processed land gravity data obtained from 2008-2017 to upgrade the local geoid model. After network adjustment and removing outliers, the precision of land gravity data is about 0.015 mGal. The precision of airborne and shipborne gravity data are 1.5 mGal and 2~3 mGal, respectively. Despite quite large amounts of gravity data, there are spatial gaps at offshore area as well as the border with North Korea. Thus, the gravity data has been filled using EGM08 at the border, and the ocean gravity data have been re-generated by combining shipborne gravity data with DTU10. The spatial resolution of the new dataset is 1'×1'.

The gravimetric geoid and new hybrid geoid model called KNGeoid18 were developed on a 1'×1' grid. In the remove-compute (Stokes' integral)-restore computation, the newly developed geopotential model XGM2016 was applied as a reference field. For the high-frequency signal, the terrain model generated by combining Korean DEM with SRTM was used. The NGII is also obtaining GNSS/Leveling data on unified control points to over whole Korean peninsula from 2008. Until the end of 2017, more than 4,500 points of new GNSS/Leveling data were obtained (Figure 52). When evaluating the gravimetric geoid based on a total of 4,492 points of GNSS/Leveling data (outlier removed), the precision was found to be about 4.4 cm. To make regular distribution and guarantee the independence of the dataset, GNSS/Leveling data were divided into 2 groups; 2,791 points for determining the hybrid geoid and the other 1,701 points for the precision evaluation of hybrid geoid. In comparison the new hybrid geoid model, KNGeoid18, with the fitting points, the precision was evaluated to be 2.33 cm. Although the precision which was evaluated using 1,701 points, quite a similar level of precision, 2.46 cm was obtained. Figure 51 shows the new hybrid geoid model, KNGeoid18.

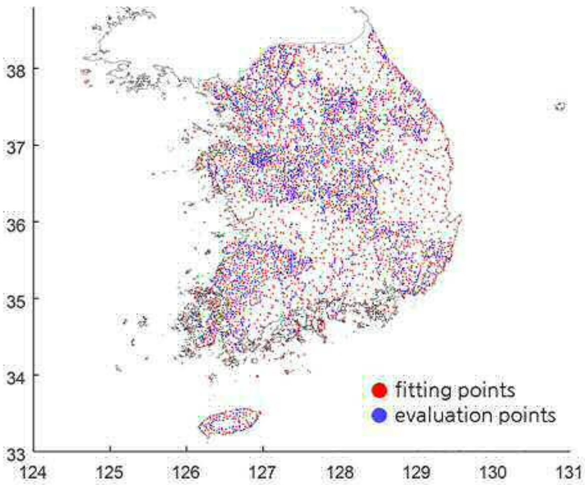

Figure 52 Distribution of GNSS/Leveling data

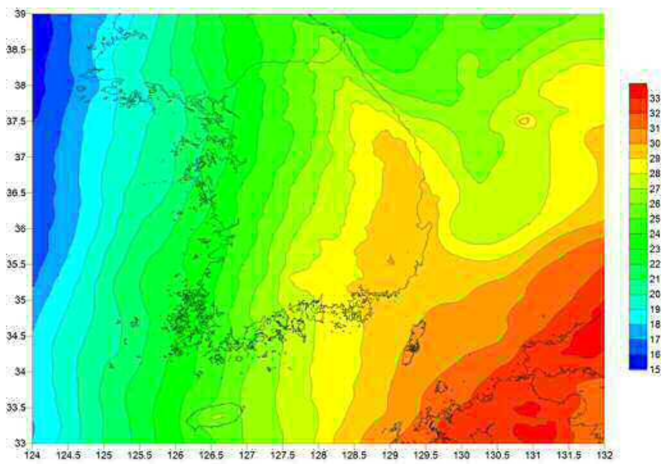

Figure 51 New hybrid geoid (KNGeoid18)

The newly developed geoid model shows high precision but some points located on the mountain have more than 7cm in terms of absolute accuracy. It is because the previous heights of the triangulation points were not accurate enough for the geoid construction. Thus, NGII has a plan to measure the height of the triangulation point using VRS. Then, the accuracy and reliability of the gravimetric geoid will be intensively tested to adopt the gravimetric geoid as the vertical reference surface instead of the hybrid geoid. The mid- and long-term plan for the height system for Korea is underway in which the strategy for the unification of the height system with the neighboring country is designed.

Recently Taiwan constructed new 1’×1’ grids of free-air and Bouguer gravity anomalies around Taiwan with well-defined error estimates (Hwang et al., 2014). Three sets of relative land gravity measurements are network-adjusted and outlier-edited, yielding accuracies of 0.03-0.09 mGal. Three airborne gravity sets are collected at altitudes 5156 and 1620 m with accuracies of 2.57-2.79 mGal. Seven offshore shipborne gravity campaigns around Taiwan and its offshore islands yield shallow-water gravity values with 0.88-2.35 mGal accuracies. All data points are with GPS-derived geodetic coordinates at cm-dm accuracies, which can be used for precise gravity reductions and computing gravity disturbances. The various datasets are combined by the band-limited least-squares collocation in a one-step procedure. In the eastern mountainous (or offshore) region, Bouguer anomalies and density contrasts without considering the oceanic (or land) topographic contribution are underestimated. The new grids (Figure 53) show unprecedented tectonic features that can revise earlier results, and can be used in a broad range of applications.

The grid free-air gravity anomalies (Figure 53) are used to determine a gravimetric and hybrid geoid model over Taiwan on a 30"× 30" grid. An EGM08-based reference field, Stokes integral, and the residual terrain model are used in the remove-compute-restore computations of the geoid models. Using GPS-measured ellipsoidal heights at >2000 first-order benchmarks with existing orthometric heights, we obtained “measured” geoidal heights to assess the gravimetric geoid and to produce a hybrid geoid. The accuracy assessments result in few cm of standard deviations for both geoid models, but the gravimetric geoid has mean differences of up to 20 cm with the measured geoidal undulations. We demonstrate an operational use of the hybrid geoid for height modernization in Taiwan. In a geodetic method based on the hybrid geoid, we determine the relative differences in sea surface topography (SST) between Taiwan and its four offshore islands, which are compared with the SST values from the oceanic (Figure 54) and altimetric methods examine the mechanisms causing the differences. The complicated ocean circulation system around Taiwan has created large differences in SST values across the main island of Taiwan and its offshore islands. A new DEM for the most part of Taiwan, referring to the vertical datum of Taiwan through a hybrid geoid model, is constructed from Lidar-derived ellipsoid heights. Lidar-based orthometric heights in a low-lying area in southern Taiwan are obtained to show the contribution and uncertainty of the geoid models in mapping floods and estimating the risk factors of relative sea level rise.

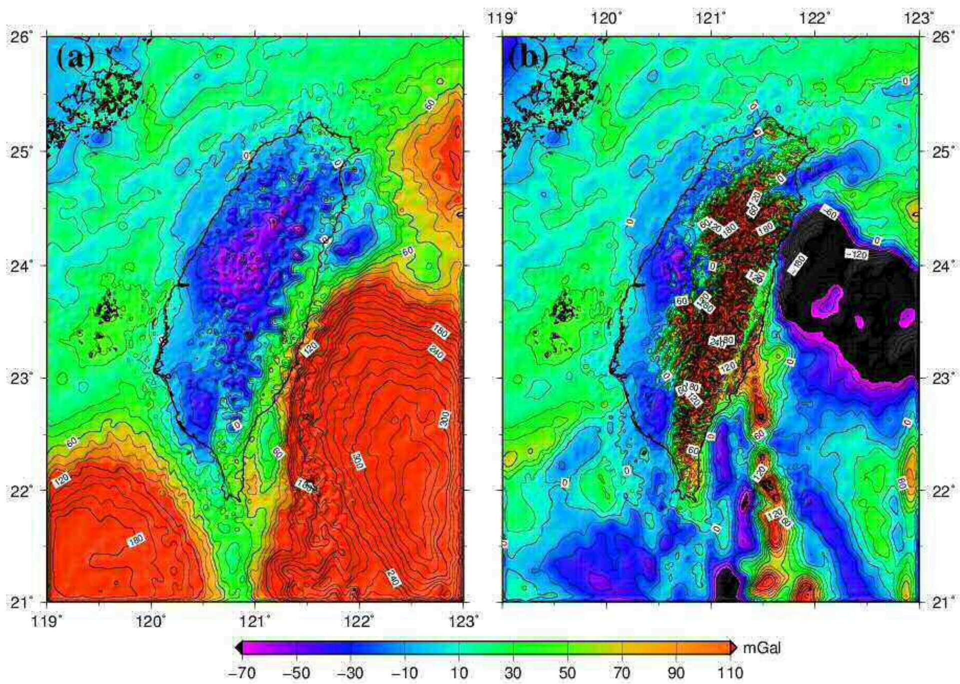

Figure 53 (left) new Bouguer gravity anomalies in Taiwan, (right) free-air gravity anomalies

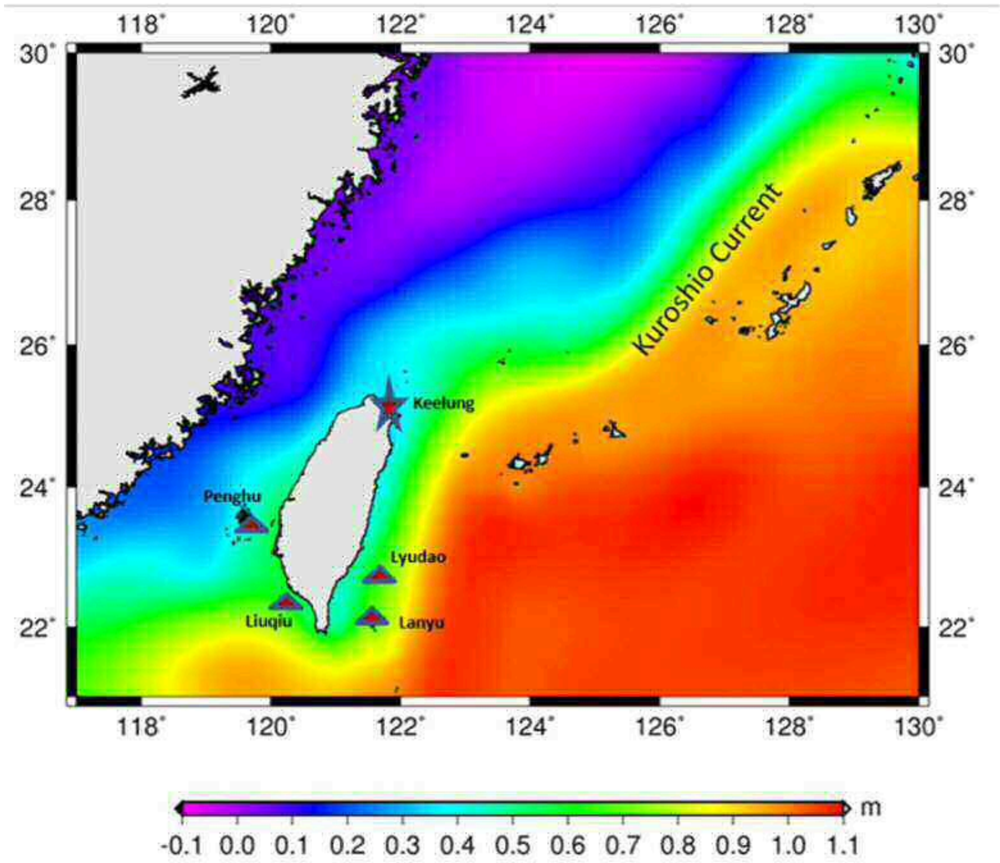

Figure 54 The sea surface topography (SST) around Taiwan from the model output of the Princeton Ocean Model (POM), with the locations of the five tide gauge stations defining the vertical datums of the islands.

Education & Research

The Korean NGII planned to collect new land gravity data and GNSS/Leveling data on 2nd order unified control points until the end of 2020. After completion of the NGII project, the height system of Korea will be changed to the Helmert orthometric height from normal-orthometric height based on the gravity measurements. Also, the local geopotential number, W0, will be determined. In 2019, the study on an examination of resolution and precision of fundamental data (gravity, GNSS, Leveling, etc.), setting up the strategy and detailed plan for height conversion and W0 determination is undergoing. In addition, absolute gravity surveying is being conducted repeatedly and the slope of gravity on each site will be determined.

In the study of the geodynamic processes in Taiwan, gravity changes of non-geodynamic origins are modeled to obtain residual gravity values of geodynamic origins, which cannot be fully explained by GPS-derived vertical displacements. In a preliminary study (Kao et al., 2017), such gravity changes were associated with deposited debris, earthquake, volcanism and Moho deepening using absolute gravity changes over 2004-2016. Gravity changes of up to 53.37 and 23.38 μGal near two Rivers in Taiwan are caused by typhoon Morakot, leading to estimated volumes of 6.0×10^5 m^3 and 3.6×10^5 m^3 in deposited debris. This shows gravimetry can be used in erosion study.

The observed co-seismic gravity change near the epicenter of the M6.9 Pingtung earthquake (December 26, 2006) is 3.12 ± 0.99 μGal, consistent with a dislocation-based gravity change at the μGal level, thereby supplying a gravity constraint on the modeled fault parameters. The AG record at the Tatun Volcano Group is the longest, but large temporal gravity effects here have led to a current gravity signal-to-noise ratio of less than one, which cannot convince a sinking magma chamber, but supply an error bound for gravity detections of long-term or transient magma movements. The gravity values at Ludao and Lanyu decline steadily at the rates of -2.20 μGal/yr and -0.50 μGal/yr, typical magma states over extinct volcanoes. The gravity change rate at an uplifting site in central Taiwan and three subsiding sites in eastern Taiwan are negative, and are potentially caused by Moho deepening at a rate of -3.34 cm/yr.

Taiwan will continue to collect absolute gravity data to investigate these phenomena and will share such data with geodesists interested in this study.

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Sub-Commission 2.4f: Gravity and Geoid in Antarctica (AntGG)

Chair: Mirko Scheinert (Germany)

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 interdisciplinarily, especially incorporating experts from the fields of geophysics and glaciology. This is also reflected in the group membership (cf. below).

Antarctic gravity anomaly collection

During the last period of 2015–2019 further progress has been made to include new data and to open access to already existing data. Here, especially the PolarGap campaign, an international effort of Denmark, the UK and Norway, led by R. Forsberg (DTU Space) has to be mentioned (Forsberg et al., 2017a).

As a highlight the publication of the first Antarctic-wide gravity anomaly dataset has to be mentioned (Scheinert et al., 2016). It was given general attention as can be seen by an EOS article (Stanley, 2016). The dataset is publically available via the PANGAEA database. However, this first gravity dataset release is far from comprising a complete coverage over Antarctica. Therefore, further updates are planned when new data will have been acquired (cf. Figure 55). First steps towards an updated Antarctic gravity dataset in consistence with a global gravity field solution have been made (cf. Zingerle et al. 2019).

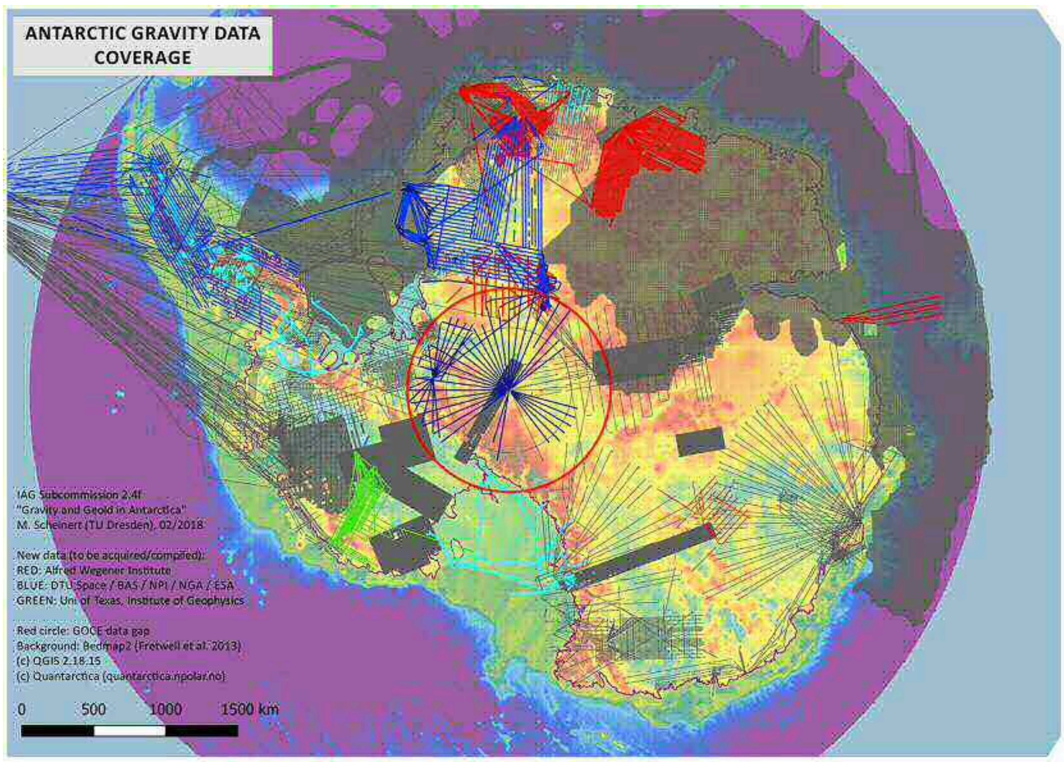

Figure 55 Terrestrial (ground-based, airborne and shipborne) gravity data hold in AntGG data base at TU Dresden. Grey and cyan color: Data already included in the compilation and published by Scheinert et al. (2016). Other colors: New data acquired / to be acquired / compiled.

A close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR), where the geodesy group (SCAR Standing Scientific Group on Geosciences (SSG-GS), Expert Group on Geospatial Information and Geodesy (GIANT Geodetic Infrastructure in Antarctica)). Its program was renewed at the biannual SCAR meetings in Kuala Lumpur, 2016, and Davos, 2018. M. Scheinert co-chairs GIANT as well as chairs the GIANT project "Gravity Field".

International Workshop

Dedicated to the goals of AntGG an International Workshop "Airborne Geodesy and Geophysics with Focus on Polar Applications" was held in Dresden, Germany, 19–21 April 2017. Besides by the IAG it was supported by the German Research Foundation (DFG), the Scientific Committee on Antarctic Research (SCAR) and the German Society for Polar Research (DGP). The workshop was the third in a series of thematic workshops on airborne techniques in polar geosciences. Following respective workshops in Dresden (Germany) in 2009 and in Potsdam (Germany) in 2012, this time we welcomed about 40 participants from six countries (Germany, United Kingdom, USA, China, Norway, Denmark). During six oral sessions, one poster session – accompanied by a small technology display – and a concluding panel discussion, the participants discussed the present status and future prospects of geoscientific airborne surveying in the polar regions. A workshop summary was published in EOS (Scheinert et al. 2017).

2nd SCAR Summer School on Polar Geodesy

Mirko Scheinert together with Martin Horwath (chair of IAG SC 1.3f) organized a 2nd SCAR Summer School on Polar Geodesy that was held at AARI Ladoga Base, Ladozhskoe Ozero, Russia, 10–19 May 2018. This summer school was locally organized by colleagues from the Arctic-Antarctic Research Institute (AARI), St. Petersburg (especially A. Klepikov, Head of the Russian Antarctic Expedition, and A. Ekaykin, AARI Glaciology). It was supported by IAG, SCAR, German Society of Polar Research (DGP), AARI, Aerogeodesya (St. Petersburg) and TU Dresden. 12 young scientists (Master and PhD students) from 7 different countries took part in this summer school. A focus was given to the application of geodetic GNSS measurements as well as of terrestrial and airborne gravimetry to geoscientific research in Antarctica.

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 followed on. Compilations of metadata and databases have to cover certain aspects of gravity surveys in Antarctica (large-scale airborne surveys, ground-based relative gravimetry, absolute gravimetry at coastal stations). The main goal to deliver a grid of terrestrial gravity data is being fulfilled (see above). Updates of this dataset are anticipated, once considerable new data is available,

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.

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Sub-commission 2.5: Satellite Altimetry

Chair: *Xiaoli Deng (Australia)*
Vice Chair: *C.K. Shum (USA)*

Overview

Research activities of IAG sub-commission 2.5 over the period 2015-2019 are described in this report. These include the algorithm development and various applications of both conventional (e.g. TOPEX/Poseidon, Jason-1, Jason-2 etc.) and new (e.g., CryoSat-2, SARAL Altika, HY-2A and Sentinel-3A) satellite altimetry missions. The sub-commission also contributed to the promotion of the Jason-2 geodetic mission (GM), international altimetry service (IAS) and altimetry training workshops.

Promoting international altimetry services

We submitted a recommendation on starting the Jason-2 geodetic mission (GM) to the committee of the Jason-2 joint steering group in May 2017. The recommendation was accepted and Jason-2 moved from an exact repeat orbit to the GM in 2015. It is believed that the dense Jason-2 GM ground tracks in the Jason-2 inclination will give better resolution of gravity anomalies with narrow east-west extent, and fill holes in coverage left by the other altimetry missions.

We have proposed to establish an International Altimetry Service (IAS). The idea was circulated and informally discussed in the “25 Years of Progress in Radar Altimetry Symposium” in September 2018. The proposal by Prof CK Shum on behalf the sub-commission was submitted to IAG in December 2018, and will be further discussed in the IUGG in July 2019. Satellite altimetry is deemed to be operational and its applications so far include flood, wind/wave monitoring, coastal circulations, water resources management, coast watch, and potential monitoring tools of vertical datum control, lake seiche or meteotsunamis, storm surge, and seismic-induced tsunamis. An envisaged IAS is to identify and pool together international resources in satellite altimetry, 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 sub-commission also held the training workshops on using altimetry tools for developing countries. A/Prof Hyongki Lee carried out training at Asia Disaster Preparedness Center (ADPC), Bangkok, Thailand, Ministry of Water Resources and Meteorology (MOWRAM), Cambodia during 3 – 4 Aug 2017 (Figure 56).

Figure 56 Pictures from Altimetry Toolkit Training.

Improving of marine gravity field and bathymetry from altimetry

We continued improving the accuracy of the global marine gravity field using new radar altimeter data from CryoSat-2 and now SARAL AltiKa (Figure 1). One of the main benefits of an improved gravity field is the ability to resolve new structures on the ocean floor (Matthews et al., 2016). The investigation had three main components: (1) develop waveform retracking algorithms and computer codes for these new satellite altimeter data sets that are optimal for gravity field recovery (Zhang and Sandwell, 2016), (2) develop global gravity grids at 1 minute resolution using the new altimeter data, and (3) continue to develop global bathymetry grids at 1 minute, 30 arc second and 15 arc second resolutions.

The contribution of each altimetry GM data to the recovery of the marine gravity field was assessed. Sandwell et al. (2019) investigated the contribution of six altimeter missions that have been placed into geodetic mapping phases for more than one year. Originally, Geosat and ERS-1 were the most important altimeters for recovery of the marine gravity field. The launch of CryoSat-2 in 2010 provides a non-exact-repeat orbit and much lower noise data source that extends to high latitudes of 88°. Both Jason-1 and Jason-2 GMs have provided major increases in the gravity recovery especially the east-west component at low latitudes. Finally, AltiKa with its high range precision (*Zhang et al.,* 2017) is rapidly becoming the most important altimeter data source for gravity field recovery (Figure 57). If this mission continues for another few years, the accuracy of the gravity field will become much closer to the 1 mGal objective. Moreover, The major limitation for recovering small scale gravity features is the sea surface roughness from ocean waves. Many repeat measurements are needed to reduce the oceanographic signals that contaminate the mean sea surface. The combination of repeated measurements from Envisat, Jason-1/2, CryoSat-2, and now AltiKa will provide a baseline mean sea surface that is needed for the upcoming SWOT experiment in order to isolate the oceanographic signals early in the mission. There have been steady improvements in instrumentation and processing methods that will continue into the future with higher frequency radars and interferometric swath altimeters planned for future missions.

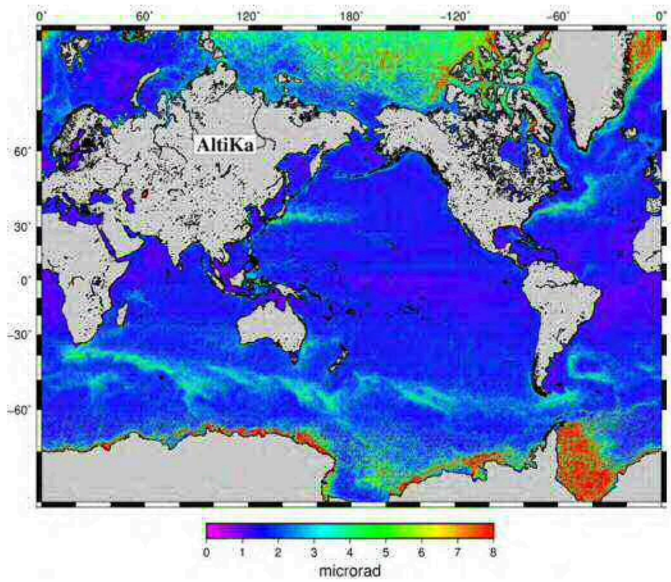

Figure 57. Median absolute deviation of along-track slope of Altika altimeter with respect to the V28 model. The differences are filtered with a 0.5 gain at 18 km wavelength. The largest difference occurs in the high latitude regions where sea ice is prevalent as well as areas of high mesoscale variability. The background noise level reflect altimeter noise mainly due to ocean waves. AltiKa has, by far, the lowest noise level when compared with other seven altimeter GM data.

Much of the gravity field improvement was due to new satellite altimeter data collected by CryoSat-2 and Jason-1. In addition, we have refined the existing tide models resulting in improved performance in coastal areas. Currently 7 years (84 months) of data are available from CryoSat-2 and the satellite has enough consumables to operate beyond 2020. More important, another radar altimeter called SARAL AltiKa altimeter has begun a non-repeat orbit phase starting in July 2016 (Figure 58). AltiKa has a new Ka-band instrument with a factor of 2 better range precision than all previous altimeters (Table 1 from Zhang and Sandwell, 2016). If it continues in this non-repeat orbit for another 6 months, this will result in an additional accuracy improvement of perhaps 1.5 times and three years of operation will result in another factor of 2 improvement in the marine gravity field.

Table 9. Altimeter noise at 20 Hz

altimeter	Noise* (mm)
Geosat	57.0
ERS-1	61.8
Envisat	51.8
Jason-1	46.4
CryoSat-LRM	42.7
CryoSat-SAR	49.7
AltiKa	**20.5**

*Standard deviation of altimeter waveforms with respect to the 1 Hz average (Zhang and Sandwell, 2016).

Regionally, Hsiao et al. (2016) determined the gravity field of the South China Sea (SCS) using sea surface heights from satellite altimeters Geosat/GM, ERS-1/GM, Jason-1/GM and Cryosat-2. The modelled gravity anomalies show a 6 mGal RMS discrepancy with shipborne measurements in shallow waters. An altimeter-only bathymetric model is then derived from this new gravity grid by the gravity-geological method that uses the latest global and regional models of the ocean depth and marine gravity as a priori knowledge. The new bathymetry model has an accuracy up to 100 m based on validation against multi-beam depth measurements, outperforming current SCS bathymetric models. Optical images from IKONOS-2, QuickBird-2, GeoEye-1, WorldView-1-2 and -3, are rectified and digitized to derive the zero (coastline) and 20-m depth contours (reef lines) around 44 atolls, which are integrated with the altimeter-only depths, giving significantly improved accuracies and spatial resolutions in modelled depths. The improvement percentages of coastlines by the satellite imagery range from 50% to 97% at 41 of the 44 atolls. The web site is available for free access to the optical and depth images, and the depth and gravity grids.

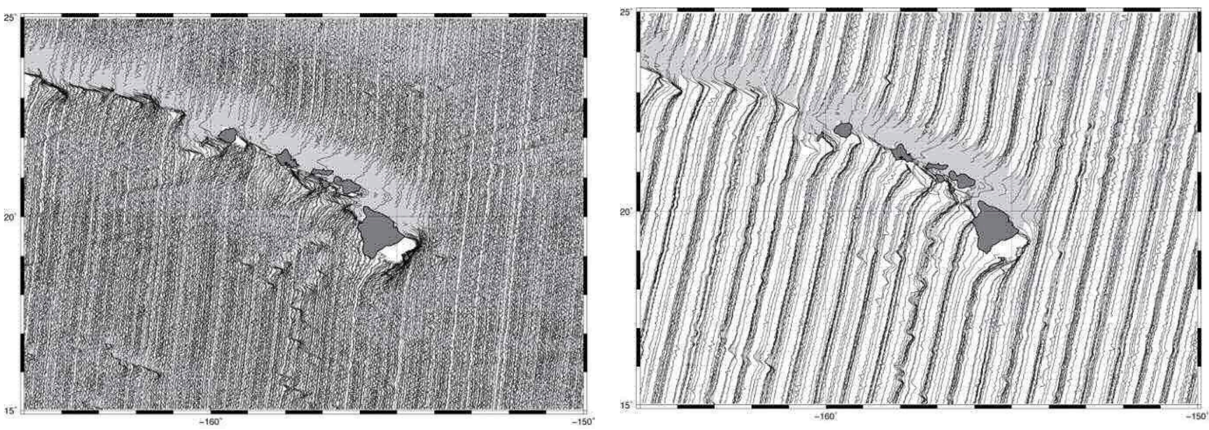

Figure 58. Along track sea surface slope profiles from CryoSat-2 (66 of the of 84 mo. available today) and AltiKa (7 of the 10 mo. available today) around Hawaii. Both satellites are healthy and still continue collecting data. AltiKa profiles are two times more precise than all previous altimeters (Table 9).

Tozer et al. (2019) present an updated global bathymetry and topography model SRTM15+ V2.0 using a spatial sampling interval of 15 arc seconds (Figure 59). The bathymetry is produced using a combination of ship- board soundings and depths predicted using satellite altimetry. New data consists of >33.6 million multi and single beam measurements collated by several institutions, namely, NGA, JAMSTEC, GA, CCOM and SIO. New altimetry data consists of 48, 14 and 12 months of retracked range measurements from Cryosat-2, SARAL/AltiKa and Jason-2 respectively. With respect to SRTM15 PLUS by Olson et al. (2016), the inclusion of these new data result in a ~1.4 km improvement in the minimum wavelength recovered for sea surface free-air gravity anomalies, a small increase in the accuracy of altimeter-derived predicted depths (10-20 m) and a 1.2% increase, from 9.60 to 10.84%, in the total area of ocean floor that is constrained by shipboard soundings at 15 arc second resolution. Bathymetric grid cells constrained by satellite altimetry have estimated uncertainties of ±150 m in the deep oceans and ±180 m landward of abyssal plains. Onshore, topography data are sourced from previously published digital elevation models, predominately SRTM-CGIAR V4.1 between 60°N-60°S. ArcticDEM is used above 60°N, while REMA is used below 60°S. Auxiliary grids illustrating shipboard data coverage, marine free-air gravity anomalies and vertical gradient gradients are also provided in common data formats.

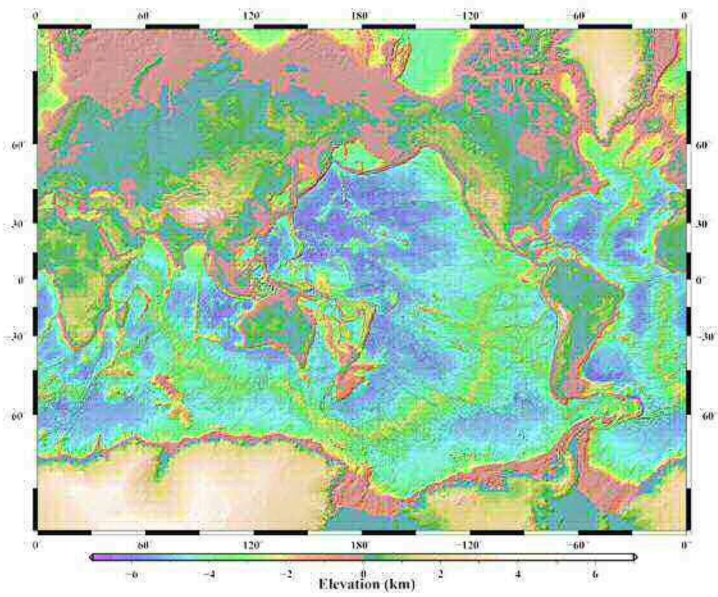

Figure 59. SRTM15+V2.0 at 15 arc second resolution plotted to latitudes ±80° using a Mercator projection.

Sea Levels, sea level extremes and ocean dynamics

Sea level changes have been investigate using radar altimeter data from the conventional low resolution mode (LRM), Delay Doppler Altimetry (DDA), and Synthetic Aperture Radar (SAR) mode. One of major benefits of DDA is the higher resolution, which opens new possibilities in the coastal zone at a few km from coast (Fenoglio-Marc et al., 2015). Our investigation had four main components: (1) assess improvement gained by using DDA altimetry methodology with respect to best in-house reprocessed conventional altimetry (CA), (2) investigate sea level change and understand each component, (3) investigate mean dynamic topography at the coast from satellite and in-situ data, and (4) investigate sea level extremes.

Assessing advantages and limitation of DDA with respect to CA. For this scope, improved re-tracking methods dedicated to the coastal zone have been used, which includes the parametric sub-waveform re-tracker TALES, similar to the ALES retracker (Passaro et al., 2015) and the

Spatio Temporal Altimetry Retracker (STAR) in Roscher et al. (2015). In this way a comparison between the two modes near coast is possible. The results have shown that the superiority of the DDA mode, as its finer resolution and higher Signal to Noise Ratio (S/N) of the CryoSat-2 data, allows the radar altimeter getting closer to shore. Several studies have shown the improvements in precision and accuracy (Fenoglio-Marc et al., 2015, Passaro et al., 2016, Dinardo et al., submitted). Land contamination starts at 2 km from coast in DDA mode and at 4 km in pseudo-CA. In the critical band 0-2 km from the coast, the impact of land contamination is lower in DDA than that in pseudo-CA/PLRM, as the median curve in SAR is closer to zero than in PLRM median curve (Figure 60). Further study, in the ESA project SCOOP, will characterise the performance of the Sentinel-3 DDA product generated by the currently specified processing baseline and then to test, implement and evaluate improved retrieval methods.

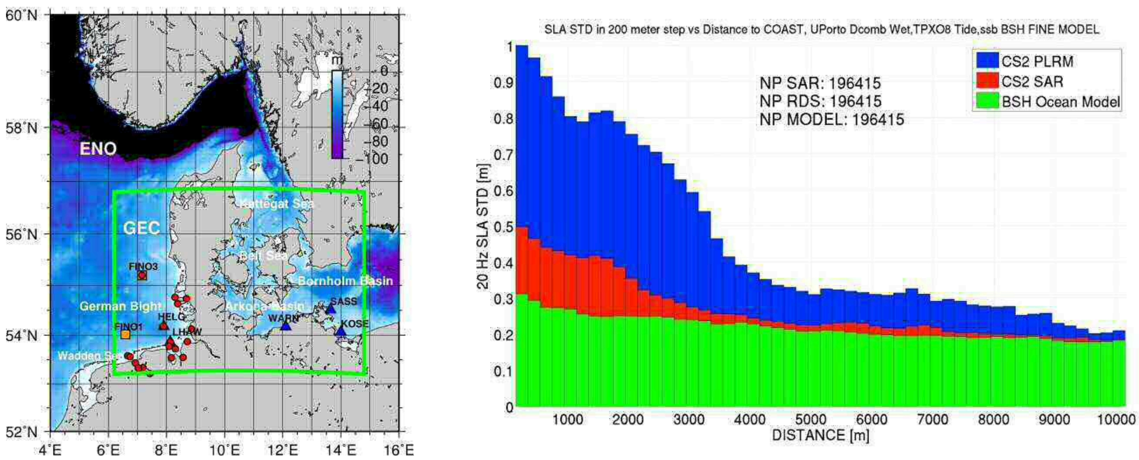

Figure 60. The GEC Region along the German coast (left). Standard variation of sea level anomalies in 200 bins of distance to coast for ocean model (green), SAR (red) and PLRM/TALES (blue) (right) in region GEC.

Addressing the sea level change and the understanding its causes. Today, the period 2002-2017 is the longest time span where space-based measurements from altimetry, GRACE and ARGO are simultaneously available for sea level, mass and steric observations.

Figure 61 shows basin averages for sea level and its components derived combining geodetic and model data. Although the combination of the first attempt provides valuable constraints on volumetric versus mass driven sea surface height changes, these data are rarely assimilated into ocean simulations and reanalysis runs. We have contributed to the regional assessment of the quality of sea level products, verifying their mission-long regional sea level trends and characterizing their error (Ablain et al., 2017). GRACE data have been used to assess mass changes. Regional ocean simulations and re-analysis have been considered. The evaluation of ocean model simulations and reanalysis using geodetic data is challenging, particularly in semi-closed ocean basins, due to the assumptions made in the ocean models and to the limitation of satellite-based data in coastal zone. Our analysis in the Mediterranean Sea Basin averages show that the sea level of both simulations and re-analysis fails to reproduce the observed long-term variability of sea level. The halosteric component is far to be correctly computed by the model runs. The thermo-steric component is finally the more accurate proxy for the long-term sea level changes, at least in basins where the steric-component is a large part of sea level change. Finally we show that the sum of model sea level and thermo-steric sea level has the highest correlation with the total sea level measured by satellite altimetry (Figure 62). Moreover, the synergy between altimeter data and model simulations is promising to overcome the errors of mass balances.

In the frame of the regional assessment of a new Altimeter Sea Level Record (Reprocessed ESA Essential Climate Variable SLCCI), we have investigated the agreement between vertical land motion (VLM) and the difference in trends between altimetry and selected tide gauges along the German coasts (Figure 63). We found that GPS-derived VLM and the trend of the altimeter and tide gauge differences depart by about 1 mm/yr, which is within the uncertainty of the trends, and which is large compared to the GPS rates. We also noticed that the agreement improves (correlation, standard deviation and difference of trends) when SLCCI data instead of the AVISO data are used. This indicates a higher quality of the SLCCI data compared to other altimeter products (Figure 3). The work is supported by the Climate Change Initiative Project (SLCCI/ESA).

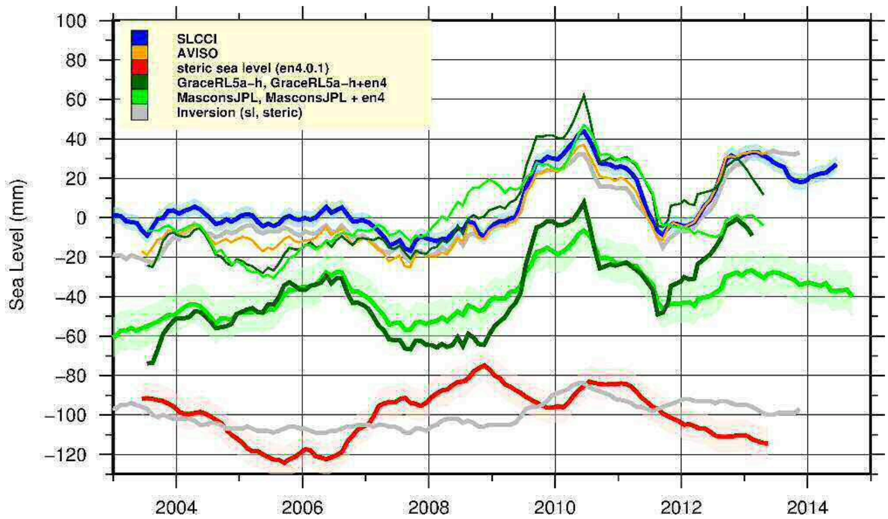

Figure 61. Mediterranean Sea: Smoothed time-series of observed and computed sea level, as well as its steric and mass components. Components are from GRACE RL05a corrected for land hydrology (dark green), JPL mascon solution (light green), temperature and salinity profiles (red) and from the inversion method (green). All monthly time-series have been de-seasonalized and smoothed by a running average with lag of 12 months.

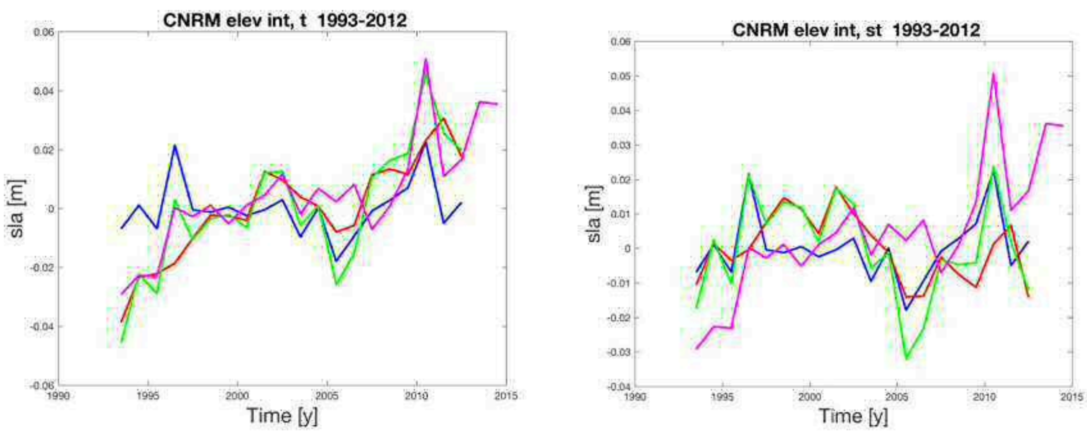

Figure 62. CNRM model for the Mediterranean Sea: Sea surface height (green) from elevation plus thermos-steric (left) and plus steric (right). Is compared to sea level from CCI grids (violet), thermo-steric (red) and elevation (blue)

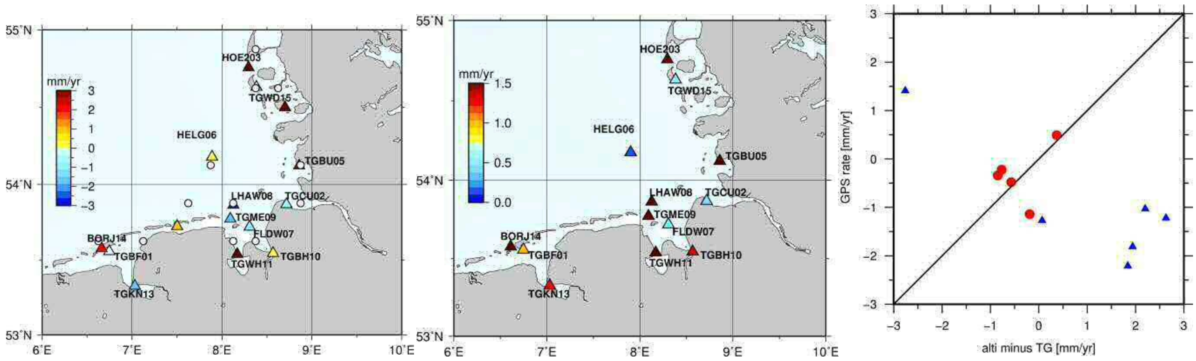

Figure 63. Left: Vertical Land Motion from altimetry minus tide gauge stations with location of both tide gauge (triangle) and altimeter point selected (circle). Centre: absolute value of the difference of VLM from the two methods. Right: Scatterplot of VLM with stations with differences smaller than 1 mm/yr in red.

Similarly to the Mediterranean Sea study, we have analyzed basin average sea level change and its components in the Bay of Bengal (Kusche et al., 2016). SAR and PLRM SAR and TALES provide improved coastal sea surface heights. This leads to both improved coastal sea surface heights and inversion results, especially at regional scales (Figure 64).

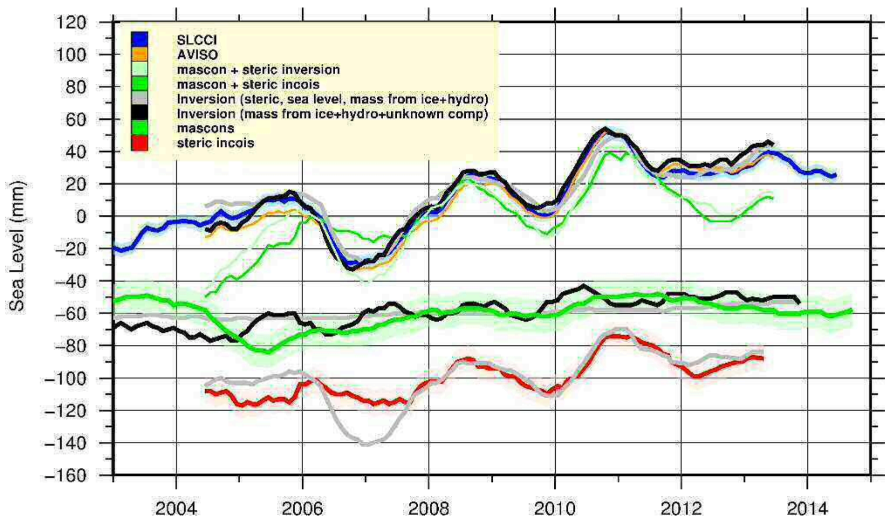

Figure 64. Bay of Bengal: Smoothed time-series of observed and computed sea level, as well as its steric and mass components. Mass components are from GRACE RL05a corrected for land hydrology (black), JPL mascon solution(green), temperature and salinity profiles and from the inversion method. All monthy time-series have been de-seasonalized and the smoothed by a running average with lag of 12 months.

Further work is planed: (1) investigate the residual signals and corresponding physical processes, (2) extend and improve the IGG Jason/GRACE joint inversion method (Rietbroek et al., 2016), (3) incorporate Cryosat-2 data in DDA and pseudo-DDA mode in the coastal zone database.

Imani et al. (2017) forecasted sea level anomalies (SLAs) derived from satellite altimetry in the tropical Pacific Ocean by using a machine learning approach. The empirical orthogonal function (EOF) is used to extract dominant signals and reduce the dimensionality of the SLAs in order to avoid data noisy. The prediction result by the machine learning approach is excellent compared with that of the conventional autoregressive integrated moving average (ARIMA) model.

Mean dynamic topography from altimetry. This study combines several elements: (1) propose and develop an approach to estimate a consistent DT at tide gauges, coastal areas, and open ocean, (2) validate the approach in well-surveyed areas where DT can be determined at tide gauges, (3) connect measurements of a global set of tide gauges and investigate trends, and (4) evaluate the improvement in mean dynamic topography and difference in trends by using the Delay Doppler altimeter data near coast (Figure 65). The work is still ongoing (ESA Project GOCE++Dycot).

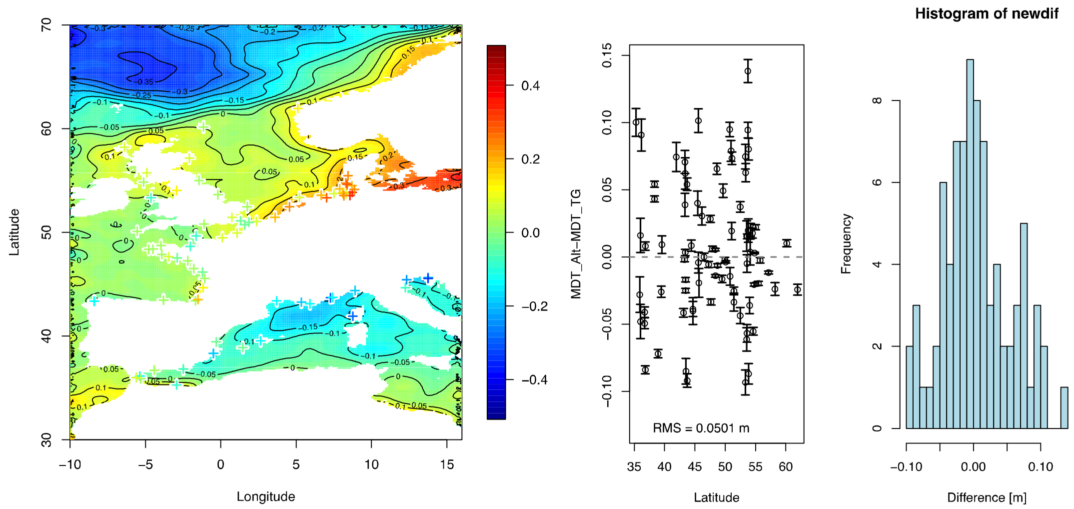

Figure 65. North-Eastern Atlantic. Mean Dynamic Topography from geodetic method in ocean and at the tide gauge (left), differences (middle) and histogram of differences (right).

In addition, Chang et al. (2016) combined multiple mission satellite altimetry along-track sea surface heights (SSHs), the Gravity field and steady-state Ocean Circulation Explorer (GOCE) time-wise solution generated geoid model, and in situ hydrographic data, to estimate global surface and subsurface absolute geostrophic currents over the period 1996-2011. They used the profile approach to process satellite altimetry data, mitigating the negative impact of omission errors resulting from the spatial resolution discrepancies between the truncated GOCE geoid model and SSHs, on the estimation of the absolute dynamic topography (ADT), which was then combined with the relative dynamic topography derived from in situ hydrographic profiles to estimate near global mesoscale geostrophic current velocities at different depth layers. The results were validated by in situ moored current meter observations from the Tropical Atmosphere Ocean/TRIangle Trans-Ocean buoy Network (TAO/TRITON) and the Prediction and Research Moored Array in the Atlantic (PIRATA), showing the outperformance of profile approach over the conventional pointwise approach in determination of geostrophic currents. The results show the statistically significant correlation between the multi-layer geostrophic current changes for Atlantic Meridional Overturning Circulation (AMOC) branches and the North Atlantic Oscillation (NAO) index.

Sea level extrmes from altimetry. A major climate hazard is coastal flooding induced by extreme water level events along low-lying, highly populated coastlines due to presently and continuously rising sea levels (Stewart and Deng, 2015). Staneva et al. (2016) addressed the impact of wind, waves, tidal forcing and baroclinicity on the sea level of the German Bight during extreme storm events. The improved skill resulting from the new developments justifies further use of the coupled-wave and three-dimensional circulation models in coastal flooding predictions.

At the Australia coast, 20 years of data from multi-missions of satellite altimetry (e.g., Topex, Jason-1, Jason-2) were integrated with 14 tide-gauge data to provide consistent sea levels (Deng et al., 2016; and Gharineiat and Deng, 2016). Moreover, Gharineiat and Deng (2016) used a state-of-the-art approach of the Multi-Adaptive Regression Splines (MARS) to consider nonlinear sea-level components along the northern coast of Australia. The result comparison of the MARS with the multiple-regression shows an improved sea level prediction, as MARS can explain 62% of sea level variance while multiple-regression only accounts for 44% of variance. The predicted sea levels during six tropical cyclones are validated against sea level observations at three independent tide-gauge sites. The comparison results show a strong correlation (~99%) between modelled and observed sea levels, suggesting that the MARS can be used for efficiently monitoring sea level extremes.

Assessing of ocean tidal models. Seifi et al. (2019) investigate the performance of recent regional and global tidal models over the Great Barrier Reef, Australia using altimetry data from TOPEX/Poseidon, Jason-1, Jason-2 and Sentinel-3A missions, as well as tide gauge data. Ten models, namely, TPXO8, TPXO9, EOT11a, HAMTIDE, FES2012, FES2014, OSUNA, OSU12, GOT 4.10 and DTU10, were considered. The accuracy of eight major tidal constituents (i.e., K1, O1, P1, Q1, M2, S2, N2 and K2) and one shallow water constituent (M4) were assessed based on the analysis of sea-level observations from coastal tide gauges and altimetry TOPEX series. The outcome was compared for four different subregions, namely, the coastline, coastal, shelf and deep ocean zones. Sea-level anomaly (SLA) data from the Sentinel-3A mission were corrected using the tidal heights predicted by each model. The root mean square (RMS) values of SLAs were then compared. According to the results, FES2012 outperforms other models with RMS values of 10.9 cm and 7.7 cm over the coastal and shelf zones, respectively. In the deeper ocean, FES2014 model performs the best with the minimum RMS 7.5 cm. In addition, the impact of sudden fluctuations in bottom topography on model performances suggest that a combination of bathymetric variations and proximity to the coast or islands contributes to tidal height prediction accuracies of the models.

Retracking, calibrating and validating of altimetry data

We continued research into optimize the satellite altimetric sea levels from multiple retracking solutions near the coast. Kuo et al. (2016) improved Envisat altimetric measurements in Taiwan coastal oceans by developing a waveform retracking system. Research by Idris et al. (2017) investigated the validation strategy for the retracked altimetry data. They compared Jason-1 altimetry retracked sea levels with the high frequency (HF) radar velocity in the Great Barrier Reef, Australia. The comparison between both datasets is not direct because the altimetry derives only the geostrophic component, while the HF radar velocity includes information on both geostrophic and ageostrophic components, such as tides and winds. The comparison of altimetry and HF radar data is performed based on the parameter of surface velocity inferred from both datasets. The results show that 48% (10 out of 21 cases) of data have high (≥0.5) spatial correlation, while the mean spatial correlation for all 21 cases is 0.43 (Figure 66). This value is within the range (0.42 to 0.5) observed by other studies.

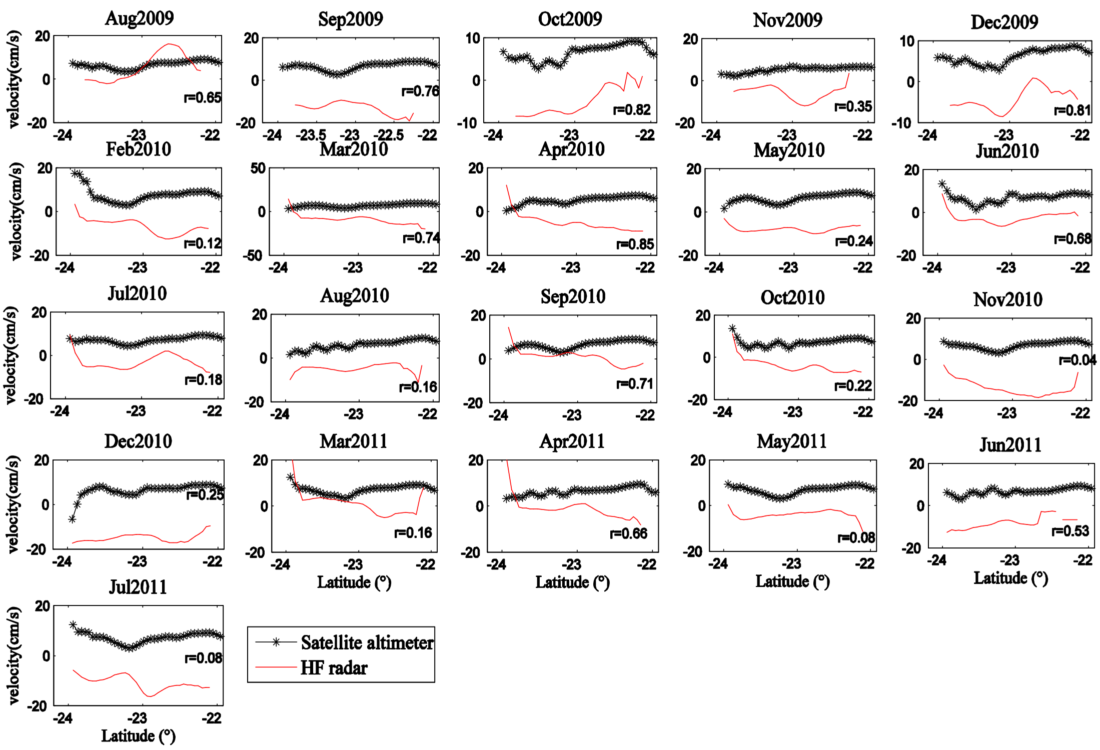

Figure 66. The monthly HF and altimeter geostrophic velocity normal to the satellite track from 2009 to 2011. The altimeter geostrophic velocities are filtered with a cut-off wavelength of 56 km. The latitude between −24 and −23 deg is situated on the continental shelf with the latitude −24 deg being the closest point to the coastline, while the latitude greater than −23 deg is situated on the continental shelf break (Idris et al. 2017).

Peng and Deng (2017) developed a new Brown-Peaky (BP) retracker (Figure 67) for altimeter peaky waveforms that usually appear within ~10 km to the coastline. The main feature of the BP is to fit peaky waveforms using the Brown model without introducing a peak function. The retracking strategy first detects the peak location and width of a waveform using an adaptive peak detection method, and then estimates retracking parameters using a weighted least squares (WLS) estimator. The WLS assigns a downsized weight to corrupted waveform gates, but an equal weight to other normal waveform gates. The BP retracker has been applied to 4-year Jason-1 waveform (2002–2006) in two Australian coastal zones. The results retracked by BP, MLE4 and ALES retrackers have been validated against tide-gauge observations located at Burnie, Lorne and Broome. The comparison results show that three retrackers have similar performance over open oceans with the correlation coefficient (~0.7) and RMSE (~13 cm) between altimetric and tide-gauge sea levels for distance >7 km offshore. The main improvement of BP retracker occurs for distance ~7 km to the coastline, where validation results indicate that data retracked by BP are more accurate (15–21 cm) than those by ALES (16–24 cm) and MLE4 (19–37 cm).

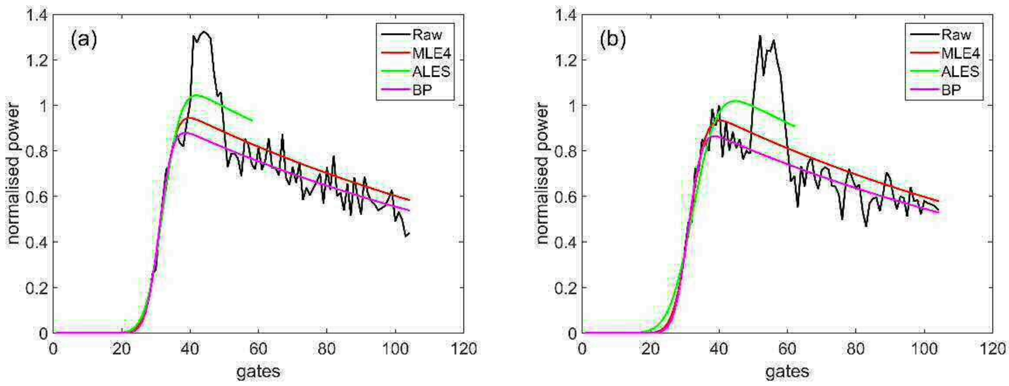

Figure 67. Examples of fitted waveforms by different retrackers. The raw waveforms are simulated with SWH=6 m. The BP solutions are derived by the WLS estimator with minimum contributions from peaky waveform samples, thus avoiding the effect of peaks. ALES sub-waveforms contain the proportion of peaks, because they are truncated around gate 58 based on the function related to the value of SWH. Therefore, both MLE4 and ALES solutions are obviously affected by peaks.

Using the new BP retracker, Peng and Deng (2018) computed improved significant wave heights (SWHs) along the east coast of Australia from 3-year Jason-1 altimetric waveforms. The BP-estimated SWHs were validated against eight waverider buoys along the coast, and compared with the SWHs estimated by the standard four-parameter maximum likelihood estimator (MLE4). When assessing 1 Hz coastal SWHs for distances from 12 km to the coast, mean standard deviations (STDs) of BP SWHs vary from ~0.5 m to 0.9 m, while those of MLE4 SWHs increase from ~0.6 m to ca. 2.3 m, indicating a dramatically drop in the quality of MLE4-derived SWHs at the coast. The validation of 1-Hz SWHs was performed by calculating the along-altimeter-track pointwise bias, STD and correlation coefficient between altimetry and buoys. The results show that within 30 km off the coast the BP dataset has better agreement with buoy's wave heights than the SGDR MLE4 dataset in terms of the BP's small absolute biases and STDs, as well as high correlation coefficients.

Since the launch of China's first altimetry and scatterometry satellite, Haiyang-2A (HY-2A), various validation studies of HY-2A radar altimetry using preliminary data products have been conducted. The HY-2A Geophysical Data Record (GDR) IGGA product has so far been generated. Bao et al. (2015) presented the first comprehensive assessment of HY-2A's altimeter data quality and the altimetry system performance through calibrating and cross-calibrating the HY-2A GDR_IGGA product. Jason-2 altimeter observations were used for the cross calibration of the HY-2A altimeter over the oceans between ±60° latitude bounds. The statistical results from single- and dual-satellite altimeter crossover analysis demonstrated that HY-2A fulfils its mission requirements. An averaged bias of -0.21 cm with respect to Jason-2 and a standard deviation of 6.98 cm from dual-satellite crossover analysis were found. It was concluded that the performance of HY-2A altimetry is similar to Jason-2 based on a detailed analysis of the paper.

Monitoring vertical land motion and glacier dynamics from altimetry

Members in Taiwan have used altimetry to monitor the land motion. Hwang et al. (2016) used multi-mission radar altimetry with an approximately 23-year data-span to quantify land subsidence in cropland areas. Subsidence rates from TOPEX/Poseidon, JASON-1, ENVISAT, and JASON-2 during 1992-2015 show time-varying trends with respect to displacement over time in California's San Joaquin Valley and central Taiwan, possibly related to changes in land use, climatic conditions (drought) and regulatory measures affecting groundwater use. Near

Hanford, California, subsidence rates reach 18 cm/yr with a cumulative subsidence of 206 cm, which potentially could adversely affect operations of the planned California High-Speed Rail. The maximum subsidence rate in central Taiwan is 8 cm/yr. Radar altimetry also reveals time-varying subsidence in the North China Plain consistent with the declines of groundwater storage and existing water infrastructure detected by the Gravity Recovery and Climate Experiment (GRACE) satellites, with rates reaching 20 cm/yr and cumulative subsidence as much as 155 cm.

Sun et al. (2017) investigated glacier dynamics in the northern Novaya Zemlya using multiple geodetic techniques (Figure 68). In order to determine the influence of glacier outflow on net mass change, they used Envisat-derived elevation changes over the glaciers in Novaya Zemlya in Russian Arctic along with other geodetic observations of glacier velocity changes from speckle matching technique and ice mass changes from GRACE. The surface gradient correction was estimated using the average of all of the available altimeter elevations as the reference digital elevation model (DEM) in order to eliminate the error due to the difference between DEM spatial resolution and altimetry footprint size.

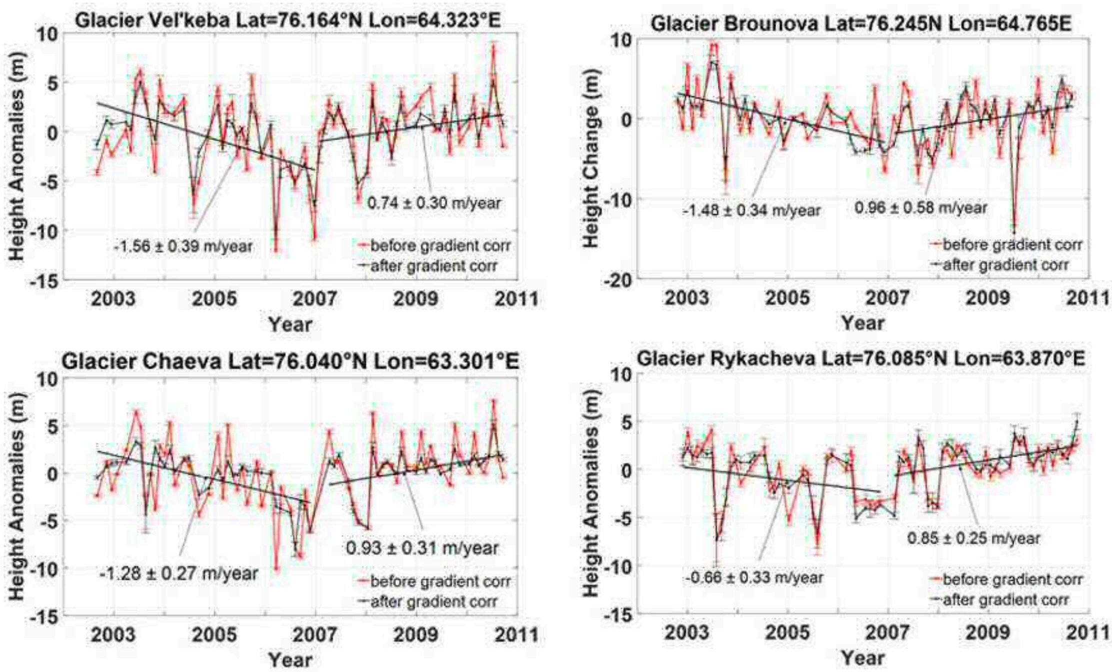

Figure 68. Time series of elevation changes over the four glaciers in northern Novaya Zemlya using retracked Envisat RA-2 data.

Kuo et al. (2015) successfully used satellite altimetry, including Topex/Poseidon and Jason-2, retrieved by novel retrackers to monitor vertical land motions in Southwestern Taiwan. Modified threshold and improved subwaveform threshold retrackers were used in the study to improve the accuracy of altimetric land surface heights (LSHs). The results indicate that the vertical motion rates derived from both retrackers coincide with those calculated by 1843 precise levelling points, with a correlation coefficient of 0.96 and mean differences of 0.43 and 0.52 cm/yr (standard deviations: 0.61 and 0.69 cm/yr).

Members in OUS (Su et al., 2015-2018) attempted to investigate the inter-annual variations of snow/firn density over the Antarctic ice sheet by combining GRACE gravimetry and Envisat altimetry. They refined their data post-processing algorithm for analyzing altimetry data over ice sheets. They conducted the joint analysis of the inter-annual anomalies of mass change from GRACE gravimetry and elevation changes from Envisat and SARAL altimetry over the

Greenland ice sheet, with the objective of obtaining high-resolution inter-annual mass variations based on altimetry data. Over the Amundsen Sea sector, they have detected the snow/firn density change during 2003-2009. The results agree with the events of excess snow accumulation and the accelerated ice discharge occurring there.

Improved inland water levels from SAR and conventional altimetry

Marshall and Deng (2016) developed a robust and automated method based on image analysis of multispectral and Advanced Synthetic Aperture Radar (ASAR) imagery for the selection of altimetry waveforms over inundated zones is presented. The advantage of the method is that the waveform footprint can be automatically assessed for inundation extent as well as level of vegetation cover, with waveforms that meet threshold levels being flagged for further retracking and water surface elevation determination (Figure 69).

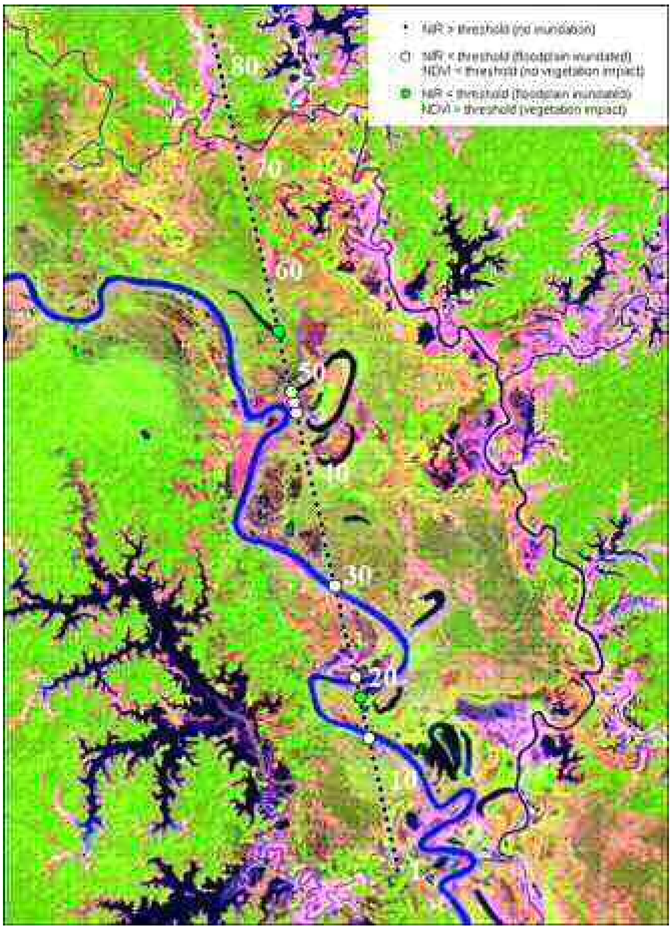

Figure 69. Landsat ETM7 (bands 5, 4, 3) on 28th October 2002, waveforms located over inundated zones overlapping Envisat RA-2 18Hz waveforms pass 0677, cycle 10. White dots over water body are automatically selected (Marshall and Deng, 2016).

Villadsen et al. (2016) developed several new methods for obtaining stable inland water levels from CryoSat-2 SAR altimetry, including the Multiple Waveform Persistent Peak (MWaPP) retracker and a method combining the physical and empirical retrackers. Using a physical SAR waveform retracker over inland water has not been attempted before but shows great promise in this study. It has found that the new empirical MWaPP retracker is easy to implement, computationally efficient, and gives a height estimate for even the most contaminated waveforms over inland waters.

In order to investigate the climate inplication, Hwang et al. (2016) investigated the multi-decadal monitoring of lake level changes in the Qinghai-Tibet Plateau, China, by using TOPEX/Poseidon-family altimeters. Su et al. (2016) improved processing algorithms for Envisat altimetry ice sheet elevation change data using the repeat-track analysis. Rateb et al. (2017) estimated spherical harmonics (SH) errors and scale factors for African hydrological regimes. Then, terrestrial water storage (TWS) in Africa was determined based on Slepian localization and compared with JPL-mascon and SH solutions. The TWS trends in the lower Nile and Sahara at −1.08 and −6.92 Gt/year, respectively, are higher than those previously reported.

Monitoring natural disasters from altimetry

Flood forecasting using Jason-2/3 altimetry and VIC model. Chang et al. (2019) developed a freely accessible model-aided satellite altimeter-based daily water level forecasting system using simple regression analysis for the Mekong River (Figure 70). The system circumvents the need of frequent altimeter samplings in the upstream by using the Variable Infiltration Capacity (VIC) macroscale hydrologic model.

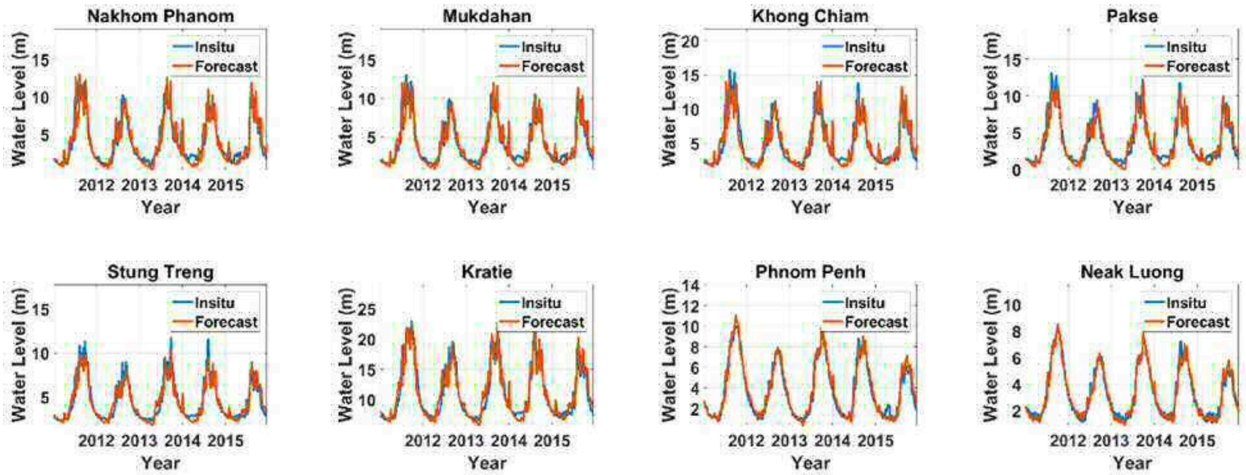

Figure 70. Examples of time series of 5-day forecasted and in situ water levels in the middle reach of the Mekong River and the Cambodian floodplain.

Estimation of river discharges with Ensemble Learning Regression using altimetry data. Kim et al. (2019) developed a new approach to estimating river discharges (Q) by applying the ensemble learning regression method (ELQ), which is one of the machine learning techniques that linearly combine several functions to reduce errors, to the altimetry-derived water levels over the Congo mainstem. Using the water level changes obtained at different Envisat virtual stations, the ELQ-estimated Q at the Brazzaville in-situ station showed reduced root-mean-square error (RMSE) of 823 m^3s^{-1} compared to the Q obtained using a single rating curve. Since ELQ can combine several variables obtained over different locations, it would be advantageous, particularly if there exist few virtual stations along a river reach.

Automated generation of water level changes from satellite altimetry data. Okeowo et al. (2017) proposed a new algorithm to automatically generate time series from satellite radar altimetry data only without user intervention. With this method, users with little knowledge on the field can independently process altimetry data for diverse applications. The method is based on K-means clustering, interquartile range, and statistical analysis of the dataset for outlier detection.

Jason-2 and Envisat data were used to demonstrate the capability of this algorithm. A total of 37 satellite crossing over 30 lakes and reservoirs located in US, Brazil, and Nigeria were used based on the availability of in-situ data (Figure 71). The RMSE values ranged from 0.09 to 1.20 m. The potential of this algorithm has been also confirmed over wetlands as well.

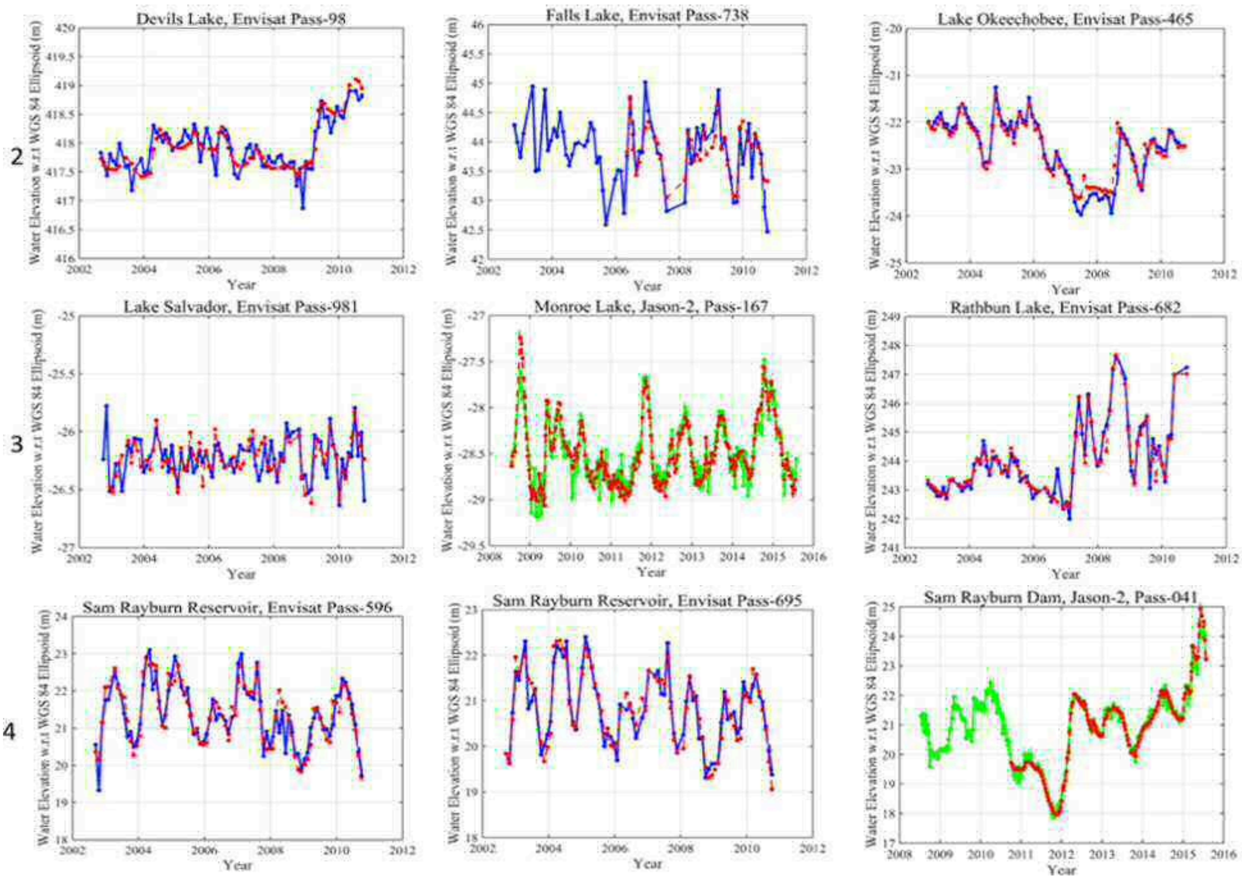

Figure 71. Examples of comparison of in-situ gauge observation (red) and altimetry-derived (Envisat: blue, Jason-2: green) water level of lakes in US.

Based on the automation algorithm, user-friendly GUI toolkits for Jason-2/3 altimetry data processing have been developed (Figure 72).

Figure 72. Interface of Jason-2/3 altimetry toolkit.

Markert et al. (2019) introduced an open-source web application to access and explore Jason-2/3 altimetry datasets for use in water level monitoring, named the Altimetry Explorer (AltEx, https://tethys.servirglobal.net/apps/altex/, c.f. Figure 73). The back-end of this web application is based on the automation method of Okeowo et al. (2017). 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 73. Interface of AltEx web application (https://tethys.servirglobal.net/apps/altex/) for Jason-2/3 altimetry data over inland water bodies.

Integration of satellite altimetry and SAR/InSAR for wetland hydraulics/hydrology

Two-dimensional water level changes over wetlands from altimetry data and SAR backscattering coefficients. Yuan et al. (2015) described the relation between L-band APLSAR backscattering coefficients and water level changes obtained from Envisat altimetry over the island of Île Mbamou in the Congo Basin where two distinctly different vegetation types are found. The study attempted to estimate water level changes based on the relation which were then compared with the Envisat altimetry and InSAR results. The study demonstrated the potential of generating two- dimensional maps of water level changes over the wetlands. Kim et al. (2017) attempted to estimate spatial-temporal water level variations over the central Congo River covered with aquatic plants using the backscattering coefficients from PALSAR ScanSAR images and water levels from Envist altimetry data (Figure 74). The water level maps were validated with ICESat altimetry-derived water levels. The RMSD of 67 cm at 100-m scale resolution of PALSAR ScanSAR image has been obtained.

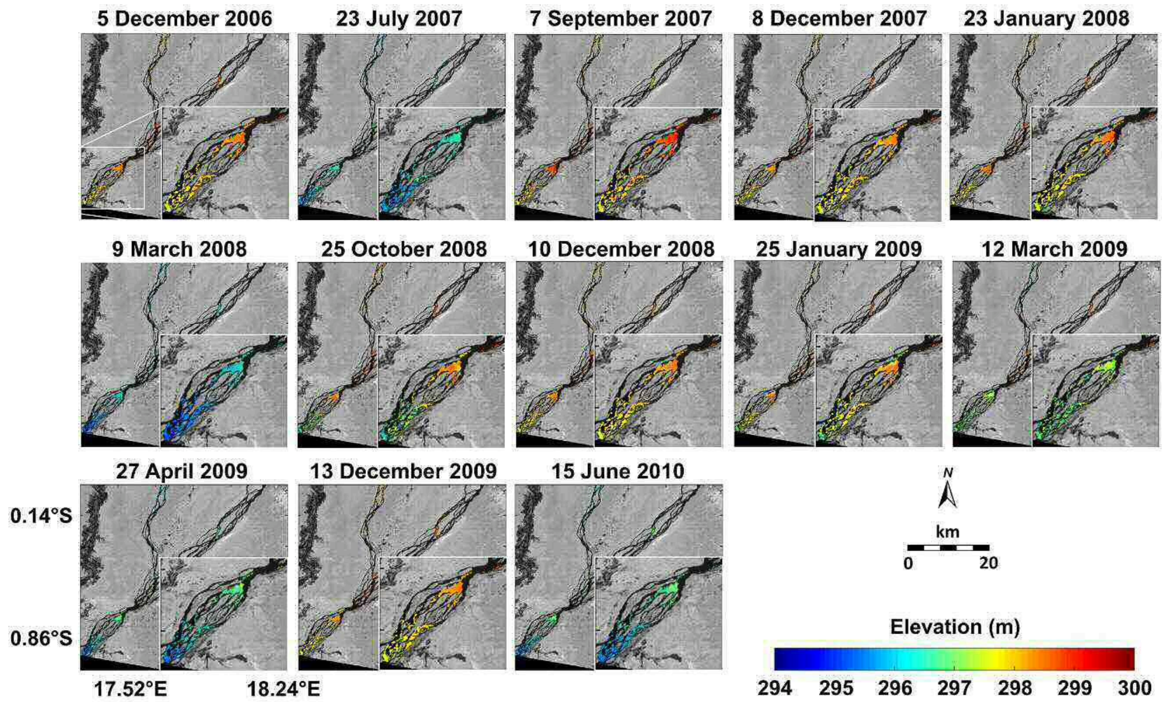

Figure 74. Multi-temporal Congo River level maps from 5 Dec 2006 to 15 June 2010 (Kim et al., 2017). The bottom left region is enlarged for visual clarity. The scale bar is used for the enlarged images.

Two-dimensional water depths over wetlands using altimetry, SAR backscattering coefficients and vegetation density. Lee et al. (2015) developed a simple linear regression model based on PALSAR ScanSAR backscattering coefficients, water levels from Envisat altimetry, and MODIS Vegetation Continuous Field (VCF) product to generate water depth maps over flooded forecast in the central Congo Basin. The water depth maps were generated relative to the lowest water level from Envisat altimetry, which is assumed a base level with essentially zero depth (Figure 75). The predicted and observed water depths along the Envisat pass showed excellent agreements with RMSD of 13 to 18 cm. The water depth maps were also independently validated with ∂h/∂t obtained from PALSAR interferometry.

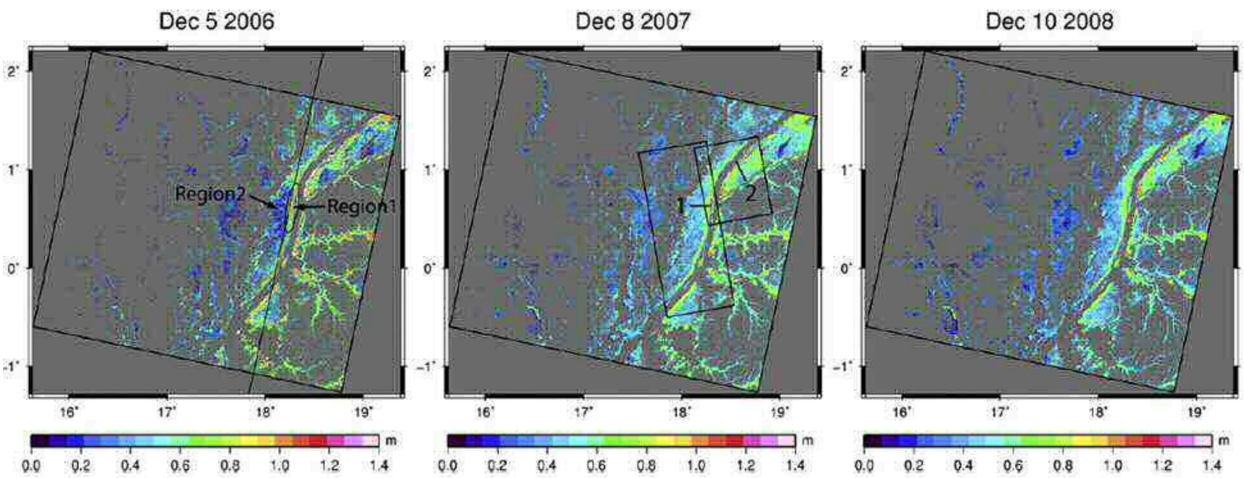

Figure 75. Maps of water depth beneath flooded forests inside the ScanSAR coverage. The black line (left) shows the track of Envisat Pass 930.

Time series of absolute water volumes over wetlands from altimetry and InSAR. Yuan et al. (2017) proposed a new method to estimate absolute water storages over the floodplains by establishing relations between water depths (d) and water volumes (V) using 2-D water depth maps from the integration of InSAR and altimetry measurements. The method was applied to the Congo River floodplains and the d–V relations were modelled using a power function (Figure 76). These d–V relations were combined with Envisat altimetry measurements to construct time series of floodplain's absolute water storages from 2002 to 2011.

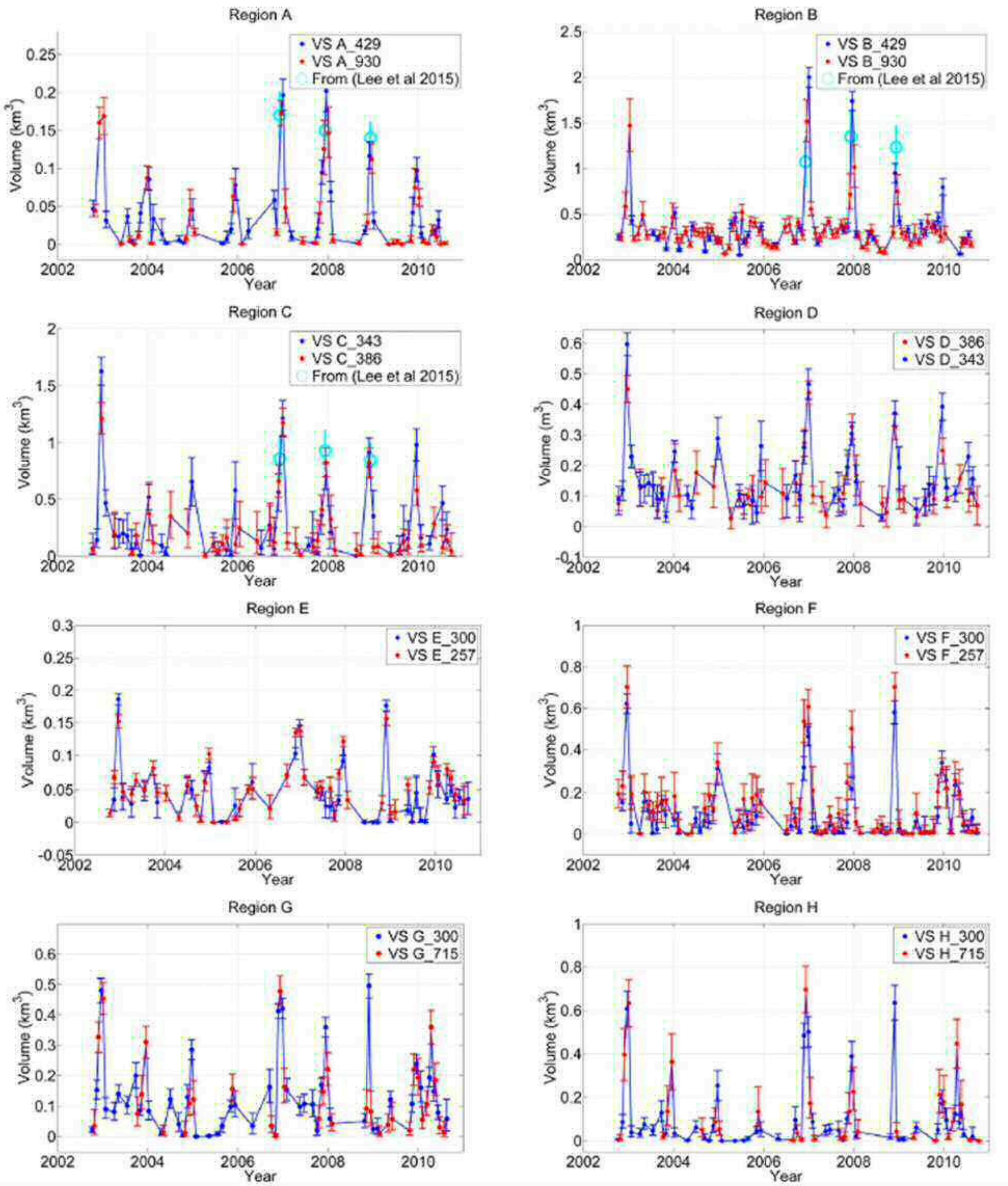

Figure 76. Time series of absolute water volumes over eight floodplains in the Congo Basin.

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Sub-commission 2.6: Gravity and Mass Transport in the Earth System

Chair: *Jürgen Kusche (Germany)*
Vice Chair: *Isabelle Panet (France)*

Overview

The Sub-commission's activities during the period 2015-2019 were mainly via its (joint) working groups.

Joint Working Groups of Sub-commission 2.6:

JWG 2.6.1: Geodetic observations for climate model evaluation

Chair: *Annette Eicker (Germany)*

Members
- *Carmen Böning (USA)*
- *Marie-Estelle Demory (UK)*
- *Albert van Dijk (Australia)*
- *Henryk Dobslaw (Germany)*
- *Wei Feng (China)*
- *Vincent Humphrey (Switzerland/USA)*
- *Harald Kunstmann (Germany)*
- *J.T. Reager (USA)*
- *Rosa Pacione (Italy)*
- *Anne Springer (Germany)*
- *Paul Tregoning (Australia)*

Activities and publications during the period 2015-2019:

Main activities of JWG 2.6.1 covered the organization of meetings (especially the dedicated workshop held in 2017 in Bonn) and conference sessions and were supported by various individual discussions and smaller splinter meetings. The activities resulted in the proposal of an IAG Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) to enable a long-term focus on the topic of the working group.

Organization of the workshop "Satellite Geodesy for Climate Studies"

One of the main events during the four year working group period was the workshop on "Satellite Geodesy for Climate Studies" that was held September 19-21, 2017, in Bonn, Germany (https://www.apmg.uni-bonn.de/aktuelles/veranstaltungen/IAG_SGCS) as a joint initiative of SC 2.6 (Gravity and Mass Transport in the Earth System) and the working groups JWG 2.6.1 and JWG 4.3.8 (GNSS Tropospheric Products for Climate). With ~70 participants giving 45 oral and 18 poster presentations the workshop brought together geodetic data specialists and climate scientists with the goal of strengthening the use of geodetic data in the climate community (Figure 77).

The rationale of the workshop was as follows: The growing record of space-gravimetric and -geodetic data (GRACE, GNSS, radar altimetry, InSAR, VLBI, …) provides a new view on Essential Climate Variables such as terrestrial water storage and continental ice-mass changes, steric and barystatic sea level variability, sea ice coverage, tropospheric water vapor variations, and others. These observational data sets have the strong advantage to be homogeneous around the globe, and independent from any other data commonly used to validate climate models. Geodetic time series start to reveal a complex picture of low-frequency natural climate variability, long-term climate change and other anthropogenic modifications in geodetic data. It is still difficult to evaluate decadal variability from geodetic data alone, but in combination with other observations or reanalyses they provide excellent tools for climate model evaluations. The workshop was organized in four sessions, with working group members serving as convenors and keynote speakers: A) What is required for validating climate models using geodetic data, B) Long and consistent geodetic time series, C) Climate modelling and observable variables, D) Prospects of future missions and constellations.

Figure 77 Workshop "Satellite Geodesy for Climate Studies", September 19-21, 2017, at the University of Bonn

As part of the workshop, geodesists and climate scientists met in breakout sessions to draft a roadmap for closer collaboration between these communities. While it is generally recognized that geodetic data like GNSS troposphere and radio-occultation observables, satellite-gravimetric surface mass change, and altimetric sea level provide invaluable information for studying the planet's changing climate, programmatic obstacles and scientifically open questions have been identified that hamper a wider acceptance of geodesy as a tool for climate research. In particular, the participants suggest that

- communication between communities be improved through networking activities and through, e.g., improving data product and modeling transparency and access,
- visibility of geodetic climate research be improved, e.g. through publishing key review papers authored by geodesy scientists in climate journals and vice versa, through involvement of associations IAG, IAMAS and IAPSO, programs such as WCRP and GCOS, the space agencies, and finally through pushing for the acknowledgement of geodesy products used in climate science as a more visible contribution of geodesy
- a new branch of early career scientists at the interface of geodesy and climate scientists should be established and supported through summer schools and joint PhD programs
- the science groundwork be improved through building, in collaboration, more showcases and publishing more joint, high-impact science papers

The main points of this roadmap have recently been included in the "Terms of Reference" document for the new proposal of the Inter-Commission Committee on "Geodesy for Climate Research" (ICCC).

Splinter meetings, sessions and further workshops

Another important part of the working group's activities was dedicated to organizing sessions at international conferences. The following sessions were initiated by the working group:

- "Geodesy for atmospheric and hydrospheric climate research", IUGG General Assembly 2019, Montreal (2019)
- Observing and Separation of geophysical signals in the Climate and Earth System through Geodesy", EGU General Assembly, Vienna (2019)
- "Hydrological Signals in Geodetic Observations: from Space to Ground", AOGS Annual Meeting, Singapore (2019)
- "Satellite Geodesy for Climate and Atmospheric Research", AGU Washington (2018)
- "Mass transport and climate-relevant processes", IAG GGHS, Copenhagen (2018)
- "Altimetry, Mass Transport and Climate Applications", IAG GGHS, Thessaloniki (2016)
- "Mass Transport and Mass Distribution in the Earth System", AGU Fall Meeting San Francisco (2016) and New Orleans (2017)

Splinter meetings of the working group members took place at the IAG GGHS meeting in Thessaloniki (September 2016) and at the EGU General Assembly (April 2017). The topic of the splinter in September was a discussion about efforts to promote satellite gravity related topics towards the European Union with the future goal of establishing satellite gravimetry within the Copernicus program. Following this discussion in Thessaloniki, two representatives of the working group (C. Böning and A. Eicker) joined the organization team for two lobby events that took place in Brussels with members of the European Commission (March 2017 and May 2017) and acted as speakers at both of these events. The second splinter meeting in Vienna in April was dedicated to the planning of the workshop "Satellite Geodesy for Climate Studies". Over the course of the last 1.5 years (2018/19) various planning meetings and discussions among different working group members were dedicated to developing the proposal for the new IAG ICCC (see below).

Additionally, an IAG workshop on HydroGeodesy, which partly also covered topics of JWG 2.6.1 was organized by working group member W. Feng in June 2018 in Wuhan, China. Additional information is provided in the corresponding report published in the IAG Newsletter http://www.iag-aig.org/index.php?tpl=text&id_c=44&id_t=744

Link to JWG 4.38 'GNSS tropospheric products for Climate'

A strong link has been established between JWG 2.6.1 and JWG 4.3.8 'GNSS tropospheric products for Climate', which is part of IAG Sub-Commission 4.3 'Atmosphere Remote Sensing', embedded in the IAG Commission 4 'Positioning and Applications'. Its main objectives are to assess existing reprocessed GNSS tropospheric products, foster the development of forthcoming reprocessing activities, review and update GNSS-based product requirements and exchange format for climate and promote their use for climate research, including a possible data assimilation of GNSS troposphere products in climate models. Refer to its Final Report (this publication) for further details. To explore the synergy effects between the different geodetic observation techniques, the two working groups jointly organized the Bonn workshop in 2017 and subsequently two sessions at international conferences (AGU 2018 and IUGG 2019). The two working groups together also form the basis for the new ICCC (see below).

Proposal of an IAG Inter-Commission Committee on "Geodesy for Climate Research"

Based on the work of JWG 2.6.1 (and other ongoing IAG activities) the use of geodetic observables for climate research has been identified as an important research area for the upcoming years. Therefore, IAG is currently planning the implementation of an Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) with the goal to facilitate a systematic and comprehensive approach among the various geodetic communities, but also to establish and foster links to climate science. The goal is to establish this ICCC as new long-term element of the IAG structure at the IUGG meeting in Montreal (July 2019). Quite similarly to the already existing Inter-Commission Committee on Theory (ICCT), the ICCC itself shall build the overarching framework, with the main purpose to trigger and coordinate initiatives. The actual working elements will be related Joint Study/Working Groups, which are also affiliated to one or more of the IAG Commissions and/or to GGOS. A respective Terms of Reference document has been formulated with the help of various members of JWG 2.6.1 and SC 2.6 and has been submitted to IAG.

Scientific work

Scientific studies of the working group members focused around the use of various geodetic data sets (e.g. GRACE, GNSS, radio occultation) for improving our understanding of climate change related processes and for evaluating respective (climate) models.

Even though the 15-year mass change data record provided by the GRACE mission is still relatively short for the investigation of climate signals, it does start to reveal long-term changes in global water storage distribution. However, an extension of the mass change record back in time would be helpful for many climate applications. In this context, Humphrey et al. (2017) used GRACE observations to train a statistical model and reconstruct pre-2002 water storage changes from historical observations of precipitation and temperature at the global scale, providing a benchmark to evaluate hydrological models over a long time span.

A review paper by Feng et al (2018) discusses groundwater storage trends over main aquifers in China using GRACE, in-situ well observations and hydrological models. Significant groundwater depletion in the North China Plain and Song-Liao Basin was highlighted in this work. The influence of long-term changes in continental water storage on sea level was investigated by Reager et al. (2016), revealing climate-change induced hydrological changes over continents to slow down sea level rise and counteract rising sea levels caused by direct human water cycle interaction like groundwater pumping.

GRACE provides an important source of information for the evaluation of climate and Earth system models. Zhang et al. (2017) validated a set of model experiments with different global land surface and hydrological models under identical atmospheric forcing with month-to-month variations of GRACE-based terrestrial water storage in order to identify strengths and weaknesses of different modelling approaches in representing the global terrestrial water cycle.

Via the terrestrial water balance equation water storage change as determined by GRACE can be linked to the net flux deficit in hydro-meteorological fluxes (precipitation minus evapotranspiration minus runoff). In Eicker et al, (2016) this relation was exploited to evaluate long-term and inter-annual changes in global atmospheric reanalyses, while Springer et al. (2017) used GRACE water storage changes in combination with discharge data for assessing the closure of the water budget in the recent high-resolution European COSMO-REA6 Reanalysis and found the regional model to be superior to global reanalyses.

Böning & Demory (2018) used GRACE time series to validate the global hydrological cycle as simulated by an atmospheric General Circulation Model (GCM) using present-day forcing. They were able to show the ability of the climate model to simulate the inter-annual variability of terrestrial water storage, finding in particular the model being able to capture the regional distribution of changes in terrestrial water transport ENSO events. First attempts have been made to use GRACE data for evaluating (coupled) climate models. Month-to-month variations in global distributions of terrestrial water storage as derived from GRACE satellite data were used to validate the terrestrial water cycle in decadal climate hindcast experiments with the global numerical climate model MPI-ESM (Zhang et al. 2016). Jensen et al. (2019, under revision) investigated the potential of GRACE data for evaluating water storage trends in the suite of climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5).

A novel aspect of the use of geodetic data for climate science was introduced in a recent study by Humphrey et al. (2018), who found the inter-annual variability of global land water storage measured by the GRACE satellites was to be negatively correlated with land carbon uptake by terrestrial ecosystems (drier years leading to less carbon sequestration), a response that seems underestimated by current global climate models.

Data assimilation techniques are an important tool for the downscaling of the GRACE data in terms of spatio-temporal resolution and for enabling the vertical decomposition of the integrated mass change signal into individual storage compartments. Synergy effects can be exploited if different types of observation data are assimilated simultaneously, as Tian et al. (2019) showed in a global joint assimilation of GRACE and SMOS satellite soil moisture data into a hydrological model.

In order to enable an easier use of GRACE data for the Earth science and climate communities, Feng (2019) developed an open-source Matlab toolbox for estimating global mass variations from GRACE data including necessary post-processing steps.

Besides the observation and understanding of global mass variations as observed by GRACE, climate-related changes in atmospheric conditions have been the focus the working group activities over the last four years. Atmospheric water vapour is highly variable, both in space and in time, and can be sensed by Ground-Based GNSS stations. The Zenith Total Delay estimates of GNSS, provided at high temporal resolution and under all weather conditions, can be converted to Integrated Water Vapour (IWV) if additional meteorological variables are available. In the past years, several long-term (20+ years) reprocessed GNSS tropospheric delay and water vapor time series datasets have been produced, on a global, regional and national scale, and have become available for climate studies.

Focusing on the European scale, in 2016 the reprocessing of the EUREF Permanent Network (EPN), established and maintained under the umbrella of the IAG Regional Reference Frame sub-commission 1.3a for Europe, was finalized. In cooperation with the WG3 of the COST Action ES1206 'GNSS4SWEC' (Bock and Pacione, 2019) five EPN ACs homogenously reprocessed the EPN for the period 1996-2014. This pan-European dataset 'EPN-Repro2' (Pacione et al. 2017) is open to the user community and it has been established as a reference data set for monitoring trend and variability in atmospheric water vapor on a European scale. In Berckmans et al. (2018) the EPN Repro2 IWV dataset is used to evaluate the regional climate model ALARO. In addition, SMHI (Swedish Meteorological and Hydrological Institute) started using EPN-Repro2 data for European Reanalysis in the framework of the Copernicus Climate Change Service.

Schmidt, T. et al. (2016) processed radio occultation data from various LEO satellites to obtain zonally averaged temperature distributions in the upper troposphere and lower stratosphere (UTLS) to validate the representation of the UTLS temperature transition zone in decadal climate hindcast experiments.

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Working Groups of Sub-commission 2.6:

WG 2.6.1: Potential field modelling with petrophysical support

Chair: Carla Braitenberg (Italy)

Members

- *Jon Kirby (Australia)*
- *Shuanggen Jin (China)*
- *Erik Ivins (USA)*
- *Xiapoping Wu (USA)*
- *Valeria Barbosa, (Brazil)*
- *Leonardo Uieda (Brazil)*
- *Orlando Alvarez (Argentina)*
- *Jörg Ebbing, (Germany)*
- *Holger Steffen (Sweden)*
- *Sabine Schmidt (Germany)*
- *Rezene Mahatsente (USA)*
- *Daniele Sampietro, (Italy)*
- *Christian Hirt (Germany)*

Activities and publications during the period 2015-2019

The activity of the working group was manifested in discussions at meetings (e.g. EGU Vienna, Austria in years 2015-2019; International Symposium on Geodesy and Geodynamics (ISGG2018)- Tectonics, earthquake and Geohazards, Kunming, China (Figure 78), 2018; Gravity, Geoid and Height Systems, (GGHS) Copenhagen, 2018, Geodynamics and Earth Tide Symposium, Triest, Italy 2016) and individual exchange of information, methodologies, software and data among the members of the group, students and other interested colleagues.

Figure 78 Group photo at International Symposium on Geodesy and Geodynamics (ISGG2018)- Tectonics, earthquake and Geohazards, 30 July-2 August 2018, Kunming, China.

The aims of the group are to develop and promote methods and software that are needed for a full understanding of the Earth's static and variable gravity and gradient field, integrating potential field modelling with the physical properties of the rocks at the in- situ conditions and using the constraining data on rock composition that are available from petrologic investigations. Another physical constraint comes from the isostatic equilibrium and the dynamic mass changes that are necessary to reach equilibrium calculable from observed GNSS movements. The petrophysical modelling must include assumptions or models of depth variation of temperature and pressure and the crust and mantle composition.

Seismic data, supported by mineralogical constraints, are coupled to the external gravity field measured by satellites and to changes in the moments of inertia of the earth and the geodetically observed pole position. Such data supported models are key to interdisciplinary study of the time-varying gravity fields measured by GRACE and the interpretation of ongoing climate-related continental and ocean basin scale changes (Adhikari et al., 2018; Caron et al., 2018; Tapley et al., 2019). Such integrative models that explicitly employ seismic, gravity and petrological constraints are important in developing models of heat flux beneath the ice sheets (e.g., (Martos et al., 2017; Seroussi et al., 2017).

Efforts were made on how to use the recent global topography reduction models which are available in spherical harmonics from the ICGEM calculation service. The use of the most recent terrestrial-satellite derived gravity models, and application of the global correction for terrain, leads to very different Bouguer gravity values compared to the classic local correction up to the 167 km Hayford radius. The global fields require special attention and dedicated study in order to be used in the regional density modeling. It is customary to reduce the gravity field for the effect of the topography, for which models in spherical harmonic expansion are available, as the model of (Hirt and Rexer, 2015), with details explained in (Rexer et al., 2016). Which functional to use when calculating the Bouguer gravity disturbance or anomaly, using the spherical harmonic expansions of the Earth's gravity field (as EIGEN6C4) and of the gravity effect of topography (as the model RET2014) is explained in (Tenzer et al., 2019). The result is a Bouguer map which is quite different from the one obtained from a local correction of the topography up to the Hayford radius of 167 km. For instance in the Alps, the Bouguer values are -60 mGal over the Alpine arc, whereas the regional Bouguer values are classically below -180 mGal.

The markedly different values obtained with the global reduction are inherent to the distant masses that are neglected in the regional reduction, but which are largely compensated by the isostatic crustal thickness variations (Szwillus et al., 2016). When fulfilling regional 3D density modeling, lateral dimensions and maximum depth of the model is limited. The limit in lateral and depth extension of the model produces a limit in the spectral content of the modelled. It is therefore necessary to reduce the lowest degrees of the gravity field of topography, since they introduce a field which is due to distant masses and are uncorrelated to the regional properties of the gravity field which is going to be modelled in the present study. It was found that starting with degree and order $N>10$ the field of topography starts resembling the regional topography, a value which can be used as lower limit for the spherical harmonic expansion of the fields. This value agrees with the findings of mantle convection flows, who define degree 10 the limit of lithospheric contributions, lower having their origin in the deep mantle or lower. The band-limited Bouguer map obtained for degrees $10 < N < 2190$ (e.g. EIGEN 6C4 and RET2014) has the same features as the non-band-limited map, with the difference that the Bouguer anomalies are more like those of the regional topographic reduction. Further discussion on spectral content of density-modelled fields are found in (Sebera et al., 2018).

Several strategies have been developed to include the temperature, pressure and compositional aspects in the density modeling. Compositional and temperature effects in petrophysical modeling were addressed and the software updates have included the following:

One useful software for compositional modeling is the "MATLAB toolbox and Excel workbook for calculating the densities, seismic wave speeds, and major element composition of minerals and rocks at pressure and temperature" by (Abers and Hacker, 2016). The software allows to calculate rock seismic velocities at elevated pressure and temperature for arbitrary compositions. The software includes a reference database to make such calculations from the physical properties of minerals. The database of 60 mineral endmembers includes the parameters needed to estimate density and elastic moduli for many crustal and mantle rocks at conditions relevant to the upper few hundreds of kilometers of Earth. The software being available in MATLAB, it can be integrated into density forward and inverse modeling enterprises.

An alternative approach for modeling density and seismic velocity is the PERPLEX software tool (Connolly, 2005), a collection of Fortran routines (http://www.perplex.ethz.ch/). Perplex is a thermodynamic calculation package suitable for creating phase diagrams of the compound. It allows estimation of rock and mineral properties for a given composition as a function of pressure and temperature conditions, from which density and seismic velocity can be obtained.

The isostatic principle is used in the lithosphere modeling process either as a constraining factor, requiring that equilibrium is reached after visco-elastic relaxation, or as a method to discriminate different lithospheric terrains. Either Bouguer or free air gravity is used in a joint analysis with topography, with the Bouguer field showing some numerical advantages (Kirby, 2014, 2019). The isostatic principle was used to estimate possible gravity change rates observable from GRACE in response to mountain building and topographic uplift successfully in Tibet and Alps (Braitenberg and Shum, 2017; Chen et al., 2018) and for applications concerned with the estimate of hydrologic masses (Li et al., 2018).

A 3D reference model for density modeling was developed by Haas and Ebbing, with the aim of having a benchmark for inversion studies and published electronically. The group showed that global qualitative analysis of satellite derived gradients correlate to tectonic large scale lithospheric properties (Ebbing et al., 2018).

At local and regional scales, new algorithms for an accurate modelling of airborne gravity data have been studied. In details, a software to compute the terrain effect (Sampietro et al., 2016) with accuracy smaller than 0.1 mGal exploiting FFT properties has been developed. Moreover, a tool to filter and grid airborne gravity observations (Sampietro et al., 2017) also considering the low frequencies coming from Global Satellite Models, has been developed and tested. The obtained grids of gravity anomalies can be inverted by means of a new Bayesian inversion algorithm able to estimate at the same time the geometry of the main discontinuities between different layers or bodies in the sub-surface and the 3D density distribution within each layer/body. The algorithm has been used to estimate the density distribution in relevant test cases in the field of hydrocarbon exploration and geoneutrino modelling (Reguzzoni et al., 2019).

The spectrum of investigations on which the above methodologies are applied is very broad, and includes, next to the aim of modeling the Earth in 3D, also topics as gravity changes associated to earthquakes (Spagnotto et al., 2018), or the search for mineral deposits (Motta et al., 2019).

Software updates: GrafLab/isGrafLab :

Gravity functionals from spherical harmonic expansion. This MATLAB tool allows to calculate gravity functionals necessary to compute for instance gravity anomaly and Bouguer gravity disturbance with the above mentioned global fields (Bucha and Janák, 2014). New releases from 2018 of GrafLab and isGrafLab focus mostly on improving large-scale computations up to ultra-high harmonic degrees. In some applications, spherical harmonic synthesis up to degrees as high as, say, 21600 has become a necessary task of a routine character. The new versions allow more efficient computation. The software is available at: https://www.svf.stuba.sk/en/departments/department-of-theoretical-geodesy/science-and-research/downloads.html?page_id=4996

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Commission 2 Joint Working Group 2.1: Relativistic Geodesy: Towards a new geodetic technique

Chair: *Jakob Flury (Germany)*
Vice Chair: *Gerard Petit (France)*

Members

- *Geoff Blewitt (US)*
- *Claude Boucher (France)*
- *Pascale Defraigne (Belgium)*
- *Pacome Delva (France)*
- *Gesine Grosche (Germany)*
- *Claus Lämmerzahl (Germany)*
- *Christian Lisdat (Germany)*
- *Jürgen Müller (Germany)*
- *Pavel Novak (Czech Republic)*
- *Paul Eric Pottie (France)*
- *Bijunath Patla (US)*
- *Nikos Pavlis (US)*
- *Piet Schmidt (Germany)*
- *Pieter Visser (The Netherlands)*
- *Marie-Francoise Lequentrec-Lalancette (France)*
- *Elena Mazurova (Russia)*
- *Sergei Kopeikin (US)*
- *Chris Hughes (UK)*
- *Davide Calonico (Italy)*

Activities during the period 2015-2019

Remark: JWG 2.1 has been established in December 2016, i.e. in the course of this IAG reporting period, based on suggestions and exchange with IAG officers. The group activities started with the first JWG 2.1 workshop in May 2017.

In recent years, major technology breakthroughs on the fields of optical frequency standards and optical frequency transfer have been achieved, which provide a new basis for relativistic geodesy. The aim of JWG 2.1 is to investigate how measurements and modeling of relativistic effects can be included into geodesy and geophysical applications. The strongest focus of the group is currently on emerging methods to observe the gravity frequency redshift and gravity potential differences on continental scales by optical frequency transfer and remote optical frequency comparison, a field where we witness very dynamic activities.

Comparisons of optical atomic clocks in laboratories, in particular in National Metrology Institutes (NMI), have achieved relative frequency accuracies in the 10^{-18} range for the best clocks. Such comparisons are included into the ongoing activities of the roadmap towards re-definition of SI second established by the Consultative Committee on Time and Frequency (CCTF) of BIPM. For chronometric leveling and for the use in geodetic networks, the development of transportable optical clocks is a key element. They are needed for the calibration of stationary clocks and for the separation of clock inaccuracies and height inaccuracies. In first measurement campaigns with the transportable Sr lattice clock of Physikalisch-Technische Bundesanstalt (PTB), Germany, relative frequency accuracies in the 10^{-17} range have been achieved (C. Lisdat, pers. comm.). The best experiments on remote frequency transfer over continental distances using phase-stabilized optical fiber links have even achieved relative frequency accuracies in the 10^{-20} range, which leaves ample room for the future comparison of more accurate optical atomic clocks. In Europe, the network of optical fiber links for remote optical frequency transfer in accuracies relevant for relativistic geodesy is currently expanding due to ongoing research and infrastructure development projects. Frequency transfer experiments have already linked Braunschweig (Germany), Munich, Paris, and London, and the network is expected to include long distance links in Italy soon.

Overall, increasingly, the elements needed for continental-scale observation of gravity frequency redshift and gravity potential differences with relativistic techniques in a relevant accuracy (10^{-18} relative frequency accuracy, corresponding to 0.1 m^2/s^2 accuracy in gravity potential difference, or 1 cm accuracy in height difference) are becoming available. There is increasing demand for concepts on the use of relativistic observations for geodetic and geophysical applications. Using networks of optical atomic clocks, it will be possible to observe both the static and time-variable gravity field, including tidal and non-tidal temporal variations of the gravity potential. Investigations should address in which locations relativistic frequency observations would be desirable and how observations in these sites can be linked to or integrated into existing and evolving geodetic networks and reference frames such as the IERS network and the International Height Reference System (IHRS). It should be studied how gravity potential differences obtained from relativistic techniques, e.g., in optical clock networks should be combined with available classical geopotential data and models. Results from chronometric leveling are expected to strengthen height information from the GNSS/geoid approach, as well as from leveling networks. The support from geospatial and mapping agencies will be important in this field. Studies should consider how potential difference observations referring to atomic standards can be used for the observation of geophysical processes, and how they can serve as height reference for a wide variety of applications in oceanography.

JWG 2.1 intends to draft a Position Paper addressing geodetic entities (such as EUREF for Europe), outlining the concepts and current status for using frequency transfer networks for chronometric leveling and geodetic reference frames. In addition, the group considers research on free-space optical links for frequency transfer as very important and promising.

The goal of the group is to bring together experts on time and frequency metrology with experts on geodetic applications and geodetic reference frames. The group has done so in two dedicated JWG 2.1 workshops. The first workshop was held on May 15-16, 2019, at Leibniz Universität Hannover, Germany. The second workshop was held on October 10-11, 2018, at BIPM in Sèvres, France.

In the following, the contributions and discussions of JWG 2.1 on the most important topics are summarized. For more details, the presentations, materials, and minutes of the workshops are available at the JWG 2.1 website https://www.ife.uni-hannover.de/de/forschung/professur-fuer-geodaetische-weltraumsensorik-und-schwerefeld/jwg-21-relativistic-geodesy/

Progress in optical clock development and campaigns of optical clock comparisons

For stationary optical clocks in NMIs, the number of optical transitions studied, compared and reported has strongly increased, with several measurements of optical frequency ratios having uncertainties much smaller than the current realization of the second. This work is monitored by a Working Group of the CCTF (Figure 79) and should lead to a future redefinition of the second. The activities of the corresponding roadmap of CCTF have been reported to the group, with important milestones being achieved, e.g., with two optical clocks contributing as secondary standards to TAI. Recent comparison campaigns linking Braunschweig (PTB), Paris

(Observatoire de Paris / SYRTE) and London (NPL) involved a total of 9 optical clocks in June 2017, and 6 optical clocks in April/May 2018. Perspectives include the development of non-destructive atomic detection in clocks to avoid dead time as a factor limiting optical clock stability. Campaigns for remote optical clock comparisons with PTB's transportable Sr lattice clock have started in 2016 (Grotti et al 2018). To date, campaigns have included measurements in PTB, Observatoire de Paris (Figure 80), Modane (LSM), Torino (INRIM), and Munich (MPQ). According to preliminary analysis, for the best sub-sets of remote clock comparison observations, a combined relative frequency uncertainty in the low 10^{-17} range (corresponding to few decimeters in height uncertainty) has been achieved. Within the ITOC campaign, gravity potential differences between Paris and several sites in Germany have been determined using classical methods with an uncertainty of the order of 3 cm equivalent height (Denker et al 2018).

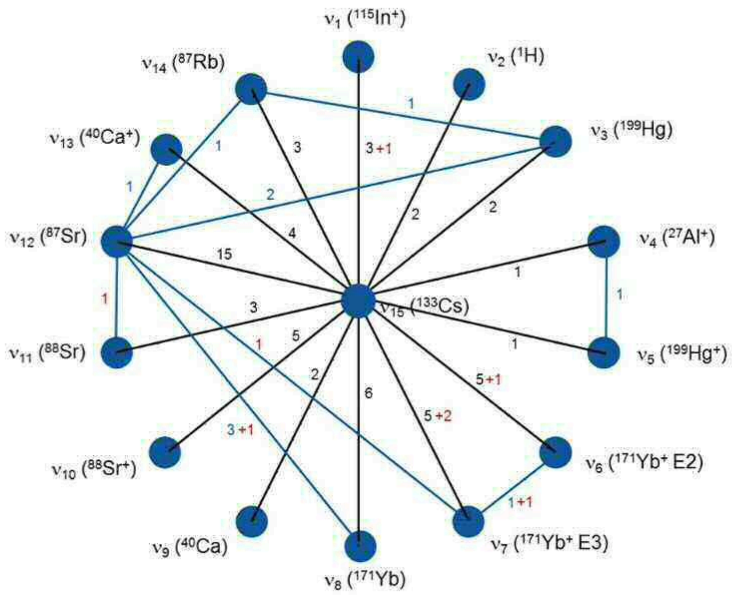

Figure 79 : Frequency ratio measurements considered by the Frequency Standards Working Group (WGFS) of the CCTF. Most were absolute frequency measurements, i.e. frequency ratios involving the caesium primary standard, but several optical frequency ratios have been determined. Source: H. Margolis / G. Petit

Figure 80 The transportable Sr lattice clock of PTB during measurements at Observatoire de Paris in 2017. Source: C. Lisdat, PTB

Progress in time and frequency transfer techniques

Remote frequency comparisons with interferometric optical fiber links have achieved effective attenuation counteraction and 10^{-20} relative frequency accuracy. They have been very successfully used for the clock comparison campaigns reported above. Currently, the infrastructure for experiments in Europe is extended by several links in France using industrial grade links with uptimes of 90% and higher, as well as by the implementation of the Italian Quantum Backbone optical fiber link with a length of 1800 km connecting Modane (LSM), Torino (INRIM), and the 3 VLBI stations in Medicina, Fucino and Matera. This opens the perspective to deliver a common clock to the radiotelescopes for applications in radioastronomy and geodesy (Figure 81). Concepts towards a sustainable, layered fiber access infrastructure in Europe are currently being developed in the Clonets project. As an alternative to optical fiber links, GPS-Integer Ambiguity Precise Point Positioning (IPPP) is being studied, achieving frequency deviations in the low 10^{-17} accuracy regime when averaged over several weeks of measurements (Leute et al 2018; Figure 82). Although this is far from sufficient to compare the best optical clocks, it is the only technique readily available capable of frequency transfer in the 10^{-17} domain between any two clocks worldwide. It allows for intercontinental frequency comparisons, which will also be provided by the upcoming ACES mission to the International Space Station (ISS).

Figure 81 Italian Quantum Backbone optical fiber network. Source: D. Calonico (INRIM)

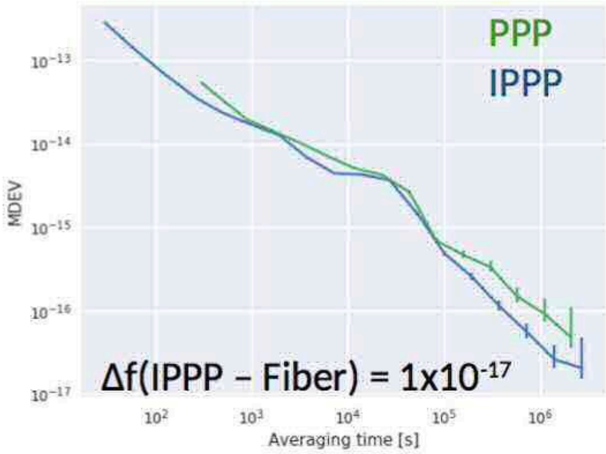

Figure 82 Modified Allan deviation of frequency deviations of GPS PPP/IPPP link for a baseline between PTB and DTAG Bremen (150 km). The GPS receivers operated in a common-clock setup linked by Optical Time Transfer. Source: J. Leute (BIPM)

Theory of relativistic geodesy

The fully relativistic description of signal propagation in optical fibers has been discussed, including frequency transfer, time transfer, tidal effects, and the Sagnac effect. It was derived that in a relativistic framework, the potential describing frequency redshift is consistent with the potential describing accelerations. It was discussed that first-order Post-Newtonian effects in the definition of the geoid would imply changes at the level of 2 mm (or 2×10^{-19}). It should be ensured that this and other uncertainties from the theory remain below that of the applications by a significant factor.

Reference frames, height networks, and time

The need for a new definition of International Atomic Time and the need of guidelines for operators of frequency standards to compute the relativistic shift with the best possible accuracy were discussed. The new definition of TAI was adopted by the CCTF in 2017 and endorsed by the General Conference of Weights and Measures in 2018. There was a consensus among the JWG 2.1 that the value of the constant L_G defining Terrestrial Time (TT) is conventional and so provides a conventional value of the gravity potential defining a "chronometric geoid", and that it should not be changed to track the progresses in determining a "classical geoid" whose surface corresponds to mean sea level.

Determination of the gravity potential with clocks

The observation of the relativistic frequency redshift in optical clock networks provides the opportunity to link gravity potential differences and height differences to atomic standards. The complementarity of chronometric observables to classical gravity observables concerning spatial resolution and sensitivity was discussed. A synthetic gravity model and synthetic measurements were used for a test case in France to test the quality of simulated geopotential determination (Lion et al 2017). A European-scale simulation addressed the elimination of offsets and tilts in regional height systems at the decimeter-scale using several clock observations in each region (Wu et al 2019). A concept of combining pointwise geopotential data from classical geopotential determination using satellite-based gravity models and high-resolution terrestrial gravity data on one hand with relativistic potential differences between clock sites on the other was proposed, motivated by the combination of best available techniques in existing reference frames such as the ITRF. A concept for a hierarchical clock network for an IHRS was proposed, including transportable clocks for densification. The potential of using accurate space-based optical clocks for direct determination of the gravity potential seems limited at this time, however, space-based optical clocks could provide the reference for Earth-based clocks to measure the gravity potential on Earth.

Applications in oceanography

Accurate height reference is needed for a wide range of applications in oceanography, from mapping and navigation in shallow areas to deep sea exploration. Applications include the planning and construction of energy generation in oceans, and hydrodynamic models for coastal safety. References for mapping often contain artefacts due to differences in chart datums (e.g., differences between local and global references). Merging and homogenization is critical, e.g., for the combination of airborne and terrestrial recovery of topography and bathymetry, and needs high-resolution geoid information. An important task is to relate the mean dynamic topography (MDT) of the oceans to the sea levels locally measured at tide gauges. This can be performed to within about 5 cm RMS for the best cases today, but with several locations where decimetric discrepancies subsist (Figure 83). Centimeter accuracy point geopotential values from optical clocks would help greatly with looking at coastal MDT at tide gauges.

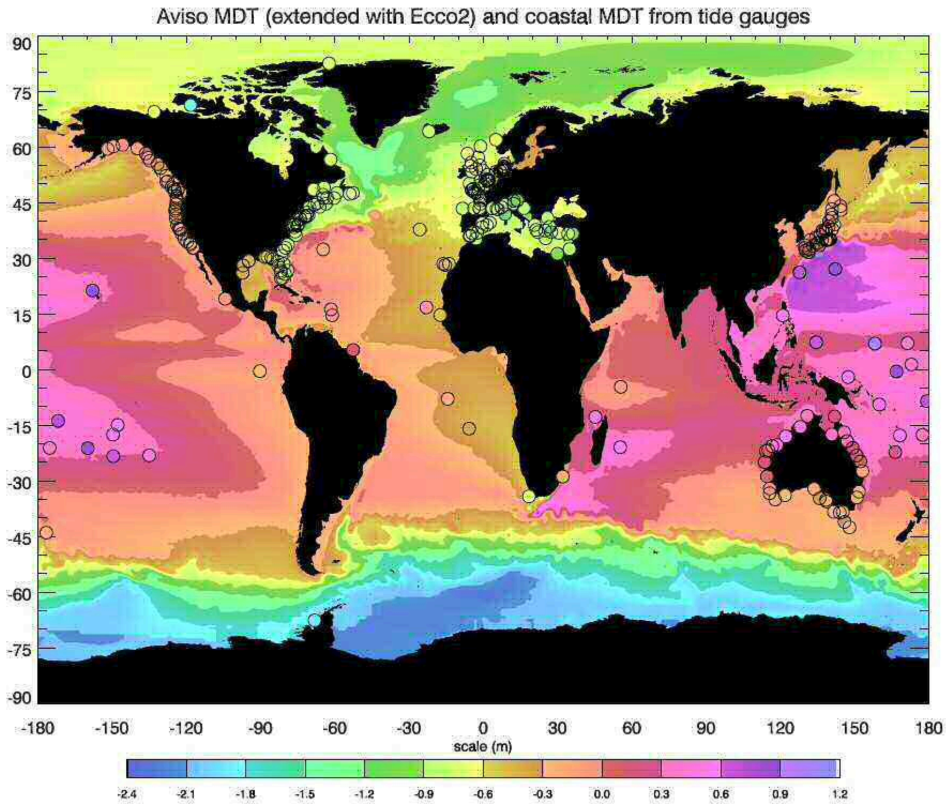

Figure 83 Contour plot: Aviso mean dynamic topography (MDT), extended with Ecco2 ocean model; circles: coastal MDT in tide gauges equipped with GPS, referred to Eigen-6c4 geoid. Source: Andersen et al (2018)

Other related activities

During the reporting period, the International Space Science Institute (ISSI), Bern, hosted a scientific team on "Spacetime Metrology, Clocks and Relativistic Geodesy". The team was led by Sergei Kopeikin and Jürgen Müller. The team members had a significant overlap with the JWG 2.1 group members, leading to a very fruitful exchange and complementarity of investigations. The ISSI team held scientific meetings in March 2018 and March 2019. Presentations and results, including an extensive list of references, are available at http://www.issibern.ch/teams/spacetimemetrology/. The ISSI team activities are ending in 2019.

The proceedings of the 2016 WE Heraeus Seminar "Relativistic Geodesy: Foundations and Applications" were published in 2019, edited by Dirk Pützfeld and Claus Lämmerzahl.

In September 2018, the workshop "1st International Symposium on Time and Frequency Applications (TAFA)" was held at Wuhan University, China, promoting the international exchange on the topics of IAG JWG 2.1.

In the reporting period, members of JWG 2.1 organized and (co-)convened several topical sessions at international conferences on the research field of JWG 2.1.

Selected Publications

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Commission 2 Joint Working Group 2.2: Validation of combined gravity model EGM2020

Chair: *Srinivas Bettadpur (USA)*
Co-chair: *Dru Smith (Australia)*

Members

- *Hussein Abd-Elmotaal (Egypt)*
- *Jonal Agren (Sweden)*
- *Kevin Ahlgren (Sweden)*
- *Riccardo Barzaghi (Italy)*
- *Denizar Blitzkow (Brazil)*
- *Sean Bruinsma (France)*
- *Gomaa Dawod (Egypt)*
- *Heiner Denker (Germany)*
- *Will Featherstone (Australia)*
- *René Forsberg (Denmark)*
- *Christoph Förste (Germany)*
- *Rupesh Garg*
- *Christian Hirt (Germany(*
- *Jialiang Huang (Canada)*
- *Jay Hyoun Kwon (Korea)*
- *Peter Morgan (Australia)*
- *David Sandwell (USA)*
- *Yan Wang (USA)*
- *Varga, Matej (Croatia)*

Corresponding Members:

- *Christopher Jekeli (USA)*
- *David Avalos (Mexico)*
- *Thomas Gruber (Germany)*
- *Sylvain Bonvalot (France)*

Activities during the period 2015-2019

Remark: JWG 2.2 has been established in spring 2017, i.e. in the course of this IAG reporting period. The terms of reference, objectives and program of activities has been adopted during the IAG EC meeting on 28 April 2017.

The National Geospatial-Intelligence Agency (NGA), in conjunction with its U.S. and international partners, is currently working on the next Earth Gravitational Model. The final version of the new 'Earth Gravitational Model 2020' (EGM2020) has an expected public release date of 2020. EGM2020 will be essentially an ellipsoidal harmonic model up to degree (n) and order (m) 2159, but will be released as a spherical harmonic model to degree 2190 and order 2159. EGM2020 will benefit from new data sources and procedures. Updated satellite gravity information from the GOCE and GRACE mission, will better support the lower harmonics, globally. Multiple new acquisitions (terrestrial, airborne and ship borne) of gravimetric data over specific geographical areas, will provide improved global coverage and resolution over the land, as well as for coastal and some ocean areas. NGA and partners are evaluating different approaches for optimally combining the new GOCE/GRACE satellite gravity models with the terrestrial data. These include the latest methods employing a full covariance adjustment.

A first preliminary version PGM2017 was distributed among the members of JWG 2.2. This model was validated by applying various methods. For this independent external validation, a full arsenal of validation methods and external independent data sources was applied. This includes validation against GPS/levelling observations, regional data bases of gravity field functionals, other global and regional gravity field models, orbit tests to assess mainly the long wavelengths of the field as well as the spectral transition from satellite to terrestrial data, assessment in the frame of mean dynamic ocean topography computations, correlation analysis with topographic potential and isostatic potential models.

Good progress has been made during this period in the PGM2017 model validation. Several issues have been identified, and model improvements have been suggested to the model producers.

The next model release is expected by end of 2019 or beginning of 2020, i.e. after the end of the current IAG period. Therefore, it is recommended to set up a similar validation group under the umbrella of IAG in the next IAG period. This would be important, because EGM2020 is a candidate model to serve as global reference for the International Height Reference System (IHRS) as part of an integrated Global Geodetic Reference Frame (GGRF).

Commission 3 – Earth Rotation and Geodynamics

http://www.rcep.dpri.kyoto-u.ac.jp/iag-commission3/Commission_3.htm

President: Manabu Hashimoto (Japan)
Vice President: Cheng-Li Huang (China)

Geodynamics is the science that studies how the Earth moves and deforms in response to forces acting on the Earth, whether they derive from outside or inside of our planet. This includes the entire range of phenomena associated with Earth rotation and Earth orientation such as polar motion, Universal Time or length of day, precession and nutation, the observation and understanding of which are critical to the transformation between terrestrial and celestial reference frames. It also includes tidal processes such as solid Earth and ocean loading tides, and crust and mantle deformation associated with tectonic motions and isostatic adjustment etc.

During the last few decades many geophysicists have come to use geodynamics in a more restricted sense to address processes such as plate tectonics and postglacial rebound that are dominantly endogenic in nature. Because the Earth as a mechanical system responds to both endogenic and exogenic forces, and because these responses are sometimes coupled, Commission 3 studies the entire range of physical processes associated with the motion and the deformation of the solid Earth. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research in this broad arena.

Structure

Sub-commission 3.1:	Earth Tides and Geodynamics
Sub-commission 3.2:	Crustal Deformation (2015-2017)
	Volcano Geodesy (2017-2019) (joint with IAVCEI)
Sub-commission 3.3:	Earth Rotation and Geophysical Fluids
Sub-commission 3.4:	Cryosphere Deformation
Sub-commission 3.5:	Tectonics and Earthquake Geodesy
Joint Study Group 3.1:	Intercomparison of Gravity and Height Change (joint with IGFS, Commissions 1 and 2)
Joint Working Group 3.1:	Theory of Earth Rotation and Validation (joint with IAU)
Joint Working Group 3.2:	Constraining Vertical Land Motion of Tide Gauges (joint with Commission 1)

Overview

Commission 3 fosters and encourages research in the areas of its sub-entities by facilitating the exchange of information and organizing Symposia, either independently or at major conferences in geodesy or geophysics. Some events will be focused narrowly on the interests of the sub-commissions and other entities listed above, and others will have a broader commission-wide focus.

Summary of the Commission’s activities during the period 2015-2019

Commission 3 members were active to hold several meetings, where they served as chairpersons of LOC or keynote speakers, and convene sessions in international conferences. In total, 6 meetings and 16 sessions or splinter meetings convened by Commission 3 members in international conferences. 3 books were published by Commission 3 members.

Commission 3 convened a session G04 "Earth Rotation and Geodynamics" in the IAG-IASPEI 2017 held in Kobe, Japan, July 31 - August 4, 2017. 29 papers were presented in 4 oral sessions and 1 poster session. The commission had a splinter meeting during IAG-IASPEI to discuss activities during next two years. Manabu Hashimoto, President of the Commission 3, delivered a key note speech entitled "Evolution of Earthquake Science with Space Geodesy" in this assembly.

Commission 3 also convened a session G04 "Earth Rotation and Geodynamics" in the coming 27th General Assembly of IUGG in Montreal, Canada, July 8 – 18, 2019. 31 papers were presented in 4 oral sessions and 1 poster session.

Commission 3 reorganized a sub-commission during this term. Sub-commission 3.2 Crustal Deformation was dissolved and a new sub-commission 3.2 Volcano Geodesy was established according to the discussion with the IAVCEI after the IAG-IASPEI 2017. This sub-commission consists of members from IAVCEI and IAG. Commission 3 is seeking for the collaboration with other associations and other commissions based on the recommendation of EC, and president Hashimoto has worked to establish a sub-commission with IASPEI and a new inter-commission commission "Marine Geodesy".

Sub-commissions held several meetings and published a couple of proceedings of past meetings.

Meetings

Journées 2017, des Systèmes de Référence et de la Rotation Terrestre, Chengli Huang , SOC member and representative of IAG C3, 25-27/9/2017, Alicante, Spain. (https://web.ua.es/journees2017/index.html).

From Space Geodesy to Astro-Geodynamics, 2017 International Symposium of Asia-Pacific Space Geodynamics (APSG) Project, Chengli Huang , LOC Chair and SOC member, 15-18/8/2017, Shanghai, China

Geodesy, Astronomy and Geophysics in Earth Rotation (GAGER2016) - A Joint IAU/IAG/IERS Symposium, Richard Gross and Chengli Huang , co-Chairs of SOC, 19/7/2016 - 23/7/2016, Wuhan, China.

Geodesic Datum and Regional and Terrestrial Reference Frame Realization, 2015 International Symposium of Asia-Pacific Space Geodynamics (APSG) Program, Chengli Huang , co-Chair of LOC, 24-28/8/2015, Moscow, Russian

Books

International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH), Hashimoto M. Ed., IAG Symposia Series 145, 168 pp., 2017.

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Publications (by President and Vice-president)

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Presentations (by President and Vice-President)

Hashimoto, M., Postseismic Deformation Following the Kumamoto EQ Detected by SAR, ALOS-2 PI Workshop 2019, Tokyo, Japan, Jan. 2019.

Hashimoto, M., Localized deformation following the April 2016 Kumamoto, Japan, earthquake detected by InSAR, AOGS2018, Honolulu, USA, Jun. 2018.

Fukushima, Y. and M. Hashimoto, Spatial variation of creep rate of the Philippine fault on Leyte island and its relation with the 6 July 2017 earthquake (Mw6.5) revealed by SAR interferometry, JpGU2018, Chiba, Japan, May 2018.

Hashimoto, M., Localized postseismic deformation following inland strike-slip event: Kobe and Kumamoto earthquakes, JpGU2018, SSS09-11, Chiba, Japan, May 2018.

Hashimoto, M., Localized deformation following the April 2016 Kumamoto, Japan, earthquake detected by InSAR, EGU2018, G3.6, SM2.20, Vienna, Austria, Apr. 2018.

Hashimoto, M., Localized postseismic deformation following inland strike slip event: Kobe and Kumamoto earthquakes, The 4th Japan-Taiwan Workshop on Crustal Dynamics, Sapporo, Japan, Mar. 2018.

Hashimoto, M., T. Nishimura, T. Ozawa, H. Munekane, and M. Tobita, Ground deformation in the Kobe-Osaka area during 22 years after the Kobe earthquake, The Joint PI Meeting of Global Environment Observation Mission FY2017 (The 3rd ALOS-2 PI Workshop), 26, Tokyo, Japan, Jan. 2018.

Hashimoto, M., Evolution of earthquake science with space geodesy, IAG-IASPEI 2017, Kobe, Japan, Jul. 2017.

Nishimura, T., M. Hashimoto, Y. Hoso, H. Sakaue, and Y. Itoh, Pre-, Co-, and Postseismic deformation of the 2016 Oct 21th M6.6 Central Tottori earthquake, IAG-IASPEI 2017, Kobe, Japan, Jul. 2017.

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Fukahata, Y., and M. Hashimoto, Simultaneous estimation of the dip angles and slip distribution on the two active faults of the 2016 Kumamoto earthquake through a weak non-linear inversion of InSAR data based on ABIC, IAG-IASPEI 2017, Kobe, Japan, Jul. 2017.

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Chung R., K.-E. Ching, M. Hashimoto, R.-J. Rau, and L.-H. Chung, Coseismic deformation and tectonic implications of the 2016 Meinong earthquake, Taiwan, JpGU-AGU2017, SSS10-P07, Chiba, Japan, May 2017.

Hashimoto, M., T. Ozawa, T. Nishimura, H. Munekane, and M. Tobita, Postseismic deformation following the 1995 Kobe, Japan, earthquake detected by space geodesy, EGU2017, X2.257, EGU2017-2874, Vienna, Austria, April 2017.

Hashimoto, M., and T. Ozawa, Ground deformation near active faults in the Kinki, district, southwest Japan, detected by InSAR, 2016 AGU Fall Meeting, G22A-02, San Francisco, USA, December 2016.

Hashimoto, M., Observation of surface deformation with ALOS-2/PALSAR-2 in southern Taiwan before, during and after the Meinong earthquake, 2016 Taiwan-Japan Workshop on Crustal Dynamics, 13-13, Tainan, Taiwan, November 2016.

Fukahata, Y., and M. Hashimoto, InSAR data inversion to simultaneously estimate the dip angles and slip distribution of the two seismogenic faults at the 2016 Kumamoto earthquake, 2016 Taiwan-Japan Workshop on Crustal Dynamics, 17-17, Tainan, Taiwan, November 2016.

Takahashi, A., M. Hashimoto, J.-C. Hu, and Y. Fukahata, Identification of crustal block structures in Taiwan islands investigated by cluster analysis of super dense GNSS data, 2016 Taiwan-Japan Workshop on Crustal Dynamics,18-18, Tainan, Taiwan, November 2016.

Hashimoto, M., Observation of earthquakes with ALOS-2/PALSAR-2, CEOS2016, Tokyo, Japan, September 2016.

Hashimoto, M., Surface deformations associated with the Meinong, Taiwan, earthquake detected by InSAR, AOGS2016, Beijing, China, August 2016.

Hashimoto, M., Observation of ground deformation in the Osaka and Kanto plains with ALOS-2/PALSAR-2, IGARSS2016, Beijing, China, July 2016.

Hashimoto, M., Observation of the Gorkha, Nepal earthquake of April 23, 2015 with ALOS-2/PALSAR-2, American Geophysical Union 2015 Fall Meeting, G21A-1011, San Francisco, USA, December 2015.

Lindsey E., R. Natsuaki, X. Xu, M. Shimada, M. Hashimoto, D. Melgar, and D. Sandwell, Line of sight displacements from ALOS-2 ScanSAR interferometry, AGU 2015 Fall Meeting, G13B-04, San Francisco, USA, December 2015.

Hashimoto, M., Ground deformation in northern Kanto, Osaka and Nagoya detected by PALSAR/PALSAR-2, The 2nd PI Workshop for ALOS-2, S2-1-02, Tokyo, Japan, November 2015.

Hashimoto, M., High resolution monitoring of surface deformation with SAR, (Key-note Speech), French-Japanese Symposium on earthquakes & Triggered Hazards, 51-52, Orleans, France, September 2015.

Hashimoto, M., Study of deformation using ALOS-2/PALSAR-2, IGARSS2015, Milan, Italy, July 2015.

Sub-commission 3.1: Earth Tides and Geodynamics

Chair: *Janusz Bogusz (Poland)*
Vice-Chair: *Carla Braitenberg (Italy)*

Overview

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 phenomena responsible for these variations include the full range of periodic and non-periodic occurrences such as solid Earth tides, ocean and atmospheric tidal loading, ocean, atmospheric and hydrologic non-tidal effects 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. Thus, the time scales range from seconds to years and for the spatial scales from local to continental dimensions. SC 3.1 national representatives are involved in:

- organization of International Symposium on Geodynamics and Earth Tide (GET Symposium held every four years) as well as other thematic conferences together with other Commission 3 SCs if possible;
- awarding of the outstanding scientists with the Paul Melchior Medal, formerly known as the Earth Tides Commission Medal;
- organization of special sessions at international meetings;
- organization of the comprehensive SC meeting together with the IGETS;
- publishing the outcome of the researches, either as stand-alone publications or as proceedings or special issues of scientific journals;
- cooperating with other Joint Study Groups (JSG), Joint Working Groups (JWG) or Inter-Commission Projects (ICP) and Committees (ICC);
- cooperate with GGOS, as mentioned above.

Summary of the Sub-commission's activities during the period 2015-2019:

Meetings:

1. 18th International Symposium on Geodynamics and Earth Tides (G-ET Symposium 2016), title of Meeting: "Intelligent Earth system sensing, scientific enquiry and discovery", venue: University of Trieste, Italy, date: June 5 (Sunday) to June 9 (Thursday) 2016, coordination: Carla Braitenberg. The Symposium attracted 105 attendants from 31 countries who presented 66 oral presentations and 40 posters. The contributions were grouped into the following sessions:

   - tides and non tidal loading.,
   - geodynamics and the earthquake cycle,
   - variations in Earth rotation,
   - tides in space geodetic observations,
   - volcano geodesy,
   - natural and anthropogenic subsurface fluid effects,
   - instrument and software developments.

   Nine invited lectures of half an hour each allowed insight into specific themes, as the principal outcomes of 18 years superconducting gravity in Medicina (Italy) (H.Wziontek), the lunisolar stress tensor and the triggering of earthquakes, the correction of observed free oscillation spectra due to local heterogeneities obtainable from tidal observations (W. Zürn), a review on the results of 40 years of longbase laser strainmeter observations in California (D. Agnew), the geodetic observation of slow slip events (SSE) or giant silent earthquakes at subduction zones (K. Heki), the role of earth tides in global plate tectonics (C. Doglioni), an overview of local to global geodetic monitoring of natural hazards and global change (H. Schuh), the separation of surface loading from time dependent tectonic deformation in GNSS observations (J. Freymueller), and a review of new developments of terrestrial and space based gravimetric instrumentation in China (Houze Xu). The program included a talk of the Rector of the University M. Fermeglia on 'The great energy challenge: how to avoid the 'perfect storm' and the President of the OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) M.C. Pedicchio. Website: https://g-et2016.units.it/.

2. co-organized with Joint Study Group 3.1: Intercomparison of Gravity and Height Changes the International Workshop on the "Inter-comparison of space and ground gravity and geometric spatial measurements", Strasbourg (France), 16-18 Oct. 2017.

3. co-organized with International Geodynamics and Earth Tide Service the 1st IGETS Workshop held at GFZ, Potsdam, 18-20 June 2018.

Special sessions at international meetings:

Joint International Workshop of the Sixth TibXS (Multi-observations and Interpretations of Tibet, Xinjiang and Siberia) during 25-29 July 2015, in Tianjin, China.

Joint International Workshop of the Seventh TibXS (Multi-observations and Interpretations of Tibet, Xinjiang and Siberia) during 26-30 July 2016, in Tianjin, China.

Paul Melchior Medal:

It's been a tradition of Earth Tides Symposia, that with the "Paul Melchior Medal" an outstanding scientists with a huge experience and high impact on to the Tidal Community who contributed significantly to develop the science and technology of tidal research used to be awarded. First Medal was given in 1997 to Paul Melchior and it has been named with the "Earth Commission Medal". After Paul Melchior passed away the name of the Medal was changed to honour his contribution to the development of tidal research.

The procedure of nomination to the 2016 Paul Melchior Medal was completed in 31st of October, 2015 with 5 successfully submitted nominations:

1. David Crossley;
2. Walter Zuern;
3. Trevor Baker;
4. Gerhard Jentzsch and
5. Shuzo Takemoto.

After that the Committee consisted of the past Awardees, Chair of the IAG's Sub-Commission 3.1 as well as 4 experienced tidalists who were not nominated, 8 people in total decided that 2016 Paul Melchior Medal will go to Trevor Baker.

Selected scientific papers:

Bán, D., Mentes, Gy., Kis, M., Koppán, A. 2018. Observation of the Earth liquid core resonance by extensometers. *Pure and Applied Geophysics*, 175(5), 1631-1642 doi:10.1007/s00024-017-1724-6.

Bogusz, J., Rosat, S., Klos, A. and A. Lenczuk, 2018. On the noise characteristics of time series recorded with nearby located GPS receivers and superconducting gravity meters, *Acta Geod. Geophys.*, 53, 201-220, doi:10.1007/s40328-018-0212-5.

Braitenberg C., Rossi G., Bogusz J., Crescentini L., Crossley D., Gross R., Heki K., Hinderer J., Jahr T., Meurers B., Schuh H. 2018. Geodynamics and Earth Tides Observations from Global to Micro Scale: Introduction. *Pure and Applied Geophysics*, Vol. 175, Issue 5, pp. 1595-1597, doi:10.1007/s00024-018-1875-0.

Braitenberg, C., Rossi, G., Bogusz, J., Crescentini, L., Crossley, D., Gross, R.S., Heki, K., Hinderer, J., Jahr, T., Meurers, B., Schuh, H., 2018: Editorial note for the Geodesy and Geodynamics journal special issue, *Geodesy and Geodynamics*, doi:10.1016/j.geog.2018.03.001.

Brimich L., Bednarik M., Vajda P., Bán D., Eper-Pápai I., Mentes G. 2016. Extensometric observation of Earth tides and local tectonic processes at the Vyhne station, Slovakia. *Contributions to Geophysics and Geodesy* 46 (2), 75-90, doi:10.1515/congeo-2016-0006.

Canuel, B., Bertoldi, A., L. Amand, E. Pozzo di Borgo, T. Chantrait, C. Danquigny M. Dovale Álvarez, B. Fang, A. Freise, R. Geiger, J. Gillot, S. Henry, J. Hinderer, D. Holleville, J. Junca, G. Lefèvre, M. Merzougui, N. Mielec, T. Monfret, S. Pelisson, M. Prevedelli, S. Reynaud, I. Riou, Y. Rogister, S. Rosat, E. Cormier, A. Landragin, W. Chaibi, S. Gaffet & P. Bouyer, 2018. Exploring gravity with the MIGA large scale atom interferometer, *Scientific Reports*, 8: 14064, doi:10.1038/s41598-018-32165-z.

Calvo, M., Rosat, S., Hinderer, J., 2016. Tidal spectroscopy from a long record of superconducting gravimeters in Strasbourg (France), In: Freymueller J.T., Sánchez L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. Int. Assoc. of Geod. Symposia, vol 147, 131-136. Springer, Cham, doi:10.1007/1345_2016_223.

Crossley, D., Calvo, M., Rosat, S. and J. Hinderer, 2018. More Thoughts on AG-SG Comparisons and SG Scale Factor Determinations, *Pure Appl. Geophys.*, 175, 1699-1725, doi:10.1007/s00024-018-1834-9.

Crossley, D., Calvo, M., Rosat, S., and Hinderer, J., 2018. More thoughts on AG-SG comparisons and SG scale factor determinations, in: Geodynamics and Earth Tides observations from global to micro scale, *Pure and Applied Geophysics*, Vol 175, Issue 5, pp. 1699-1725, Springer.

Gruszczynska M., Klos A., Rosat S., Bogusz J., 2017. Deriving common seasonal signals in GPS position time series by using Multichannel Singular Spectrum Analysis, *Acta Geodyn. Geomater.*, vol. 14, No. 3(187), 267-278, doi:10.13168/AGG.2017.0010.

Gruszczynska, M., Rosat, S., Klos, A., Gruszczynski, M. and J. Bogusz, 2018. Multichannel Singular Spectrum Analysis in the estimates of common environmental effects affecting GPS observations, *Pure Appl. Geophys.*, 175, 1805-1822, doi:10.1007/s00024-018-1814-0.

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Mentes G. 2015. Artificial neural network model as a potential alternative for barometric correction of extensometric data. *Bull. Inf. Marées Terrestres*, 149, 12001-12012.

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Meurers, B., Van Camp, M., Francis, O., Pálinkáš, V., 2016: Temporal variation of tidal parameters in superconducting gravimeter time-series. *Geophys. J. Int.*, 205 (1), 284-300, doi:10.1093/gji/ggw017.

Meurers, B., Ruess, D., Ullrich, Ch., Nießner, A., 2016: Gravity Monitoring at the Conrad Observatory (CO). Proceedings of the 4th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements, 12-15 April 2016, Saint Petersburg, Russia, 149-153.

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Meurers, B., 2017: Scintrex CG5 used for superconducting gravimeter calibration, *Geodesy and Geodynamics*, Available online 2 May 2017, ISSN 1674-9847, doi:10.1016/j.geog.2017.02.009.

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Rochester M.G., Crossley D, Chao B.F., 2018. On the Physics of the Inner-Core Wobble; Corrections to "Dynamics of the Inner-Core Wobble Under Mantle-Inner-Core Gravitational Interactions" by B. F. Chao, *Journal of Geophysical Research*: Solid Earth; doi:10.1029/2018JB016506.

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Rosat, S., Calvo, M., Hinderer, J., Riccardi, U., Arnoso, J. Zürn W., 2015. Comparison of the performances of different Spring and Superconducting Gravimeters and a STS-2 Seismometer at the Gravimetric Observatory of Strasbourg, France, *Stud. Geophys. Geod.*, 59, 58-82, doi:10.1007/s11200-014-0830-5.

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Ruotsalainen H., Nordman M., Virtanen J., Virtanen H., 2015. Ocean tide, Baltic Sea and atmospheric loading model tilt comparisons with interferometric geodynamic tilt observation - case study at Lohja2 geodynamic station, southern Finland, *Journal of Geodetic Science*,Volume 5, Issue 1, doi:10.1515/jogs-2015-0015.

Ruotsalainen H. 2019. Interferometric Water Level Tilt Meter Development in Finland and Comparison with Combined Earth Tide and Ocean Loading Models. Pure and Applied Geophysics, Vol. 175, Issue 5, 1659-1667, doi:10.1007/s00024-017-1562-6.

Scherneck, Hans-Georg and Rajner, Marcin, 2019. Using a Superconducting Gravimeter in Support of Absolute Gravity Campaigning - A feasibility study. Accepted for *Geophysica*, 14 pp.

Tamura, Y., Sato T., Jike T. 2018. Gravity Tide Observations at VERA Stations, *J. Geod. Soc. Japan*, 63, 139-156, doi:10.11366/sokuchi.63.139 (in Japanese with English abstract, tables and figures).

Van Camp, M., Meurers, B., de Viron, O., Forbriger, Th., 2015: Optimized strategy for the calibration of superconducting gravimeters at the one per mille level. *J. Geodesy*, doi:10.1007/s00190-015-0856-7.

Van Camp, M., de Viron, O., Watlet, A., Meurers, B., Francis, O. & Caudron, C., 2017: Geophysics from terrestrial time-variable gravity measurements, *Reviews of Geophysics*, 55, doi:10.1002/2017RG000566.

Van Camp, M., de Viron, O., Watlet, A., Meurers, B., Francis, O., Caudron, C., 2017: The gravity of geophysics, *Eos*, 98, doi:10.1029/2018EO086407.

Ziegler Y., Rogister Y., Hinderer J., Rosat, S., 2016. Chandler Wobble and frequency dependency of the ratio between gravity variation and vertical displacement for a simple Earth model with Maxwell or Burgers rheologies, In: Freymueller J.T., Sánchez L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. Int. Assoc. of Geod. Symposia, vol 147, 155-161. Springer, Cham, doi:10.1007/1345_2016_247.

Ziegler Y., Rogister Y., Hinderer J., Rosat, S., 2016. Estimation of the gravimetric pole tide by stacking long time-series of GGP superconducting gravimeters, *Geophys. J. Int.*, 205, 77-88, doi:10.1093/gji/ggw007.

Sub-commission 3.2: Crustal Deformation (2015-2017)

Chair: *Zheng-Kang Shen (China)*
Vice-Chair: *Banrjee (Singapore)*

Summary of the Sub-commission's activities during the period 2015-2017:

Meetings and Special Sessions:

AOGS 2016, 31 July - 5 August, 2016, Beijing, China
SC3.2 hosted a special session, "Geodetic Observations, Modeling Of Earthquake Cycle Deformation, And Tectonics" (SE13), in the Asia Oceania Geoscience Meeting on August 1. 29 papers were presented, among which 18 were oral and 11 were poster papers. The number of participants of our session exceeded 100.

Peer-reviewed publications co-authored by SC members:

Tian, Y., and Z-K. Shen, Extracting the regional common-mode component of GPS station position time series from dense continuous network, J. Geophys. Res., in press, 2016.
Tao, W., T. Masterlark, Z.-K. Shen, and E. Ronchin, Impoundment of the Zipingpu reservoir and triggering of the 2008 Mw 7.9 Wenchuan earthquake, China, J. Geophys. Res., 120, 7033-7047, 2015.
Ge, W.-P., P. Molnar, Z.-K. Shen, and Q. Li, Present-day crustal thinning in the southern and northern Tibetan Plateau revealed by GPS measurements, Geophys. Res. Lett., 42, 5227-5235, doi:10.1002/2015GL064347, 2015.
Shen, Z.-K., M. Wang, Y. Zeng, and F. Wang, Strain determination using spatially discrete geodetic data, Bull. Seismol. Soc. Am., 105(4), 2117–2127, doi: 10.1785/0120140247, 2015.
Wang, F., M. Wang, Y. Wang, and Z.-K. Shen, Earthquake potential of the Sichuan-Yunnan region, western China, J. Asian Ear. Sci., 107, 232-243, doi:10.1016/j.jseaes.2015.04.041, 2015.

Sub-commission 3.2: Volcano Geodesy
Inter-Association with IASPEI Commission "Volcano Geodesy" (since 2017)

The IAVCEI Volcano Geodesy Commission (also IAG Sub-Commission 3.2 Volcano Geodesy) was formally founded on January 29, 2017, with the acceptance of the proposal for the commission to IAVCEI. The initial focus of the commission was on defining the role and governance structure of the group. To this end, splinter meetings were held at the 2017 European Geosciences Union and IAVCEI General Assembly meetings, and at the 2018 Cities on Volcanoes meeting. At these meetings, the leadership was formalized, with co-chairs supported by a steering committee:

Chair: *Emily Montgomery-Brown (USA)*
Vice-Chair: *Alessandro Bonforte (Italy)*

Summary of the Sub-commission's activities during the period 2017-2019:

Since its founding, the commission has sponsored (in part or in full) the following conference symposia:

IAVCEI Cities on Volcanoes 10: **S01.13 - Geodesy: A critical component of multidisciplinary volcano monitoring and hazards mitigation efforts** (8 oral presentations, 21 poster presentations)

2018 EGU General Assembly: Volcanic processes: Tectonics, Deformation, Geodesy (18 oral presentations, 37 poster presentations)

2018 Fall Meeting, AGU: **G14A and G21B Better Living Through Volcano Geodesy: Constraints on Volcanic Hazards from Geodetic Observations and Multidisciplinary Models** (8 oral presentations, 10 poster presentations)

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)

In addition, the commission has accomplished the following tasks:

- A workshop on Volcano Geodesy was held at the Cities on Volcanoes 10 meeting (Naples, Italy)
- A volcano geodesy moderated listserv was established (through UNAVCO)
- A website has been secured, and is being populated with content
- Twitter account and Facebook group have been established
- An on-line log system (for posting of results and discussion) has been established
- Plans are being made for a community workshop to be held in conjunction with the October 2019 IRIS-UNAVCO community meeting
- Plans are being made for a stand-alone volcano geodesy workshop in 2020 (location TBD)

Sub-commission 3.3: Earth Rotation and Geophysical Fluids

Chair: *Jianli Chen (USA)*
Vice-Chair: *Michael Schindelegger (Austria)*

Overview

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 state-of-the-art models; some of these models are already con-strained 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 Com-mission 3. In order 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 2015-2019:

Meetings and Special Sessions:

AOGS 2016, July 31- August 5, 2016, Beijing, China

SC3.3 hosted a special session on "Earth Rotation and Reference Frame", with Dr. Jianli Chen (USA, Chair of SC3.3) as the main convener, Dr. Richard Gross (USA) and Dr. Michael Schindelegger (Austria, Vice-Chair of SC3.3) as co-conveners. This was the first ever AOGS session focusing on Earth rotation during its first 13-years history of AOGS (the first AOGS was held in 2014). The main consideration for proposing the session is to help promote related research in the Asia and Oceania regions, and broaden the solid Earth component at the AOGS. While the session size is relatively small, with ~ one dozen abstracts submitted, this is a good start in the AOGS community.

AOGS 2017, August 6 - August 11, 2017, Singapore

SC3.3 hosted a special session (SE09) on "Earth Rotation and Reference Frame", with with Dr. Jianli Chen (USA, Chair of SC3.3) as the main convener, Dr. Richard Gross (USA) and Dr. Michael Schindelegger (Austria, Vice-Chair of SC3.3) as co-conveners.

AOGS 2018, June 3 - June 8, 2018, Honolulu, Hawaii

SC3.3 hosted a special session at the AOGS 2018 on "Global Mass Transport, Earth Rotation and Low-Degree Gravitational Change", with Dr. Jianli Chen (USA, Chair of SC3.3) as the main convener, Dr. Richard Gross (USA), Dr. Henryk Dobslaw (Germany), and Dr. Koji Matsuo (Japan) as co-conveners. This session has a broad scope and two oral sessions are allocated, with one focusing on Earth rotation related presentations (and the other on GRACE applications).

Selected peer-reviewed publications co-authored by chair and vice-chair:

Chen, J.L., Satellite Gravimetry and Mass Transport in the Earth System, *Geodesy and Geodynamics*, https://doi.org/10.1016/j.geog.2018.07.001, 2018.

Chen, J.L., B.D. Tapley, H. Save, M. Tamisiea, S. Bettadpur, J. Ries, Quantification of ocean mass change using GRACE gravity, satellite altimeter and Argo floats observations, *J. Geophys. Res.* Solid Earth, Vol. 123, Issue11, 10,212-10,225, DOI: 10.1002/2018JB016095, 2018.

Li, J. J.L. Chen, S.N. NI, L. Tang, X.G. Hu, Long-term and inter-annual mass changes of Patagonia Ice Field from GRACE, *Geodesy and Geodynamics*, https://doi.org/10.1016/j.geog.2018.06.001, 2018.

Wang, S.Y., J.L. Chen, C.R. Wilson, J. Li, X.G. Hu, Vertical motion at TEHN (Iran) from Caspian Sea and other environmental loads, *J. Geodynamics*, Vol. 122, 17–24, https://doi.org/10.1016/j.jog.2018.10.003, 2018.

Jeon, T., K.-W. Seo, K. Youm, J.L. Chen, C.R. Wilson, Global sea level change signatures observed by GRACE satellite gravimetry, *Scientific Reports*, 8:13519, DOI:10.1038/s41598-018-31972-8, 2018.

Wang, S.Y., J.L. Chen, C.R. Wilson, J. Li, X.G. Hu, Reconciling GRACE and GPS estimates of long-term load deformation in southern Greenland, *G. J. Internat.*, Vol. 212, Issue 2, 1302–1313, https://doi.org/10.1093/gji/ggx473, 2018.

Li, Z., J.L. Chen, J. Li, X.G. Hu, Temporal and spatial variations of global steric sea level change from Argo measurements, 2005-2015, *Geodesy and Geodynamics*, Vol. 38, No.9, 923-929, 2018.

Chen, J.L., C.R. Wilson, J.S. Famiglietti, B.R. Scanlon (2018), Groundwater Storage Monitoring from Space. In S. Liang (Ed.), *Comprehensive Remote Sensing*, vol. 4, pp. 295–314. Oxford: Elsevier.

Chen, J.L., T. Pekker, C.R. Wilson, B.D. Tapley, A.G. Kostianoy, J.-F. Cretaux, E.S. Safarov (2017), Long-Term Caspian Sea Level Change, *Geophys. Res. Lett.*, 44 (13), 6993–7001, DOI: 10.1002/2017GL073958.

Chen, J.L., C.R. Wilson, B.D. Tapley, H. Save, J.-F. Cretaux (2017), Long-Term and Seasonal Caspian Sea Level Change from Satellite Gravity and Altimeter Measurements, *J. Geophys. Res.* Solid Earth, 122, DOI: 10.1002/2016JB013595.

Ni, S.N., J.L. Chen, C.R. Wilson, J. Li, X.G. Hu, R. Fu, Global terrestrial water storage changes and connections to ENSO events, *Surveys in Geophysics*, 1–22, DOI 10.1007/s10712-017-9421-7, 2017.

Van Dam, T., J.L. Chen, and T. Meyrath, Geodetic observations as a monitor of Climate change, in Global change and Future Earth: The geodetic and geophysics perspective, Cambridge University Press, 2017.

Kuang, W., B.F. Chao, J.L. Chen, Decadal polar motion of the Earth excited by the convective outer core from geodynamo simulations, *J. Geophys. Res.* Solid Earth, 122, DOI: 10.1002/ 2017JB014555, 2017.

Ni, S.N., J.L. Chen, C.R. Wilson, X.G. Hu, Long-term water storage changes of Lake Volta from GRACE and satellite altimeter and connections with regional climate change, *Remote Sensing*, 9(8): 842, 2017.

Youm, K., K.-W. Seo, T. Jeon, S.-H. Na, J.L. Chen, and C.R. Wilson, Understanding Antarctic and Greenland ice mass balance (1979-2010) using Earth's polar motion, *J. Geodynamics*, 106 (2017) 66–73, DOI:10.1016/j.jog.2017.01.008, 2017.

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Scanlon, B.R., Z. Zhang, H. Save, D.N. Wiese, F.W. Landerer, D. Long, L. Longuevergne, J.L. Chen, Global Evaluation of New GRACE Mascons Products for Hydrologic Applications, *Water Resour. Res.*, 52, doi:10.1002/2016WR019494, 2016.

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Cazenave, A., N. Champollion, J. Benveniste, and J.L. Chen, Foreword: International Space Science Institute (ISSI) Workshop on Remote Sensing and Water Resources, *Surveys in Geophysics*, 37: 191–194, DOI 10.1007/s10712-016-9356-4, 2016 (http://link.springer.com/article/10.1007/s10712-016-9356-4).

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Seo, K.W., J.L. Chen, C.R. Wilson, C.K. Lee, Decadal variations of Earth's oblateness and polar ice mass balance from 1979 to 2010, *Geophys. J. Int.*, 203, 475–481, doi: 10.1093/gji/ggv312, 2015.

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Sun, A. Y., Chen, J., and Donges, J.: Global terrestrial water storage connectivity revealed using complex climate network analyses, *Nonlin. Processes Geophys.*, 22, 433-446, doi:10.5194/npg-22-433-2015, 2015.

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Schindelegger, M., Green, J. A. M., Wilmes, S.-B., & Haigh, I. D. (2018). Can we model the effect of observed sea level rise on tides? Journal of Geophysical Research: Oceans, 123, 4593– 4609. https://doi.org/10.1029/2018JC013959.

Girdiuk A., Schindelegger, M., M. Madzak, Böhm J. (2018) Detection of the atmospheric S1 tide in VLBI polar motion time series. In: Freymueller JT, Sánchez L. (eds.) International Symposium on Earth and Environmental Sciences for Future Generations. International Association of Geodesy Symposia, vol. 147, 163-169, doi: 10.1007 / 1345_2016_234.

Schindelegger, M., (2017), Earth Rotation - a springboard to the study of ocean tides. Austrian Journal of Surveying and Geoinformation (VGI), 2017 (4), 218-229.

Schindelegger, M., Salstein D., Einšpigel D., Mayerhofer C. (2017), Diurnal atmosphere-ocean signals in Earth's rotation rate and possible modulation through ENSO. Geophysical Research Letters, 44 (6), 2755-2762, doi: 10.1002 / 2017GL072633.

Madzak M., Schindelegger, M., Böhm J., Bosch W., Hagedoorn J. (2016), High-frequency Earth rotation variations deduced from altimetry-based ocean tides. Journal of Geodesy, 90 (11), 1237-1253, doi: 10.1007 / s00190-016-0919-4.

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Bohm, J., Moller, G., Schindelegger, M., Pain, G., Weber, R. (2015) Development of an improved empirical model for slant delays in the troposphere (GPT2w). GPS Solutions, 19 (3), 433-441, doi.org/10.1007/s10291-014-0403-7.

Sub-Commission 3.4: Cryospheric Deformation

Chair: Shfaqat Abbas Khan (Denmark)
Vice-Chair: Matt King (Australia)

Terms of Reference

Past and present changes in the mass balance of the Earth's glaciers and ice complexes induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Of principal interest is 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. Using geometric measurements alone, elastic and GIA deformations cannot be separated without additional models or observations. Reference frames of GIA models do not allow direct comparison to measurements in an International Terrestrial Reference Frame and ambiguity currently exists over the exact transformation between the two. Furthermore, there is no publicly available and easy-to-use tool for model computations of elastic effects based on observed elevation/mass changes over the spatial scales of interest (small valley glaciers to large ice streams) and including gravitational/rotational feedbacks. This SC will focus on resolving these technical issues and work on dissemination of these measurements within the glaciological community (notably IACS).

Summary of the Sub-commission's activities during the period 2015-2019:

AGU Fall meeting 2015:
Session G33A: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability

AGU Fall meeting 2016:
Session G33B: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability

AGU Fall meeting 2016:
Session G11B: Separating and Explaining Multiple Signals in Geodetic Data

AGU Fall meeting 2017:
G31E: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability I
G31A: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability II

Workshop in 2015 on Glacial Isostatic Adjustment and Elastic Deformation at Geophysical Institute, University of Alaska Fairbanks, USA.
Session 1. Relative Sea Level & Ice History.
Session 2. GIA since the Little Ice Age.
Session 3. Solid Earth response to "rapid" stress change.
Session 4. Recent Changes in Greenland's Ice Sheet.
Session 3. Geodetic measurement of viscoelastic deformation.

Workshop in 2017 on Glacial Isostatic Adjustment and Elastic Deformation in Reykjavik, Iceland during September 5-7, 2017.
Title: "Workshop on Glacial Isostatic Adjustment and Elastic Deformation"
Website: http://www.polar.dtu.dk/english/workshop-on-glacial-isostatic-adjustment-and-elastic-deformation-2017
Session 1. Observations of present-day changes in glaciers, ice caps and ice sheets and the associated Earth deformation.
Session 2. Measurement and Models of Elastic Rebound.
Session 3. Glacial isostatic adjustment on a heterogeneous Earth.
Session 4. Reconciling models and observations of GIA.

AGU Fall meeting 2018:
G31E: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability I
G31A: Geodetic Measurements of the Earth's Elastic Response to Surface Mass Variability II

Ongoing activity: (*delayed until fall 2019*)
Establish and publish a list of PSMSL tide gauges that are subject to large, time-variable elastic deformation associated with present-day glacier mass change.

Ongoing activity:
Compile a database of predictions for relative sea level changes at tide gauges, gravity field, and 3D deformation rates at geodetic sites and on global or regional grids for a set of reasonable GIA models, both for the deglaciation after LGM and more recent ice changes. While this database may not lead to consensus about the "best" model, it will clarify the range of predictions made by models that have some support within the broader community.
"We expect to complete the data base during 2019"

Selected peer-reviewed publications co-authored by chair and vice-chair:

Aschwanden, Andy, Mark A. Fahnestock, Martin Truffer, Douglas J. Brinkerhoff, Regine Hock, Constantine Khroulev, Ruth Mottram, and S. Abbas Khan, Contribution of the Greenland Ice Sheet to sea-level over the next millennium, *science advances*, publication date: 19 June 2019

Bao Zhang, Lin Liu, Shfaqat Abbas Khan, Tonie van Dam, Anders Anker Bjørk, Yannick Peings, Enze Zhang, Michael Bevis, Yibin Yao, Brice Noël, Geodetic and model data reveal different spatio-temporal patterns of transient mass changes over Greenland from 2007 to 2017, *Earth and planetary science Letters*, 515,154-163, doi: https://doi.org/10.1016/j.epsl.2019.03.028, 2019

Bao Zhang, Enze Zhang, Lin Liu, Shfaqat Abbas Khan, Tonie van Dam, Yibin Yao, Michael Bevis, and Veit Helm, Geodetic measurements characterize the short-term changes of glacial mass near Jakobshavn Isbræ (Greenland) from 2007 to 2017, *Earth and planetary science Letters*, vol 503, 216-226, DOI: 10.1016/j.epsl.2018.09.029, 2018.

Barletta Valentina R., Michael Bevis, Benjamin E. Smith, Terry Wilson, Abel Brown, Andrea Bordoni, Michael Willis, Shfaqat Abbas Khan, Marc Rovira-Navarro, Ian Dalziel, Robert Smalley Jr., Eric Kendrick, Stephanie Konfal, Dana J. Caccamise II, Richard C. Aster, Andy Nyblade and Douglas A. Wiens, Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability, *Science*, 360 (6395), 1335-1339, DOI: 10.1126/science.aao1447, 2018

Bevis, Michael, Christopher Harig, Shfaqat A. Khan, Abel Brown, Frederik J. Simons, Michael Willis, Xavier Fettweis, Michiel R. van den Broeke, Finn Bo Madsen, Eric Kendrick, Dana J. Caccamise II, Tonie van Dam, Per Knudsen, and Thomas Nylen, Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing, *Proceedings of the National Academy of Sciences*, vol 116 (6), 1934-1939, doi: 10.1073/pnas.1806562116, 2019

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Frederikse, T., Riva, R.E.M., King, M.A., Ocean Bottom Deformation Due To Present-Day Mass Redistribution and Its Impact on Sea Level Observations, *Geophysical Research Letters* 44(24), pp. 12,306-12,314

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Khan, Shfaqat Khan, Ingo Sasgen, Michael Bevis, Tonie van Dam, Jonathan L. Bamber, John Wahr, Michael Willis, Kurt H. Kjær, Bert Wouters, Veit Helm, Beata Csatho, Kevin Fleming, Anders A. Bjørk, Andy Aschwanden, Per Knudsen and Peter Kuipers Munneke, Geodetic measurements reveal similarities between post–Last Glacial Maximum and present-day mass loss from the Greenland ice sheet, *Science Advances*, 2, e1600931, DOI: 10.1126/sciadv.1600931, 2016.

Khan, Shfaqat Abbas, Andy Aschwaden, Anders A. Bjørk, John Wahr, Kristian K. Kjeldsen, and Kurt H. Kjær, Greenland ice sheet mass balance: a review, *Reports on Progress in Physics,* 78, 046801, doi:10.1088/0034-4885/78/4/04680, 2015.

Kjeldsen, K.K., Korsgaard, N.J., Bjørk, A.A., Khan, S.A., Box, J.E, Funder, S., Larsen, N.K., Bamber, J.L. Colgan, W., Van Den Broeke, M., Siggaard-Andersen, M.-L., Nuth, C., Schomacker, A., Andresen, C.S., Willerslev, E., Kjær, K.H., Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900, *Nature*, 528, 7582, 396-400, DOI: 10.1038/nature16183, 2015.

Liu, Lin, Shfaqat Abbas Khan, Tonie van Dam, Joseph Ho Yin Ma, Michael Bevis, Annual variations in GPS-measured vertical displacements near Upernavik Isstrøm (Greenland) and contributions from surface mass loading, Journal of Geophysical Research – Solid Earth, 122, 677–691, doi:10.1002/2016JB013494, 2017.

Liu, B., King, M., Dai, W., Common mode error in Antarctic GPS coordinate time-series on its effect on bedrock-uplift estimates, Geophysical Journal International 214(3), pp. 1652-1664, 2018

Linsong Wang, Shfaqat A. Khan, Michael Bevis, Michiel R. van den Broeke, Mikhail K. Kaban, Maik Thomas, Chao Chen, Downscaling GRACE predictions of the crustal response to the present-day mass change in Greenland, *Journal of Geophysical Res., 2018.*

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Whitehouse, P.L., Gomez, N., King, M.A., Wiens, D.A., Solid Earth change and the evolution of the Antarctic Ice Sheet, Nature Communications, 10(1),503, 2019

Zhang Bao, Lin Liu, Shfaqat Abbas Khan, Tonie van Dam, Enze Zhang, Yibin Yao, Transient variations in glacial Mass near Upernavik Isstrøm (west Greenland) detected by the combined use of GPS and GRACE data, Journal of Geophysical Research – Solid Earth, 122,10,626–10,642. https://doi.org/10.1002/2017JB014529, 2017.

Zhao, C., King, M.A., Watson, C.S., (...), Dell, M., Whitehouse, P.L., Rapid ice unloading in the Fleming Glacier region, southern Antarctic Peninsula, and its effect on bedrock uplift rates, Earth and Planetary Science Letters 473, pp. 164-176, 2017

Sub-commission 3.5: Tectonics and Earthquake Geodesy

Chair: Haluk Ozener (Turkey)

Overview

SC 3.5, (WEGENER group), aims to encourage cooperation between all geoscientists studying the Eurasian/African/Arabian plate boundary deformation zone with a focus on mitigating earthquake, tsunami, and volcanic hazards. Towards these ends, it organizes periodic workshops and meetings with special emphasis on integrating the broadest range of Earth observations, sharing analysis and modelling approaches, and promoting the use of standard procedures for geodetic data acquisition, quality evaluation, and processing. WEGENER organizes dedicated meetings, arranges special sessions in other international meetings, organizes special issues in peer-reviewed journals, and takes initiative to promote and facilitate open access to geodetic databases.

Summary of the Sub-commission's activities during the period 2015-2019

Meetings:

General Assembly of WEGENER

18th General Assembly of WEGENER

WEGENER organizes bi-annual conferences to serve as high-level international forums in which scientists from all over the world share results, and strengthen collaborations between countries in the greater Mediterranean region and beyond.

In this respect, the 18th General Assembly of WEGENER was held in Ponta Delgada, Azores, Portugal between 12 and 15 September 2016. Around 100 scientists from all around the world attended the meeting. A total of 46 oral and 9 poster presentations were made under the theme "Understanding Earth deformation at plate boundaries".
The meeting was conducted on five different sessions as follows:

1- "*Current Plate Motions, Inter and Intraplate Deformation with a Focus on Europe, the Mediterranean, Africa and Middle East*",
2- "*Continental Faulting and Earthquake Cycle*",
3- "*Elastic surface displacements, surface and satellite gravity observations, global and regional sea-level change*",
4- "*Data and infrastructures, Instrumentation & Co-location for continuous monitoring of the changing Earth"* and
5- "*Transient signals in Geodetic Time Series: detection and modeling*".

Information and experience in the use of geodetic methods for geodynamic studies such as GPS, InSAR, and terrestrial methods were shared in a wide range of applications from large scale studies such as the studies of continental boundaries to small scale studies such as local observations focusing on single faults. Invited talks enabled the attendees to keep up with the latest research of world leading scientists and the latest technological developments in instrumentation, analysis, modeling, and interpretation. The meeting was carried out in a workshop form, including extensive and inclusive discussions of the results and the methods presented within each session.

Detailed information about the 18th General Assembly of WEGENER can be found at: http://wegener.segal.ubi.pt/

19th General Assembly of WEGENER

The 19th General Assembly of WEGENER, on earth deformation and the study of earthquakes using geodesy and geodynamics, was held at the Site Bergès - CRAYA Amphitheatre in Grenoble University in Grenoble, France, from 10-13 September 2018. The assembly consisted of seven thematic sessions arranged by an international scientific committee with 26 scientists (details on https://wegener2018.sciencesconf.org/) are as follows;

1- "*Active faults: reconciling short- and long-term observations*",
2- "*The seismic cycle: from transient and precursory deformation to seismic rupture*",
3- "*Technical and methodological developments, and large networks handling*",
4- "*Intracontinental deformation and slowly deforming areas*",
5- "*Multi-timescale glacier and landslide processes*",
6- "*Improving understanding of magmatic and volcanic process*",
7- "*Vertical movements of the earth surface, sea level and potential fields*".

In the frame of this assembly, 170 scientists from 27 countries across all continents gathered for an intense scientific discussion for four days. 7 keynote speeches, 72 oral presentations and more than 100 poster presentations related to the "Tectonics and Earthquake Geodesy" that covered joint application of geodetic and other geoscientific methods to investigate geodynamics of the Earth were given during the seven thematic oral and two poster sessions.

The details of the 19th General Assembly of WEGENER and presentations can be found at: https://wegener2018.sciencesconf.org/

WEGENER Sessions in other Scientific Meetings

WEGENER Session in 2015 EGU (12-17 April 2015-Vienna)

A session titled "Monitoring and modelling of geodynamics and crustal deformation: progress during 34 years of the WEGENER initiative" was organized and convened by Haluk Ozener, Susanna Zerbini and Mustapha Meghraoui in the EGU General Assembly 2015. Presentations emphasized multidisciplinary studies of Earth deformation using geodetic techniques (GPS, InSAR, LiDAR, space/air/terrestrial gravity, ground-based geodetic observations), complementary tectonic and geophysical observations, and modeling approaches focusing on the European-Mediterranean and Northern African regions. In total, 21 studies were presented in two successive sessions. More detailed information can be found at:
http://meetingorganizer. copernicus.org/EGU2015/session/18028

WEGENER Session in 2016 EGU (17-22 April 2016-Vienna)

During the European Geosciences Union (EGU) General Assembly 2016, a session titled "Monitoring and modelling of geodynamics and crustal deformation: progress during 35 years of the WEGENER initiative" was convened by Dr. Haluk Ozener, Dr. Susanna Zerbini and Dr. Mustapha Meghraoui. Six oral talk and twenty five posters were presented in two successive sessions. More detailed information can be found at:
http://meetingorganizer.copernicus.org/EGU2016/session/20161

WEGENER Session in 2017 EGU (23-28 April 2017-Vienna)

On behalf of SC3.5, a session on "Monitoring and modelling of geodynamics and crustal deformation: progress during 36 years of the WEGENER initiative" has been organized at the EGU General Assembly 2017, with Dr. Haluk Ozener (Chair of SC3.5) as the main convener, Dr. Susanna Zerbini, Dr. Matthias Becker and Dr. Sara Bruni as co-conveners. Six oral talk and seventeen posters were presented in two successive sessions. More detailed information can be found at: http://meetingorganizer.copernicus.org/EGU2017/session/22877

WEGENER Session in 2018 EGU (8-13 April 2018-Vienna)

At EGU General Assembly 2018, a session entitled "Monitoring and modelling of geodynamics and crustal deformation: progress during 37 years of the WEGENER initiative" was organized by convener Dr. Haluk Ozener and co-conveners Dr. Susanna Zerbini, Dr. Matthias Becker and Dr. Sara Bruni. During the session, the Earth deformation processes from various tectonic regimes were intensely discussed by international scientists through thirteen poster presentations based on geodetic, geodynamic and seismic methods. The studies examined both short- and long-term deformation mainly in relation to the fault activities. The details of the session can be found at: https://meetingorganizer.copernicus.org/EGU2018/session/26523

WEGENER Session in 2019 EGU (7-12 April 2019-Vienna)

A session entitled "Monitoring and modelling of geodynamics and crustal deformation: progress during 38 years of the WEGENER initiative" was held during EGU General Assembly 2019. This dedicated session was conducted by conveners Dr. Haluk Ozener, Dr. Matthias Becker, Dr. Sara Bruni and Dr. Susanna Zerbini. Seven oral and seventeen poster presentations were performed during the session and enabled the scientists to discuss and share their knowledge related to deformation of the Earth. The accepted abstracts that range from the Earth's deformation process to the physics of earthquake and failure patterns of large earthquakes provided an opportunity to the attendees to see the application areas of geodesy in a broad spectrum. More detailed information can be found at:
https://meetingorganizer.copernicus.org/EGU2019/session/30377.

Other Activities

- Starting in 2016, 25 permanent GPS stations has been established to study crustal deformation around the North Anatolian Fault in the Marmara Region, Turkey.
- Reports on the 18th and 19th WEGENER activities were submitted to the IAG newsletter.
- WEGENER Board Meetings were organized in 2015, 2017 and 2019 EGU General Assemblies.
- In an interdisciplinary approach of Geodesy and Geology a first assessment of vertical crustal motion by space borne and local observations in the Rhine-Main and Upper Rhinegraben Region was started in 2017.
- Darmstadt is studied by global and local monitoring with geodetic and geological sensors. Regional trends of motion are monitored by GNSS sites of IGS, EUREF, SAPOS and dedicated installations with > 10 years of continuous observations and Interferometric SAR-PS analysis of Sentinel 1 scenes.
- A dedicated in situ observatory at an exposure of the fault in Darmstadt is equipped with a 3-D strain gauge, seismometer and radon sensor. Further GNSS and levelling activities on selected lines across the fault are observed.

- Our commission members have contributed to international conferences (e.g. African Seismological Commission, CEGRN – Central European Geodynamics Research Network Consortium, Conference on East African Rift System and Annual meeting of the IGCP-659 UNESCO project "A platform for the Geodynamics and Seismic Hazard Evaluation in the East African Rift System", EGU – European Geosciences Union General Assembly, Mitigating the Impact of Natural Hazards in Africa) as member of scientific committee, convener and chairman.
- Maintenance of the GNSS permanent networks; weekly network adjustment; analysis of Time Series; evaluation of Key Performance Indicators (KPI) of the Galileo GNSS for positioning, navigation and timing, and its interoperability with GPS, Glonass, BeiDou; modelling of the inferred velocities, correlation of the areas of high strain with structural geology and historical seismicity are some of the works have been performed in different regions by our commission members to strengthen geodetic studies in the world.
- IAG SC1.3 – WG1 has been supported by our SC members in integration of dense velocity fields into the ITRF by sending SINEX files of the Italian network to EUREF for combination and stacking with the EPN.
- Several publications and presentations regarding WEGENER activities were prepared and given.

Upcoming Event

The WEGENER board is planning that the 20th General Assembly will be held in Marrakech, Morocco in 2020.

Peer-reviewed publications co-authored by SC members:

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Joint Study Group 3.1: Intercomparison of Gravity and Height Changes

Chair: Séverine Rosat (France)

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José Arnoso (Spain)
Valentina Barletta (Denmark)
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Andrea Bordoni (Denmark)
Yoichi Fukuda (Japan)
Anthony Mémin (France)
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Holger Steffen (Sweden)

Activities and publications during the period 2015-2019

A website coordinates and documents the group activities: http://iag-jsg.u-strasbg.fr/. It includes the terms of references, objectives, and contact information of the study group members, reports of the study group activities and a complete list of publications originating from the years 2015-2019.

Activities during the period 2015-2019

- Study of the noise characteristics of GNSS height change and Superconducting Gravimeter gravity change measurements (Bogusz et al. 2018).
- Influence of rheology on the gravity-to-height ratio: Ziegler et al. (2016) performed a first theoretical study for a homogeneous compressible Earth model with a Maxwell and a Burgers rheology. For the harmonic degree-2, the ratio between the gravity variation and the vertical surface displacement due to surface loading is almost constant and equal to -0.26 µGal/mm in the elastic domain, up to the relaxation time of the rheological model. In the viscoelastic domain, above 10,000 years, the gravity-to-height ratio tends to -0.08 µGal/mm. In between, the transition is smooth.
- Investigation of the gravity-change-to-height-change ratio in the Fennoscandian postglacial rebound area: Olsson et al. (2019) performed a comprehensive study of 30 years of absolute gravity measurements in northern Europe as well as a comparison to GNSS-derived height changes using different approaches. Ratios between -0.163 and -0.177 µGal/mm were determined for the best stations. Olsson et al. (2019) suggested that the ratio of -0.163 µGal/mm, which is supported by geophysical modelling, should be used to convert height changes to gravity changes in the Fennoscandian postglacial rebound area. A gravity change model called NKG2016LU_gdot has been generated and made available for download: https://www.lantmateriet.se/en/maps-and-geographic-information/GPS-och-geodetisk-matning/Referenssystem/Landhojning/
- Estimate of the geocenter motion by combining GNSS and gravity measurements: a first work has been published by Rogister et al. (2016) to show that time-varying surface gravity are independent of the terrestrial reference frame. In this study, a preliminary combination of GRACE solutions with surface gravity records has been used to correct hydrological effects that mask the degree-one geocenter motion. Indeed, the separation of degree-one signal from other spectral content is impossible with a discrete network at the Earth's surface since spherical harmonics are not orthogonal any more.

- Application of new analytical methods for deriving the instrumental drift and seasonal changes with amplitudes varying in time, characteristic either for gravity or for GNSS-derived vertical time series (Gruszczynska et al., 2017; 2018).

Workshop organized by the Joint Study Group

The Joint Study Group organized an International Workshop on the inter-comparison of space and ground gravity and geometric spatial measurements in Strasbourg (France) on October 16-18, 2017. The workshop website is at https://geodesy.sciencesconf.org/. It was funded by the University of Strasbourg, Institut de Physique du Globe de Strasbourg and the CNFGG (Comité National Français de Géodésie et de Géophysique – French contributor to the IUGG). There were 50 participants mostly from European countries. The workshop covered different topics in relation with space and ground observations of mass variations and deformation and their modeling. Three sessions were organized:

1. Comparison gravity - space technique (chaired by J. Arnoso and H. Steffen)
2. Love numbers, rheology... (chaired by Y. Rogister and S. Rosat)
3. Realization of a terrestrial reference frame (chaired by J. Bogusz and J.-P. Boy)

Picture of participants to the International Workshop on the inter-comparison of space and ground gravity and geometric spatial measurements, Strasbourg, 16-18 October 2017

Relevant peer-reviewed publications 2015-2019 co-authored by JSG members

Barletta, V. R., Bevis, M., Smith, B. E., Wilson, T., Brown, A., Bordoni, A., Willis, M., Abbas Khan, S., Rovira-Navarro, M., Dalziel, I., Smalley, R. Jr., Kendrick, E., Konfal, S., Caccamise II, D. J., Aster, R. C., Nyblade, A., Wiens, D. A. (2018). Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability, Science, 360 (6395), 1335-1339, doi: 10.1126/science.aao1447

Bogusz, J., Rosat, S., Klos, A., Lenczuk, A. (2018). On the noise characteristics of time series recorded with nearby located GPS receivers and superconducting gravity meters, Acta Geod. Geophys., 53(2), 201-220, doi:10.1007/s40328-018-0212-5

Gruszczynska M., Klos A., Rosat S., Bogusz J. (2017). Deriving common seasonal signals in GPS position time series by using Multichannel Singular Spectrum Analysis, Acta Geodyn. Geomater., 14(3), 273-284, doi: 10.13168/AGG.2017.0010

Gruszczynska, M., Rosat, S., Klos, A., Gruszczynski, M., Bogusz, J. (2018). Multichannel Singular Spectrum Analysis in the estimates of common environmental effects affecting GPS observations, Pure Appl. Geophys., 175(5), 1805-1822, doi:10.1007/s00024-018-1814-0

Li, T., Wu, P., Wang, H., Jia, L., Steffen, H. (2018). Hydrology signal from GRACE gravity data in the Nelson River basin, Canada: a comparison of two approaches, Earth Planets Space, 70:41, doi :10.1186/s40623-018-0804-x

Métivier, L., Caron, L., Greff-Lefftz, M., Pajot-Métivier, G., Fleitout, L., Rouby, H. (2016). Evidence for postglacial signatures in gravity gradients: A clue in lower mantle viscosity, Earth Planet. Sc. Lett., 452, 146-156.

Olsson, P.-A., Breili, K., Ophaug, V., Steffen, H., Bilker-Koivula, M., Nielsen, E., Oja, T., Timmen, L. (2019). Postglacial gravity change in Fennoscandia: Three decades of repeated absolute gravity observations, Geophys. J. Int., 217, 1141-1156, doi:10.1093/gji/ggz054

Riccardi, U., Arnoso, J. A., Benavent, M.J., Vélez, Tammaro, U., Montesinos, FG. (2018). Exploring deformation scenarios in Timanfaya volcanic area (Lanzarote, Canary Islands) from GNSS and ground based geodetic observations, J. Volcanology and Geothermal Res., 357, 14-24, doi:10.1016/j.jvolgeores.2018.04.009

Rogister, Y., Mémin, A., Rosat, S., Hinderer, J., Calvo, M. (2016). Constraints provided by ground gravity observations on geocentre motions, Geophys. J. Int., 206, 1431-1439, doi:10.1093/gji/ggw220

Wang, H., Xiang, L., Jia, L., Wu, P., Steffen, H., Jiang, L., Shen, Q. (2015). Water storage changes in North America retrieved from GRACE gravity and GPS data. Geodesy and Geodynamics 6(4), 267-273, doi:10.1016/j.geog.2015.07.002.

Ziegler Y., Rogister Y., Hinderer J., Rosat, S. (2016). Chandler Wobble and frequency dependency of the ratio between gravity variation and vertical displacement for a simple Earth model with Maxwell or Burgers rheologies, Int. Assoc. of Geod. Symposia, Prague (Czech Rep.), Springer Berlin Heidelberg, doi:10.1007/1345_2016_247

Joint Working Group 3.1: Theory of Earth Rotation and Validation
(Joint with IAU)

Chair: José Ferrándiz (Spain)
Vice Chair: Richard Gross (USA)

Members

According to the Commission 3 bylaws for the current term, the JWG is structured in three sub-WGs that operate in coordination:

1. Precession/Nutation
Chair: Juan Getino (Spain)
Co-Chair: Alberto Escapa (Spain)

Members: N Capitaine (France), V Dehant (Belgium), CL Huang (China), J Vondrak (Czech Republic)
Correspondents: T Baenas (Spain), S Dickman (USA), M Folgueira (Spain), A Gusev (Russia), T Herring (USA), G Kaplan (USA), J Mueller (Germany), H Schuh (Germany), J Souchay (France), S Urban (USA), V Zharov (Russia)

2. Polar Motion and UT1
Chair: Aleksander Brzezinski (Poland)

Members: C Bizouard (France), BF Chao (Taipei), WB Chen (China), J Nastula (Poland), F Seitz (Germany)
Correspondents: CL Huang (China), G Kaplan (USA), W Kosek (Poland), J Ray (USA), C Ron (Czech Republic), D Salstein (USA), H Schuh (Germany), W Shen (China), D Thaller (Germany), QJ Wang (China), YH Zhou (China)

3. Numerical Solutions and Validation
Chair: Robert Heinkelmann (Germany)

Members: S Belda (Spain), WB Chen (China), B Luzum (USA), Z Malkin (Russia), M Schindelegger (Germany)
Correspondents: BF Chao (Taipei), V Dehant (Belgium), D Gambis (France), E Gerlach (Germany), CL Huang (China), JF Navarro (Spain), ME Sansaturio (Spain), H Schuh (Germany), F Seitz (Germany), M Thomas (Germany), QJ Wang (China)

Activities and publications during the period 2015-2019

Web site:

A website was set up at the University of Alicante, Spain, to facilitate documenting the group activities: <http://web.ua.es/en/wgterv>. Reports of many of the JWG meetings and copies of presentations can be posted and found on-line. Reports of the JWG meetings, including progress reports of the three SWGs and the whole JWG, minutes of sessions and discussions when relevant, and material provided by members as well, can be found on-line on it (although with a latency larger than wanted in recent times due to a temporary staff loss). The web site contains also a link to the documents elaborated by the previous Commission 3 JWG on Theory of Earth rotation, joint with IAU, which operated in the period 2013-2015.

Meetings:

The JWG chairing people have organized splinter meetings and special sessions at conferences of particular relevance for its activity, open to the interested conference attendants. They have also co-convened sessions on Earth rotation, or including it, at large meetings or served in scientific organizing committees, as well as many others JWG members. Among the first group, the following meetings took place so far:

- ***Open splinter meeting of the JWG TERV at the EGU General Assembly 2016***. Vienna, April 20, 2016 (SMP14, http://meetingorganizer.copernicus.org/EGU2016/session/22333).

- ***Session 8 at GAGER 2016*** (Geodesy, Astronomy And Geophysics In Earth Rotation - A Joint IAU / IAG / IERS Symposium), entitled: Open meeting on "Current situation, progress, and challenges of the theory of Earth rotation from the JWG TERV perspective". Reports of progress of all the SWGs were presented in this session, and afterwards there was a long and fruitful discussion whose minutes are available at: https://web.ua.es/es/wgterv/jwg-terv-meetings/open-meeting-at-gager2016.html

- ***Open splinter meeting of the JWG TERV at EGU General Assembly 2017***. Vienna, April 24, 2017 (SMP85, http://meetingorganizer.copernicus.org/EGU2017/session/26247).

- ***"Journées 2017, des Systèmes de Référence et de la Rotation Terrestre*"**, 25 to 27 September 2017, Alicante, Spain. (https://web.ua.es/journees2017/index.html).

The organization of this meeting was of particular relevance for the Earth rotation researchers since it allowed continuing the successful series of *Journées "Systèmes de Référence spatio-temporels",* supported by IAU and IAG for many years, which was initiated in 1988 and whose concluding edition was held in 2014.

The "Journées" were intended as a forum of advanced discussion devoted to the study of the space-time celestial and terrestrial reference systems and their evolution with time, with emphasis on the rotation of the Earth. The sub-title of the renewed 2017 edition was ***"Furthering our knowledge of Earth Rotation"*** and it addressed the challenges brought to Earth rotation by the accuracy requirements of GGOS, with a scope ranging from concepts and theoretical solutions to observational techniques and data analysis. It was co-chaired by Ferrándiz and Bizouard, and Capitaine was appointed the honorary chair. The JWG played a relevant role in its organization, since most of the SOC members were affiliated to the JWG either as chairing people, regular member or correspondent.

- ***Open splinter meeting of the JWG TERV at the EGU General Assembly 2018***. Vienna, April 11, 2018 (SMP40, https://meetingorganizer.copernicus.org/EGU2018/session/29605)

- ***Special presentation on the JWG goals and tasks at the ISGG 2018*** (International Symposium on Geodesy and Geodynamics, Kunming, China, July 30 – August 2).

- ***Business Meeting of the JWG TERV at the XXX IAU General Assembly 2018***, Vienna, on August 28.

- ***Report on the JWG TERV activity and findings at the GGOS Days 2018*** (Tsukuba, Japan)

A few items may be highlighted in the second group:

- ***Session G24 "Earth and Planetary Rotation: Improving Theories, Models and Observations"*** at the ***AGU FM*** (American Geophysical Union Fall Meeting) ***2015***, December 15-16 (https://agu.confex.com/agu/fm15/meetingapp.cgi/Session/8434)

- ***Session G41B "The Global Geodetic Observing System: Ground- and Space-Based Infrastructure for Earth and Planetary Rotation", at the AGU Fall Meeting 2016***, December 15 (https://agu.confex.com/agu/fm16/meetingapp.cgi/Session/16158).

- ***Session G11A "Earth and Planetary Rotation: From Core to Crust" at the AGU FM 2017***, December 11 (https://agu.confex.com/agu/fm17/meetingapp.cgi/Session/22871)

- ***Sessions G31B and G33A "The Global Geodetic Observing System: Essential Geodesy for Earth and Planetary Rotations" at the AGU FM 2018***, December 12 (https://agu.confex.com/agu/fm18/meetingapp.cgi/Session/60631).

- ***Session G3.1 "Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation" at the EGU General Assembly 2019***, April 10-11 (https://meetingorganizer.copernicus.org/EGU2019/orals/30375)

Figure 1 JOURNÉES 2017

Cooperation with the IAU and the IAG components:

The JWG 3.1 is connected to the International Astronomical Union through its Commission A2, Rotation of the Earth. The cooperation was tight and fruitful along the past IAU term, in which practically all of the officers and members of the A2 Organizing Committee (OC) belonged to the JWG, as also happens in this IAU triennium. That fluent relation made easier to share ideas and objectives related to Earth's rotation between IAU and IAG. A main result was that IAU Commission A2 proposed the Resolution B1 "*On Geocentric and International Terrestrial Reference Systems and Frames*" endorsing Resolution 2 of the IUGG 2007 General Assembly.

Close cooperation with GGOS was mandatory according to the Terms of Reference (ToRs), and we got the objective smoothly through common affiliates. It is remarkable that R. Gross, Vice-chair of the JWG, was Chair of the GGOS Science Panel in the first biennium and President of GGOS since 2017. Currently the JWG chair belongs to the Science Panel.

The relation with the IERS is of great relevance for studying Earth rotation and is also aided by common members. They include, among others, current or immediate past chairs of several

IERS Centers, like C. Bizouard, B. Luzum and D. Thaller. Reciprocally, the chairs of the JWG and SWG1 are involved since few months ago in the elaboration of new IERS Conventions 2022, and the chair of SWG3 was inaugurated this year as the new IERS Analysis Coordinator – the former also belongs to the JWG. We consider this kind of bridges is important to reach the highest consistency levels, given the stringent accuracy demands.

Progress of the research and outcomes:

This JWG was established with the purpose of promoting the development of theories of Earth rotation fully consistent and in agreement with observations, useful for providing predictions of the Earth orientation parameters (EOP) with the accuracy required to meet the needs of the near future as recommended by GGOS. Research has been conducted in this term according to the ToRs, which insistently demanded looking for better consistency and accuracy, giving as guidelines, among others, searching for sources of systematic differences between theory and observations (including those due to differences in reference frame realizations), corrections to the current theories or new developments leading to validated improvement of their performance.

Within this framework, next we outline briefly some of the main facts and ideas underneath the research activity of the members and correspondents and present a short selection of their findings. More details can be found on the reports of the JWG and its three SWGs and other presentations by the chairing people (like the recent Ferrándiz et al 2018 & 2019), on the original papers of contributors, and hopefully on a technical paper still in preparation when published.

First, let us notice that the accuracy of the EOP determined with the concourse of the main space geodetic observing techniques has improved to the point that the theories adopted by the IAU and IAG/IUGG, namely IAU2000 and IAU2006, are unable to predict the EOP or explain their determined values with a level of accuracy and stability close enough to the targets established by GGOS for the reference frames - about 30 µas and 3 µas/y in terms of geocentric angles, which are the benchmark adopted by the JWG. Differences among individual or combined solutions are still significant (e.g. Malkin 2016) and their understanding requires further theoretical insight.

Therefore, the current theory of Earth's rotation needs thus to be improved an updated in several aspects. Its performance is limited by several inconsistencies, either internal or related with ancillary models, simplifications, or inaccuracies that are no longer suitable at the current level of observational accuracy. Limitations identified in the last years include among others:

1. The amplitudes of the main nutation terms have to be updated after almost 20 years of their determination. This is particularly important for the 21 frequencies used to fit the nutation theory IAU2000, at a time in which the amplitude formal errors were not better than 5 µas (Herring et al 2002). Currently the number of separable frequencies has increased drastically up to several tens, and the uncertainties of the fitted amplitudes reduced to about 2-3 µas (see e.g. Belda et al 2017, Gattano et al 2017, Schuh et al 2017, Zhu et al 2017). The issue is even more involved because spurious periods can emerge from the sampling when analyzing VLBI observations, as shown by Panafidina et al (2017).
2. Though required by IAU Resolution B1 endorsing P03 (Capitaine et al 2003) as the new precession theory IAU2006, the latter is not fully dynamically consistent with IAU2000 (MHB2000 by Mathews et al, 2002), and consistency requires applying certain corrections to the nutation part, as already pointed by Capitaine et al (2005). The set of corrections already recommended in the IERS Conventions (2010) have be found incomplete, but full consistency can be achieved by applying to IAU2000 a recently determined set of small

corrections that include several so-called Poisson or secular-mixed terms, whose amplitudes are factorized by the time (Escapa et al 2017, Escapa and Capitaine 2018a). While these effects are small, they are systematic, not random, and should therefore be included in an improved theory according to the discussions inside the JWG (Escapa and Capitaine 2018b), but preferably along with other updating for the final users' convenience.

3. The precession model has been re-assessed as well, and a set of minor contributions to the longitude rate has been improved, particularly two gathering respectively the mathematical second order solution component and the anelasticity effects – the latter named as "non-linear" by Mathews et al (2002). Besides, those findings imply that the value of the Earth's dynamical ellipticity, H_d, must be adjusted since the observed precession rate is of course unchanged. The H_d variation is of some ppm and the resulting corrections to nutations, or "indirect" effects (Escapa et al 2016), are non-negligible since they reach more than 50 µas for certain terms (Ferrándiz et al 2017, Baenas et al 2017, 2019).
4. As for nutation theory, it has been found that the lunisolar and planetary blocks that compose the IAU2000 series are inconsistent each other (Ferrándiz et al 2018). That is because the MHB2000 transfer function was not applied to the amplitudes of the planetary direct and indirect terms (Herring et al 2002), which were taken without change from an early version of the rigid theory REN2000 since the expected variation was assumed to be negligible. It is not the case nowadays, since the magnitude of this effect reaches near 20 µas in single amplitudes, a value larger than the joint contribution of hundreds of planetary terms, and the joint effect can be above the GGOS threshold.
5. Also in nutation theory, the geophysical models in the background of IAU2000, and particularly those corresponding to the ocean mass and currents time variations, were the best ones available before 2000. It poses a new source of inconsistency, since those models are different from the later models currently used to process the observation data when determining the EOP, either separately or jointly with a terrestrial reference frame (TRF). However the update needed to improve consistency is not straightforward, since the final MHB2000 nutation series were computed numerically from the dynamical equations and not from the simpler resonance formulae, as described in 6.1 of Mathews et al 2002; besides, the full set of oceanic contributions was never published separately.
6. The free core nutation (FCN) modeling has been addressed by different approaches; some of them new like convolution (Chao & Hsieh 2015) and numerical integration (Vondrak & Ron 2015, 2018). Besides, new accurate empirical models with higher temporal resolution were derived by Belda et al (2016) using a sliding window approach with high temporal resolution, therefore closer to Malkin's approach (2013, 2014, 2016) than to Lambert's (2007). Furthermore, FCN models are dependent on the EOP solutions used in their derivation (Malkin 2017).
7. Given the relevance of joining the efforts for improving the EOP predictions (Stamatakos 2017), the capability of the new FCN models to derive FCN predictions has been applied to the prediction of the celestial intermediate pole offsets (CPO), allowing accuracy gains of up to nearly a 40% as described by Belda et al (2018). Also in relation with the EOP prediction, different authors belonging or external to the JWG have introduced new methods for the prediction of polar motion or LOD, owning very varied features. They may work for short- to long-term, be based only on past data, or make use of geophysical excitation functions to various extents - as e.g. do, Modiri et al (2018), Stamatakos et al (2018), Shuch et al (2018) or Modiri et al (2019).
8. In the search for other potential sources of discrepancies between theory and observations, several experiments have assessed the impacts of the variations of reference frames or processing strategies. It has been shown that different realizations of TRF or data processing

strategies can give rise to not negligible differences in the EOP determination at the GGOS level of accuracy (see e.g. Gross et al 2014, Wielgosz et al 2016, Heinkelmann et al 2015 & 2018, Belda et al 2017, Soja et al 2018). This is not irrelevant from the theoretical perspective since theory must explain observations - and the matter was indeed included in the JWG ToRs. However, theory does not accommodate to the actual observational environment as tightly as desirable in some aspects; for instance, the basic terrestrial reference system used in the derivation of IAU2000 has been never realized (Chen and Shen 2010, Ferrándiz et al 2015 & 2019 - in preparation), although the current conventional EOP 14C04 series (Bizouard et al 2019) links indeed the ITRF14 (Altamimi et al 2016) and the ICRF2-ext2 (Fey et al 2015) – recently superseded by the ICRF3.

Moreover, many advances in different aspects of the theoretical formulations have been published along the last years or are in a latter stage of development, and it is thus reasonably expected that they should allow improving the Earth rotation theory either for modeling or better predicting the EOP at a relatively short term. As examples of those improvements, which should be integrated in a framework that ensures the internal consistency of the whole set of EOP, the following, not at all comprehensive selection is given:

a) The theories for the rotation of triaxial two- and three-layer Earth models developed by Chen & Shen (2010) and Chen et al (2013 a & b) have been extended to a three-layer, triaxial Earth model accounting for anelastic and viscoelectromagnetic effects at both boundaries of the outer core. The theory is general although the results focus on polar motion so far; the new effects on the free frequencies are not undetectable, and the expressions of the transfer functions have been derived also (Guo & Shen 2019). The relevance of triaxiality is confirmed by other recent research papers, like e.g. Bizouard (2016)
b) The research on geophysical excitation of the polar motion (PM) and UT1 at different frequency bands has also advanced inside the JWG (e.g. Göttl et al 2015, Zotov & Bizouard 2015 & 2018, Chen et al 2017, Wińska et al 2018). A few publications comprehend the whole EOP set (Vondrak and Ron 2016, Vondrak et al 2016) since their analyses include the celestial pole offsets (CPO). However, more insight is needed still: For instance, decadal variations or the 6-year oscillation found on PM and UT1 are not fully understood yet in spite of the recent progress on the topic (Kuang et al 2017, Ding & Chao 2018, Watkins et al 2018); explaining the observations at high frequencies, either short period nutations or diurnal / subdiurnal PM, needs also improving the modeling of excitations (e.g. Madzak et al 2016, Yu et al 2018). The excitation of the Chandler wobble (CW) as well as the monitoring of its period and quality factor are classic topics requiring permanent attention (e.g. Nastula and Gross, 2015, Zotov and Bizouard 2015-2016, Vondrak et al 2017). Of course the advances in this area are conditioned by the quality and consistency of the background geophysical models.
c) The Hamiltonian method has recently been applied to re-compute the second order (quadratic in H_d) contributions to nutations for a simplified two-layer Earth model, showing that the transfer function method is not enough precise for deriving them at the GGOS accuracy level (Getino et al 2019). Other contributions to nutations, either of new physical origin or better approximations to previous solutions, are under study. Although there are very small corrections in general, several terms may exceed the GGOS accuracy threshold according to preliminary solutions emerged a few years ago.
d) Further improvements of the Earth's interior modeling and the evaluation of the ellipticity of its inner layers have been made or are in progress, and the theoretical estimates of the free periods, particularly Chandler's, have been brought closer to their observed values (Huang et al 2019, Liu et al 2019). More insight has been got into effects arising from the improvement of our Earth's interior knowledge, for instance those associated to the lateral heterogeneity of the mantle (Liu et al 2016) or related to the inner gravitational interactions

among the Earth's components (Chao 2017 a & b, Rochester et al 2018). The RotaNut team headed by Dehant is also advancing in the modeling of the inner Earth layers, particularly the effects of the topography of the core-mantle boundary, and obtained updated values of the basic earth parameters adopted in the IAU2000 theory (Zhu et al 2017).

From all those findings and research in progress, it is possible to conclude that at least a partial update of the Earth rotation theory, taking advantage of the available state-of-art models and leading to more accurate and consistent EOP models and predictions, is feasible within a reasonable time span. Not only accuracy but also better consistency among EOP, ICRF, and ITRF are main goals. As stated on the JWG ToRs, it is desirable that the new theoretical framework be as adaptable as possible to future updates of the conventional ICRF and ITRF and the various geophysical models ancillary to data analysis, especially those recommended in the existing and forthcoming IERS Conventions.

In any case, the extent of the renewal is to be determined in the forthcoming years, since neither any complete new theory nor any integrated set of corrections aimed at improving the theories in force have been published or proposed so far. Future potential candidates should be thoroughly validated with observations and compared to the current theories regarding accuracy and consistency before taking decisions on the update.

References and a sample of peer-reviewed publications co-authored by JWG members:

Note: The number of publications on the topic of the working group resulting from the activity of its members and correspondents is so high that the following list is limited to include the references cited above and a non-comprehensive selection of peer-reviewed journal articles.

Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, T. van Dam, and X. Wu (2017) JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, J. Geophys. Res., 122, 8474-8510, DOI: 10.1002/2017/ JB014360.

Altamimi Z, Rebischung P, Métivier L, Collilieux X (2016) ITRF2014: A new release of the International Terrestrial Reference Frame modeling non-linear station motions. J Geophys Res., 121, 6109-6131, DOI: 10.1002/2016JB013098

Baenas, T., Escapa, A., Ferrándiz, J.M. (2019) Precession of the non-rigid Earth: Effect of the mass redistribution. Astronomy & Astrophysics DOI: 10.1051/0004-6361/201935472

Baenas, T., Escapa, A., Ferrándiz, J.M., Getino, J. (2017) Application of first-order canonical perturbation method with dissipative Hori-like kernel. International Journal of Non-Linear Mechanics, 90, 11-20. DOI: 10.1016/j.ijnonlinmec.2016.12.017

Baenas, T., Ferrándiz, J.M., Escapa, A., Getino, J., Navarro, J.F. (2017) Contributions of the Elasticity to the Precession of a Two-layer Earth Model. The Astronomical Journal, 153, id. 79, 11 pp. DOI: 10.3847/1538-3881/153/2/79

Belda, S., Heinkelmann, R., Ferrandiz, J. M., Karbon, M., Nilsson, T., Schuh, H. (2017) An Improved Empirical Harmonic Model of the Celestial Intermediate Pole Offsets from a Global VLBI Solution. Astronomical Journal DOI: 10.3847/1538-3881/aa8869

Belda, S., Heinkelmann, R., Ferrándiz, J.M., Nilsson, T., Schuh, H. (2017) On the consistency of the current conventional EOP series and the celestial and terrestrial reference frames. Journal of Geodesy, 91, 2, 135-149. DOI: 10.1007/s00190-016-0944-3

Belda, S., Ferrándiz, J.M., Heinkelmann, R., Schuh, H. (2018) A new method to improve the prediction of the celestial pole. Scientific Reports 8:13861. DOI: 10.1038/s41598-018-32082-1

Belda S, Ferrándiz JM, Heinkelmann R, Nilsson T, Schuh H (2016) Testing a new free core nutation empirical model. J Geodyn 94:59– 67. DOI: 10.1016/j.jog.2016.02.002

Bizouard, C. (2016) Elliptic polarisation of the polar motion Excitation. Journal of Geodesy, 90, 179-188 DOI: 10.1007/s00190-015-0864-7

Bizouard, C.; Lambert, S.; Gattano, C.; Becker, O.; Richard, J. (2019) The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014. Journal of Geodesy, 93, 621-633. DOI: 10.1007/s00190-018-1186-3

Capitaine N, Wallace PT, Chapront J (2003) Expressions for IAU 2000 precession quantities. A&A 412:567–586. DOI:10.1051/ 0004- 6361:20031539

Capitaine N, Wallace PT, Chapront J (2005) Improvement of the IAU 2000 precession model. A&A 432:355–367. DOI:10.1051/ 0004- 6361:20041908

Chao, B.F. (2017a) Dynamics of axial torsional libration under the mantle-inner core gravitational interaction. Journal of Geophysical Research: Solid Earth 122, 560-571. DOI: 10.1002/2016JB013515

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Joint Working Group 3.2: Constraining Vertical Land Motion of Tide Gauges

Chair: Alvaro Santamaría-Gómez (France)

Members:

Matt King (Australia)
Tonie van Dam (Luxembourg)
Tilo Schöne (Germany)
Guy Wöppelmann (France).

Activities and publications during the period 2015-2019

During the period 2015-2019, the Joint Working Group's objective has been to gather all available global GPS vertical velocity field solutions and to compare them at the velocity estimate level. The two main outcomes of this activity have been:

1) The production of a global combined GPS vertical velocity field
2) The assessment of vertical land motion (VLM) uncertainties from the repeatability of estimates for the same site.

More than 20 different global GPS vertical velocity solutions were collected using both double-differenced and zero-differenced algorithms, including also PPP solutions, though not all the provided solutions were finally included in the combination. The number of available velocity estimates per solution varies between a few hundred to more than 14 thousand estimates, but only estimates with at least 5 years of data were considered. Also sites for which a velocity discontinuity was known or suspected were also removed. With these constraints and the solutions being considered, the number of sites considered was over 7000, from which over more than 1000 had three or more estimates. The three major difficulties that were addressed in the processing of the available velocity field solutions were:

1) The identification of sites having the same ID but being at different locations. Sites with the same ID were identified and renamed based on their separation distances.
2) The different realization of the terrestrial reference frame drift (origin and scale). A "core" network was extracted for each input solution and used for alignment to the ITRF2014.
3) The different procedures and assumptions used to provide the velocity formal uncertainties. The velocity error bars are not consistent amongst the submitted solutions and different weighting approaches were considered.

A preliminary combination of all these solutions has been carried out. The target reference frame is the ITRF2014 and the repeatability of the vertical velocities has been obtained for each site. For each solution and site, a preliminary WRMS has been obtained. The solution WRMS indicates its agreement with respect to the average (combination) of the available solutions, after the weighting of each solution. The site WRMS provides the velocity repeatability amongst the solutions considered and represents an alternative assessment of the velocity uncertainty for each site.

The sea-level community has expressed interest in the combined global VLM field which will be published in the near future. Further steps include the correction of the velocity solutions for present-day mass loading and assessing whether these corrections improve the repeatability of the combined field.

Communications

Santamaría-Gómez, A., M. King, T. Schöne, T. van Dam, G. Wöppelmann (2016). Constraining vertical land motion of tide gauges (IAG JWG 3.2): scope and aims. European Geosciences Union General Assembly, April 23 – 28, Vienna, Austria.

Santamaría-Gómez, A., M. King, T. Schöne, T. van Dam, G. Wöppelmann (2016). Constraining vertical land motion of tide gauges (IAG JWG 3.2): first results. Ocean Surface Topography Science Team (OSTST) meeting, November 1 – 4, La Rochelle, France.

Santamaría-Gómez, A., M. Gravelle, S. Dangendorf, M. Marcos, G. Spada, G. Wöppelmann (2017). Uncertainty of the 20th Century sea-level rise due to vertical land motion errors. International WCRP/IOC Conference 2017. Regional Sea Level Changes and Coastal Impacts. 10-14 July 2017, New-York, USA.

Santamaría-Gómez, A., M. King, T. Schöne, T. van Dam, G. Wöppelmann (2017). Constraining vertical land motion of tide gauges (IAG JWG 3.2): combination of velocity fields. Joint Scientific Assembly of IAG and IASPEI, July 30 – August 4, 2017, Kobe, Japan.

Santamaría-Gómez, A. (2017). Progress in estimating VLM at tide gauges from GPS. First ISSI Workshop "Towards a Unified Sea Level Record: Assessing the Performance of Global Mean Sea Level Reconstructions from Satellite Altimetry, Tide Gauges, Paleo-Proxies and Geophysical Models". December 4 – 7, 2017, Bern, Switzerland.

Santamaría-Gómez, A. (2019). The current status of a new global vertical land motion dataset. Second ISSI Workshop "Towards a Unified Sea Level Record: Assessing the Performance of Global Mean Sea Level Reconstructions from Satellite Altimetry, Tide Gauges, Paleo-Proxies and Geophysical Models". January 28 – 31, 2019, Bern, Switzerland.

Commission 4 – Positioning and Applications

http://IAG-Comm4.gge.unb.ca

President: Marcelo Santos (Canada)
Vice President: Allison Kealy (Australia)

Structure

Sub-commission 4.1: Emerging Positioning Technologies and GNSS Augmentation
Sub-commission 4.2: Geo-spatial Mapping and Geodetic Engineering
Sub-commission 4.3: Atmosphere Remote Sensing
Sub-commission 4.4: Multi-constellation GNSS

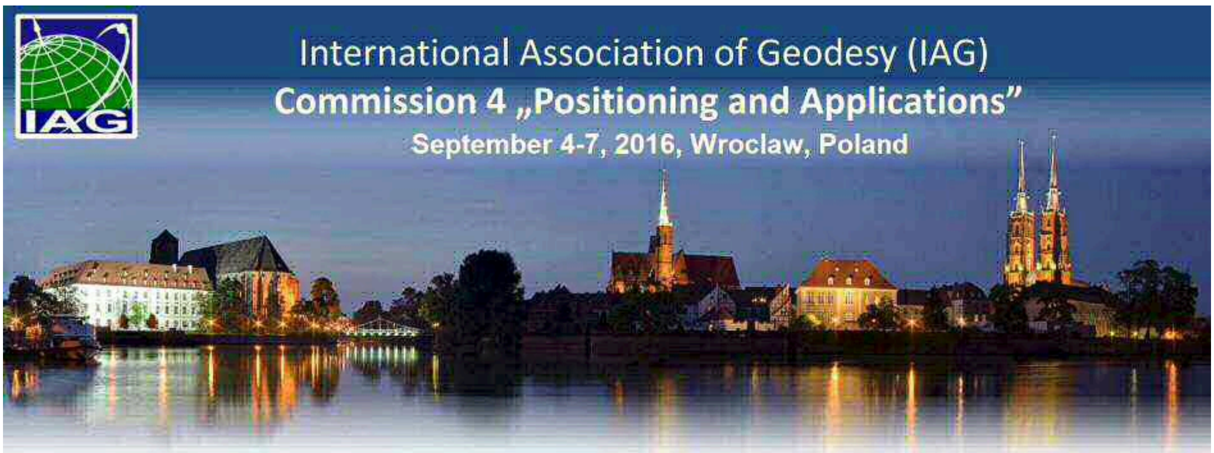
Joint Study Group 0.10: High rate GNSS
Joint Study Group 0.14: Fusion of multi-technique geodetic data
Joint Study Group 0.17: Multi-GNSS theory and algorithms
Joint Study Group 0.20: Space weather and ionosphere

Joint Working Group 1.3: Troposphere Ties

Overview

The great work done by the several segments within IAG Commission 4, "Positioning and Applications", is described in the next pages. This preamble highlights few of them.

The **First Commission 4 Symposium** took place in Wroclaw, Poland, from September 4 to 7, 2016. The venue was the Didactic and Scientific Center of the Faculty of Environmental Engineering and Geodesy, on Grunwaldzki Square 24a. A total of 67 geodesists participated in the event, with the presentation of 58 scientific contributions being 40 orals and 18 posters. Link to the presentation slides and posters is possible via the online programme at http://www.igig.up.wroc.pl/IAG2016/?page=2. The Second Commission 4 Symposium is scheduled for summer 2020 and initial details will be provided during the Montreal IUGG Scientific Assembly.



Symposium banner

Two other meetings deserve to be highlighted.

One of them was the **Workshop on Satellite Geodesy for Climate Studies,** which took place at the University of Bonn, Germany, on September 19-21, 2017. This Workshop was a joint effort of Sub-Commission 2.6 (Working Groups 2.6.1 Geodetic Observations for Climate Model Evaluation) and Working Group 4.3.8 GNSS Tropospheric Products for Climate. Besides its scientific importance, this Workshop helped to pave the way to the creation of an Inter-Committee Commission on Geodesy for Climate Research, for the next period 2019-2023. Website: https://www.apmg.uni-bonn.de/aktuelles/veranstaltungen/IAG_SGCS.

Another important event was the **4th Joint International Symposium on Deformation Monitoring** (JISDM), 15-17 May 2019, Athens, Greece. This important symposium was sponsored by Sub-Commission 4.1, and co-sponsored by the FIG and ISPRS. Website: https://jisdm2019.org/.

Commission 4 Executive held several meetings taking advantage of conferences such as the IAG Scientific Assembly in Kobe, Japan (2017) and the general assemblies of the European Geosciences Union.

Commission 4 Executive, Kobe, Japan, 2017.
From left to right. Seated: Michael Schmidt, Marcelo Santos, Jinling Wang and Vassilis Gikas. Standing: Robert Heinkelmann, Jens Wickert, Paweł Wielgosz and João Francisco Galera Monico. (Missing, Allison Kealy)

Sub-commission 4.1: Emerging positioning technologies and GNSS augmentation

Chair: *Vassilis Gikas (Greece)*
Vice Chair: *Günther Retscher (Austria)*
Secretary: *Harris Pertakis (Greece)*

Overview

The scope of SC4.1 is to undertake, promote and report on research that leverages emerging positioning techniques and technologies aiming to address practical and theoretical solutions for positioning, navigation and guidance, including spatio-temporal monitoring and tracking of objects at various scales. The focus of SC4.1 is on multi-sensor cooperative systems operating in adverse GNSS conditions for transportation, personal mobility, industrial and indoor positioning applications and to a lesser extent environmental monitoring. Except GNSS, the primary sensors of interest include inertial and wireless technologies as well as vision-based systems and laser scanning. SC 4.1 will foster linkages and pursue its goal in close collaboration with other IAG Entities, as well as sister scientific and professional organizations, primarily the ISPRS, FIG, ION and IEEE.

The main objectives are

- To address and evaluate new algorithms and multi-sensor systems for cooperative and ubiquitous positioning for land and airborne navigation applications including UAV systems.
- To examine the potential and capabilities of low-cost sensors including GNSS systems and smartphone navigation sensors.
- To follow the technical advances in wireless systems such as RFID, UWB, WiFi, LED, DSRC for personal mobility and road applications.
- To evaluate the usability of emerging positioning technologies for urban traffic navigation and improved routing using collaborative driving systems and crowdsourcing traffic information.
- To study vision-based and optical systems including cameras and laser scanning both for navigation and object tracking and monitoring purposes
- To contribute in research that depends on big data handling, sensor synchronization, data fusion, real-time processing as well as to support standardization activities.
- To study and monitor the progress of new multi-sensor applications, as well as, to support and promote knowledge exchange and reporting on the development trends, possibilities and limitations of emerging positioning technologies.
- To work closely, promote and present through publications and workshops the SC work at IAG events and those of sister organizations including the FIG, ISPRS, IEEE, ION, as well as, in collaboration with more specialized initiatives, such as the EU COST Action SaPPART.

Major Sub-Commission 4.1 Activities

The IAG SC4.1 has co-organized the **4th Joint International Symposium on Deformation Monitoring and Analysis** (JISDM) in May 15-17 2019 in Athens, Greece. JISDM carries the 40 years long tradition of the FIG and IAG joint symposia in the field of deformation monitoring and more recently the active sponsorship of ISPRS. The symposium aimed to connect research in deformation measurement / techniques, analysis and interpretation with advanced practice. The School of Rural and Surveying Engineering (SRSE) of the National Technical University of Athens (NTUA) was the host institution of this event.

During the three days of the symposium, 95 oral and 37 poster presentations were given originating from 27 countries from 5 continents. Conference topics were related to core methodological, technical and practical achievements in the field of monitoring. Some examples include point-cloud monitoring techniques, GNSS and fibre-optics for deformation measurements, quality analysis of geodetic networks and modern approaches to structural and geo-monitoring. The authors had the opportunity to submit their paper for a peer-review process resulting in 44 papers successfully passed the review process. After the symposium, authors of peer and non-peer-review papers will have the opportunity to submit extended versions of their work for a special issue in widely accepted journals.

During the conference Professor Carmelo Gentile, (Polytechnico di Milano), Dr. Charalampos (Haris) Kontoes (National Observatory of Athens) and Dorota A. Grejner-Brzezinska (The Ohio State University) introduced the latest tendencies in the field of deformation monitoring and shared their vision on the evolution of technologies and methods for monitoring both natural phenomena and man-made structures. Due to the great success of the conference, it was decided to hold the 5th JISDM in two years. The organizers will announce soon the location and time for the next edition.

Working Groups of Sub-commission 4.1:

WG 4.1.1: Multi-Sensor Systems

Chair: *Allison Kealy (Australia)*
Vice Chair: *Guenther Retscher (Austria)*

Members
- *Dorora Grejner-Brzezinska (USA)*
- *Charles Toth (USA)*
- *Vassilis Gikas (Greece)*
- *Salil Goel (India)*
- *Andrea Masiero (Italy)*
- *Antonio Vettore (Italy)*
- *Jelena Gabela (Australia)*
- *Yan Li (Australia)*
- *Błaszczak-Bąk (Poland)*
- *Terry Moore (UK)*

Activities and publications during the period 2015-2019

This group is a joint working group between IAG and the International Federation of Surveyors (FIG). It focuses on the development of shared resources that extend our understanding of the theory, tools and technologies applicable to the development of multi-sensor systems.

The major focus of this Working Group is on:
- Performance characterization of positioning sensors and technologies that can play a role in augmenting core GNSS capabilities,
- Theoretical and practical evaluation of current algorithms for measurement integration within multi-sensor systems,
- Development of new measurement integration algorithms based around innovative modeling techniques in other research domains such as machine learning and genetic algorithms, spatial cognition etc.,
- Establishing links between the outcomes of this WG and other IAG and FIG WGs (across the whole period),
- Generating formal parameters that describe the performance of current and emerging positioning technologies that can inform IAG and FIG members.

Between 2017-2019 activity centred around multi-sensor systems for GNSS difficult environments. Two specific areas were indoor positioning and autonomous vehicles in urban environments. The major activity undertaken by members of this joint IAG WG and FIG WG were two major field campaigns at the Vienna University of Technology (TU Wien), in September 2016 and the Ohio State University in October 2017. These campaigns involved experiments across collaborative navigation, navigation in indoor environments as well as indoor/outdoor transition zones. Collaborative positioning is an integrated positioning solution that employs multiple location sensors with different accuracy on different platforms for sharing of their absolute and relative localizations. Typical application scenarios are dismounted soldiers, swarms of UAV's, team of robots, emergency crews and first responders. The stakeholders of the solution (i.e., mobile sensors, users, fixed stations and external databases) are involved in an iterative algorithm to estimate or improve the accuracy of each node's position based on statistical models. For this purpose different sensor platforms have been fitted with similar type of sensors, such as geodetic and low-cost high-sensitivity GNSS receivers, tactical grade IMU's, MEMS-based IMU's, miscellaneous sensors, including magnetometers, barometric pressure and step sensors, as well as imaging sensors, such as digital cameras and LiDAR, and ultra-wide band (UWB) receivers.

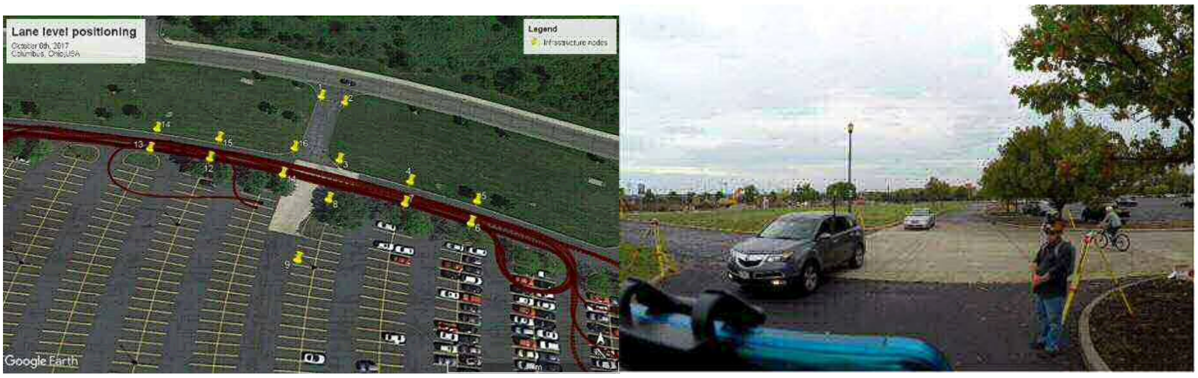


Fig. 4.1.1-1 OSU field campaign 2017. Outdoor vehicle – pedestrian interaction lane level experiment. Map of the trajectory for one vehicle (left), data collection process and the experimental set-up on field (right)

Fig. 4.1.1-2 OSU field campaign 2017. Outdoor vehicle – pedestrian interaction intersection level experiment. Map of the trajectory for one vehicle (left), data collection process and the experimental set-up on field (right)

Our processing techniques focus on three primary areas – firstly, more representative statistical error distributions for the non traditional sensors such as wifi and ultra wideband based on real-world data; secondly, the implementation of novel techniques such as differential wifi and information grammar as approaches to improving the positioning solution achievable from traditional sensor fusion techniques and thirdly, robust, decentralised fusion algorithms for scalable and practical collaborative networks. Contributions to each of these three areas are being made by RMIT University, Australia, the University of Melbourne, Australia, the Ohio State University, USA, TU Wien, Austria, Athens Technical University, University of Padova, Padova, Indian Institute of Technology, Kanpur, India. The full details around these approaches, the research hypotheses, datasets used, experimental setups and results are detailed in the publications listed here.

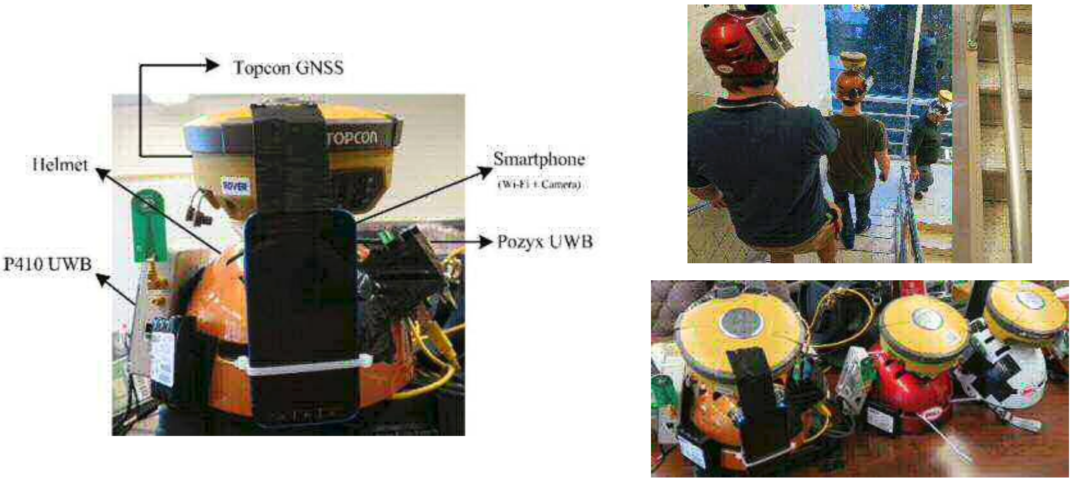


Fig. 4.1.1-3 OSU field campaign 2017. Sensors installed on a helmet (left), indoor-outdoor experiment (top right), and the three of the four helmets used in the research (bottom right).

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2. Retscher G., F. Roth (2017): Wi-Fi Fingerprinting with Reduced Signal Strength Observations from Long-time Measurements. in: Gartner G, H. Huang (Eds.), Progress in Location-Based Services 2016, Lecture Notes in Geoinformation and Cartography, Springer Verlag, ISBN 978-3-319-47289-8, DOI 10.1007/978-3-319-47289-8_1, pp. 3-24.
3. Retscher G., A. Kealy (2018): Navigation Based on Sensors in Smartphones. Chapter 9 in Yu K. (Ed.): Positioning and Navigation in Complex Environments. IGI Global, Hershey PA, USA, ISBN 9781522535287 (hardcover), ISBN 9781522535294 (ebook), DOI: 10.4018/978-1-5225-3528-7.ch009, pp. 368-396.

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2. Retscher G., T. Tatschl (2017): Positionierung in Gebäuden mit differenziellem WLAN. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (ZfV), Vol. 142, No. 2, DOI: 10.12902/zfv-0149-2016, pp. 111-125 (in German).
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The working group also maintained a strong and active presence at major international events through participation in coordinating workshops, scientific and organizing committees, delivering short courses and tutorials, publishing papers and presentations, session chairing, etc. These included:

- ION GNSS+ : Miami, 2018; Portland, 2017 and 2016
- IPIN: Nantes, 2018; Madrid, 2016; Calgary, 2015
- IGNSS, Sydney, 2018; Gold Coast, 2017 and 2015
- FIG: Hanoi, 2019; Istanbul, 2018; Helsinki, 2017; Christchurch, 2016; Sofia, 2015
- International Symposium on GNSS: Bali, 2018
- PLANS: Monterrey, 2018
- MMT: Shenzhen, 2019; Cairo, 2017; Sydney, 2015
- ION PNT: Hawaii, 2019 and 2017, 2015
- UPINLBS: Wuhan, 2018;
- ISPRS Geospatial Week (Indoor 3D): Wuhan, 2018

This WG initiated an outreach program in Sri Lanka. Working collaboratively with the Sabaragamuwa University (Geomatics Department), a workshop was conducted specifically with a knowledge transfer focus. We expect to continue to deepen this relationship in the future. Members of this WG are also very active in promoting the women in positioning, navigation and timing (PNT) activities underway in other professional associations such as the ION and RIN.

WG 4.1.2: Indoor Positioning and Navigation

Chair: *Kefei Zhang (Australia)*
Vice Chair: *Ruizhi Chen (China)*

Members

- *Adriano J.C. Moreira (Portugal)*
- *Binghao Li (Australia)*
- *Guenther Retscher (Austria)*
- *Kyle O'Keefe (Canada)*
- *Vassilis Gikas (Greece)*
- *Yunjia Wang (China)*
- *Liang Chen (China)*
- *Kegen Yu (China)*
- *Naser El-Sheimy (Canada)*
- *Xuejing Bi (China)*
- *Guoliang Chen (China)*
- *Franscesco Potroti (Italy)*

Activities and publications during the period 2015-2019

The needs for indoor positioning and navigation have experienced unprecedented growth in the past decade due to the proliferation and ubiquitous usages of mobile devices and rapid development of Internet of Things. Location information of people and objects in indoor environments becomes a key issue for many emerging and innovative applications

The primary aims of this Working Group are:

- Investigate emerging sensor technologies (e.g. LED, magnetometers), integrated techniques and protocols for indoor positioning and tracking
- Discuss, investigate and develop new algorithm and smart solutions
- Bring key researchers and developers in this area together
- Disseminate effectively the-state-of-the-art knowledge and new discoveries in the geospatial communities

In the past four years, special study group (SSG) members have been active in the field of indoor localization and ubiquitous positioning. A number of international conferences related to positioning and navigation have been organized and many SSG members have been involved in very frontier / cutting edge research in this area, in particular in international collaboration and large funded projects. For instance, Prof. Ruizhi Chen was the general chair of *UPINLBS2016* and *UPINLBS2018*; Prof. Kyle O'Keefe was a co-chair of *IPIN2015* and *IPIN2016*; Prof. Adriano J. C. Moreira and Dr Binghao Li were a co-chair of *IPIN2015*; Dr. Valerie Renaudin and Binghao Li were a co-chair of *IPIN2018*; Prof. Kegen Yu was a co-chair of the positioning and navigation track of both *2016VTC-fall* and *2017VTC-spring*; and Prof. Jian Wang is a co-chair of *UPINLBS2019*. A number of members are chief investigators for several large government-funded research and development programs, such as the *National Key Research and Development Program of China* associated with indoor positioning and navigation. Since 2015, committee members have published more than 100 indoor localization-related articles in the top-tier journals, such as *IEEE IOT*, *IEEE JSAC*, *IEEE TMC*, *IEEE TVT* and *Information Fusion*. They also published a good number of books and chapters focusing on indoor localization, such as the three books *Positioning and Navigation in Complex*

Environments, *Wireless Positioning: Principles and Practice*, and *Indoor Positioning and Navigation* by Prof. Kegen Yu, the book *Carrier-Class Oriented High Precision Indoor Location Standards, Systems and Technology* by Prof. Zhongliang Deng, the chapter of "Indoor Navigation" by Prof. Guenther Retscher in *Encyclopedia of Geodesy*, the chapter "Identifying In-App User Actions from Mobile Web Logs" by Dr. Mark Sanderson in *Advances in Knowledge Discovery and Data Mining*, and the chapter "Cross-Provider Cooperation for Improved Network-Based Localization" by Shih-Hau Fang in *Cooperative Localization and Navigation: Theory, Research and Practice*. This is only a short brief snapshot of the selected achievements by the members of this special study group.

Fig. 4.1.2-1 WiFi/Zigbee and blue-tooth-based indoor test bed built by the China University of Mining and Technology, China

Fig. 4.1.2-1 LED based indoor test bed built by the China University of Mining and Technology, China

The major research projects that WG 4.1.2 members have been involved in are as follows. "*Indoor Hybrid Intelligent Positioning and GIS technology with High-availability and High-precision*", Ministry of Science and Technology of the P. R. C., (Ruizhi Chen); "*Research on Indoor Hybrid Intelligent Positioning and GIS technology as well as Their Demonstrating*

Applications", Ministry of Science and Technology of the P. R. C., (Zhongliang Deng); "*Research on Theory and Method of Seamless High-precision Positioning in the urban environment based on GNSS and UWB*," National Natural Science Foundation of China (Jian Wang); "*Tracking Indoor Information Behaviour*," (Kefei Zhang, Mark Sanderson); "*LPWAN-IoT*", (Kyle O'Keefe); , "*Decimeter-level Indoor Positioning on Wi-Fi*" Tao Gu; "*Non-intrusive human activity sensing with radio signals*" (Tao Gu); "*Device-free Bluetooth Indoor Localization for Internet of Things*" (Tao Gu); "*Research on Key Issues of GNSS/INS/UWB/WIFI Based Indoor Seamless Positioning*," (Kegen Yu); "*Smartphone based PDR*", "*Multi-Sensor System based Positioning and Navigation*" and "*Navigation Database Generation and Crowdsourcing*" (Naser El-Sheimy).

Fig. 4.1.2-3 A Map/INS/Wi-Fi Integrated System for Indoor Location-Based Service Applications "Smartphone-based Indoor Localization and Navigation Experimental" research project

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Involvement of WG 4.2.2 members in international conferences under the capacity of general chair, general co-chair, scientific committee member, organizing workshops and tutorials, PCT member, etc. include:

- Indoor Positioning and Indoor Navigation (IPIN) 2016, 2017, 2018,
- Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS) 2016, 2018,
- Vehicular Technology Conference (VTC) 2016 fall, 2017 spring,
- Indoor Positioning and Navigation Workshop, UNSW.

WG 4.1.3: 3D Point Cloud based Spatio-temporal Monitoring

Chair: *Jens-André Paffenholz (Germany)*
Vice Chair: *Corinna Harmening (Austria)*

Members

- *Petra Helmholz (Australia)*
- *Christoph Holst (Germany)*
- *Florian Schill (Germany)*
- *Daniel Wujanz (Germany)*

Activities and publications during the period 2015-2019

The WG focuses on spatio-temporal monitoring of artificial and natural objects with the aid of 3D point clouds acquired by means of multi-sensor-systems (MSS). The emphasis is placed on laser scanning technology and to certain extend on digital cameras. In general, monitoring applications over a certain period of time require a geo-referencing of the acquired data with respect to a known datum. Also, a kinematic MSS requires for a referencing to determine the time-dependent seven degrees of freedom (translation, rotation and scale).

The major focus of this Working Group is on:

- Performance characterization of laser scanners and cameras and their fusion in MSS with respect to spatio-temporal monitoring of artificial and natural objects in different scales. Potential objects or scenarios can range from plant phenotyping to infrastructure buildings,
- Evaluate the object abstraction for epochal comparison by means of discrete point-wise, areas-based and shape-based approaches. One suitable method to investigate will be B-spline surfaces,
- Investigate and develop suitable algorithms for change tracking over time in 3D point clouds, for instance by means of feature point tracking or shape matching,
- Evaluate the fusion of heterogeneous data like 3D point clouds and ground-based synthetic aperture radar (GB-SAR) data with respect to structural health monitoring applications including infrastructure buildings,
- Algorithms will be implemented in Python, Matlab, C++ whereas for basic 3D point cloud operations open source libraries should be used, such as point cloud library (PCL),
- Establishing links to colleagues from civil and mechanical engineering to benefit from each other in terms of structural health monitoring,
- Establishing working links between this working group and similar national and international working groups such as DVW, ISPRS, IAG and FIG working groups.

The WG was active in the period 2015-2017 in terms of recruiting a small core of interested people to share knowledge in the scope of 3D point cloud based spatio-temporal monitoring.
In the ongoing period 2018 to 2019 the collaboration and interaction of the members has been realized by personal meeting, meetings at conferences and work on joined manuscripts for future publications.

To gain visibility for the WG and initiate further collaboration with interested people, a project corresponding to the WG at the social networking site ResearchGate was established (https://www.researchgate.net/project/3D-point-cloud-based-spatio-temporal-monitoring).

Research project: Loading tests on an historic railway arch bridge

The chair and some members contributed to an outstanding loading test on an historic railway arch bridge. After 150 years in use the historic masonry arch bridge over the river Aller near Verden (Northern Germany) was taken out of service in October 2015 and was demolished in summer 2016. The time gap between decommission and demolition offered the unique chance for an experimental investigation of the load-deformation behaviour of the arch-row by load testing. A project team under the leadership of the Institute of Concrete Construction of the Leibniz Universität Hannover has carried out two load tests with a maximum load of 570 t (!) in March and June 2016. By means of the load tests the influence of the front wall and the sealing layer on the bearing behaviour could be detected and also quantified with a large number of local and global deformation measurements. The experimental results form the basis for an improvement of the calculation methods and models, allowing a more realistic evaluation of the bearing safety of existing arch bridges. Following Geodesy colleagues contributed to the loading test:

- Institute of Geodesy and Geoinformation Science, Technical University Berlin: 3D laser scanner and stereo cameras;
- Institute of Geodesy and Photogrammetry, Technical University Braunschweig: terrestrial radar sensor;
- Institute of Geodesy, Section Geodetic Measuring Systems and Sensor Technology Technical University Darmstadt: Profile laser scanner;
- Institute for Applied Photogrammetry and Geoinformatics, Jade University of applied sciences: Camera system;
- Geodetic Institute Hannover, Leibniz Universität Hannover: 3D laser scanner and laser tracker.

Fig. 4.1.3-1 Side view from West of the arch under investigation of the historic masonry arch bridge. The whitewashed area indicates the area of the direct influence of the load application. On the bridge: four hydraulic cylinders for the load application (left), 3D point cloud to 3D point cloud differences (M3C2) for the load scenario of 5 MN. Clearly visible is an arch displacement of up to 14 mm. [Paffenholz &Wujanz, 2019] (right)

The results of the loading tests are published in:

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PAFFENHOLZ, J.-A. (2018): 3-D Messverfahren zur Verformungsmessung. Vortrag, 11. Mauerwerk Kalender-Tag, Dresden, 27.03.2018 *(invited presentation)*.

PAFFENHOLZ, J.-A. (2017): Laserscanning und Lasertracking für das Monitoring von Brückenbauwerken am Beispiel der Allerbrücke. ALLSAT-Forum: Global Monitoring, Hannover, 06.12.2017 *(invited presentation)*.

PAFFENHOLZ, J.-A. (2017): Interdisziplinäres Monitoring von Infrastrukturbauwerken - Vertikalverformungen aus 3D-Punkwolken. BauScan 2017, Magdeburg, 16.11.2017 *(invited presentation)*.

PAFFENHOLZ, J.-A.& STENZ, U. (2017): Integration von Lasertracking und Laserscanning zur optimalen Bestimmung von lastinduzierten Gewölbeverformungen. In: Werner Lienhart (Hg.): Ingenieurvermessung 2017. Beiträge zum 18. Internationalen Ingenieurvermessungskurs Graz. Ingenieurvermessung 17. Graz, 25-29. April. Berlin/Offenbach: Herbert Wichmann Verlag, 373-388.

PAFFENHOLZ, J.-A.; STENZ, U.; WUJANZ, D.; NEITZEL, F.; NEUMANN, I. (2017): 3D-Punktwolken-basiertes Monitoring von Infrastrukturbauwerken am Beispiel einer historischen Gewölbebrücke. In: DVW e. V. (Hrsg.): Terrestrisches Laserscanning 2017 (TLS 2017). DVW-Schriftenreihe, Band 88, Wißner-Verlag, Augsburg, 2017, S. 115-127.

WUJANZ, D.; BURGER, M.; NEITZEL, F.; LICHTENBERGER, R.; SCHILL, F.; EICHHORN, A.; STENZ, U.; NEUMANN, I.; PAFFENHOLZ, J.-A. (2018): Belastungsversuche an einer Mauerwerksbrücke: Terrestrisches Laserscanning zur Verformungsmessung. In: Jäger, W. (Hrsg.): Mauerwerk-Kalender 2018, Ernst & Sohn: Berlin, S. 221-239, doi: 10.1002/9783433608050.ch10.

Research project: 3D point cloud-based quantification of soil erosion: Comparison of methods on different spatial scales

- Evaluation of methods for 3D point cloud acquisition by terrestrial laser scanner in static mode and optional on a moving platform as well as by UAV-based image acquisition with the goal of quantification of soil erosion of farmland in soil erosion monitoring areas in Lower Saxony, Germany.
- Jens-André Paffenholz with colleagues from Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover
- Partially funded by Leibniz Forschungszentrum FZ:GEO

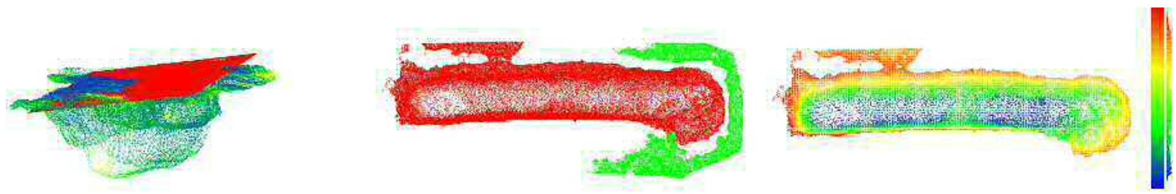

Figure: Work flow of the automated volume determination. Left: Estimated plane by means of RANSAC for the 3D point cloud. Middle: Segmented 3D point cloud by means of euclidean cluster extraction. Right: Raster approximation of the 3D point cloud. [Steinhoff-Knopp et al., 2019].

STEINHOFF-KNOPP, B.; ELTNER, A.; HAKE, F.; PAFFENHOLZ, J.-A. (2019): Methoden zur skalenübergreifend hochaufgelösten Erfassung und Quantifizierung von Bodenerosion durch Wasser. In: Alkhatib, H.; Paffenholz, J.-A. (Hrsg.): Tagungsband GeoMonitoring 2019. GeoMonitoring. Hannover, S. 75–89, doi:10.15488/4514.

Small research project "Scanning of live blue mussels (Mytilus edulis)"

Jens-André Paffenholz with colleagues from Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz University Hannover, Germany
Background: lines are conducted to obtain a realistic digital model. Centred on the 3D-point clouds, a suitable descriptor for the mass distribution over the surface is identified and 3D-printed surrogates of the blue mussel are developed for further testing. These are evaluated regarding their fit to the original 3D-point cloud data of the live blue mussels.

Experimental setup for capturing 3D-point clouds of the blue mussel dropper with the Z+F Imager 5016 (left). 3D-point cloud side view (middle). 3D-point cloud with zoomed detail (right). For further details on the processing, analysis and results see Landmann et al. (2019).

See further details in:

LANDMANN, J.; ONGSIEK, T.; GOSEBERG, N.; HEASMAN, K.; BUCK, B.; PAFFENHOLZ, J.-A.; HILDEBRANDT, A. (2019): Physical Modelling of Blue Mussel Dropper Lines for the Development of Surrogates and Hydrodynamic Coefficients. In: JMSE (Journal of Marine Science and Engineering) 7 (3), p. 65, 2019. DOI: 10.3390/jmse7030065.

LANDMANN, J.; ONGSIEK, T.; GOSEBERG, N.; HEASMAN, K.; BUCK B.H.; PAFFENHOLZ, J.-A.; HILDEBRANDT, A. (2018): Investigating drag and inertia characteristics of full-scale blue mussel dropper lines. Proceedings of the 7th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab18), Santander, Spain, May 22-26.

General publications (selected) to the themes of the WG

JOURNALS

BUREICK, J., NEUNER, H., HARMENING, C.& NEUMANN, I. (2016): Curve and surface approximation of 3D point clouds. In: *avn* **123** (11-12), S. 315–327.
HARMENING, C.& NEUNER, H. (2017): Choosing the optimal number of B-spline control points. Part 2: Approximation of surfaces and applications. In: *Journal of Applied Geodesy* **11** (1). DOI: 10.1515/jag-2016-0036.
HARMENING, C.& NEUNER, H. (2016): Choosing the Optimal Number of B-spline Control Points. Part 1: Methodology and Approximation of Curves. In: *Journal of Applied Geodesy* **10** (3). DOI: 10.1515/jag-2016-0003.
HOLST, C.& KUHLMANN, H. (2016): Challenges and Present Fields of Action at Laser Scanner Based Deformation Analyses. In: *Journal of Applied Geodesy* **10** (1). DOI: 10.1515/jag-2015-0025.
NEUNER, H., HOLST, C.& KUHLMANN, H. (2016): Overview on current modelling strategies of point clouds for deformation analysis. In: *avn* **123** (11-12), S. 328–339.
OMIDALIZARANDI, M.; KARGOLL, B.; PAFFENHOLZ, J.-A.; NEUMANN, I. (2018): Accurate vision based displacement and vibration analysis of bridge structures by means of an image assisted total station. In: Advances in Mechanical Engineering 10 (6), doi:10.1177/1687814018780052.
WUNDERLICH, T. A., NIEMEIER, W., WUJANZ, D., HOLST, C., NEITZEL, F.& KUHLMANN, H. (2016): Areal deformation analysis from TLS point clouds – the challenge. In: *avn* **123** (11-12), S. 340–351.

CONFERENCES

GIKAS, V.; RETSCHER, G.; KEALY, A.; ZHANG, K.; PAFFENHOLZ, J.-A.; RUOTSALAINEN, L.; PERAKIS, H.; SANTOS, M. (2016): IAG SC 4.1 "Emerging Positioning Technologies and GNSS Augmentation" Objectives and Structure for the Term 2015-19. Proceedings of the 2016 European Navigation Conference, Helsinki, Finland, May 30 - June 2, 2016, p. 4.
HARMENING, C; TEODORI, G; NEUNER, H. (2017): Evaluating the freeform modelling of point clouds by means of a test specimen. Proceedings of INGEO 2017 – 7th International Conference on Engineering Surveying. Lisbon, Portugal, October 18-20, 2017
HARMENING, C; NEUNER, H. (2019): Evaluating the performance of a space- and time-continuous deformation model. Proceedings of the 4th Joint International Symposium on Deformation Monitoring (JISDM), Athens, Greece.
KAUKER, S.; HARMENING, C.; SCHWIEGER, V.; NEUNER, H. (2017): Modellierung und Auswirkung von Korrelationen bei der Schätzung von Deformationsparametern beim terrestrischen Laserscanning. In: Werner Lienhart (Hg.): Ingenieurvermessung 2017. Beiträge zum 18. Internationalen Ingenieurvermessungskurs Graz. Ingenieurvermessung 17. Graz, 25-29. April. Berlin/Offenbach: Herbert Wichmann Verlag, 321-336.
KERSTEN, T.; PAFFENHOLZ, J.-A.: Noise Analysis of High Sensitivity GNSS-Receivers for Direct Geo-Referencing of Multi-Sensor Systems. Presentation. IAG Commission 4 Positioning and Applications Symposium, Wroclaw, Poland, September 6, 2016.
OMIDALIZARANDI, M., PAFFENHOLZ, J.-A., STENZ, U.& NEUMANN, I. (2016): Highly accurate extrinsic calibration of terrestrial laser scanner and digital camera for structural monitoring applications. In: Proceedings of the 3rd Joint International Symposium on Deformation Monitoring. JISDM2016. Vienna, 30 March - 01 April, S. 8.
PAFFENHOLZ, J.-A.; BECKER, A.; OMIDALIZARANDI, M.; BUSSE, V. (2018): Untertägige Verformungsüberwachung diskreter Ankerköpfe mittels Videotachymetrie. In: Busch, W. (Hrsg.): Tagungsband GeoMonitoring 2018, Clausthal-Zellerfeld, S. 225-240.
PAFFENHOLZ, J.-A.; BUREICK, J.; DMITRI, D.; LINK, J. (2016): Synchronization aspects of sensor and data fusion in a research multi-sensor-system. In: Proceedings of the 5th International Conference on Machine Control & Guidance. Clermont-Ferrand, France, October 5-6.

Meetings and Conferences

The members presented their individual and partially collaborative research results at the following conferences:

- 3rd Joint International Symposium on Deformation Monitoring (JISDM), Vienna (Austria), April 2016
- IAG Commission 4 Positioning and Applications Symposium, Wroclaw (Poland), September 2016
- 5th International conference on Machine Control & Guidance (MCG), Vichy (France), October 2016
- 18. Internationaler Ingenieurvermessungskurs, Graz (Austria), April 2017
- 7th International Conference on Engineering Surveying (INGEO), Lisbon (Portugal), October 2017
- 4rd Joint International Symposium on Deformation Monitoring (JISDM), Athens (Greece), Mai 2019

Upcoming events with contributions of WG members are:

- ISPRS Geospatial Week 2019, Enschede (The Netherlands), June 2019; in particular Workshops Laserscanning and Joint EuroCOW - M3DMaN
- HARTMANN, J.; VON GÖSSELN, I.; SCHILD, N.; DORNDORF, A.; PAFFENHOLZ, J.-A.: NEUMANN, I. (2019): Optimisation Of The Calibration Process of a K-TLS Based Multi-Sensor-System by Genetic Algorithms. Oral Presentation.
- 27th IUGG General Assembly, Montreal (Canada), July 2019
- PAFFENHOLZ, J.-A.; HARMENING, C.; GIKAS, V. (2019): 3D Point Cloud based Spatio-temporal Monitoring. Poster.

Cooperation with other Organizations

- Established link to DVW Working Group - Engineering Geodesy; Elected members Christoph Holst, Jens-André Paffenholz.
- Established links to ISPRS WG I/10 - Sensor Systems Verification, Benchmarks, Evaluation (Petra Helmholz) and ISPRS WG II/10 - 3D Mapping for Environmental & Infrastructure Monitoring (Daniel Wujanz)
- Established link to FIG Commission 6 – Engineering Surveys (Corinna Harmening)

WG 4.1.1: Robust Positioning for Urban Traffic

Chair: *Laura Ruotsalainen (Finland)*
Vice Chair: *Fabio Dovis (Italy)*

Members

- *Pierre-Yves Gilleron, Switzerland*
- *Juliette Marais, France*
- *Valerie Renaudin, France*
- *Aiden Morrison, Norway*
- *Ling Pei, China*
- *Marco Pini, Italy*
- *Marco Piras, Italy*
- *Vassilis Gikas, Greece*
- *Emerson Cavalheri, Canada*
- *Gunther Retscher, Austria*
- *Mark Petovello, Canada*

Activities and publications during the period 2015-2019

The Working Group focuses on the navigation challenges on the urban environments for greener, safer and more comfortable traffic. At present, navigation is mainly based on the use of Global Navigation Satellite Systems (GNSS), providing good performance in open outdoor environments. However, navigation solution with sufficient accuracy and integrity is needed in urban canyons, where GNSS is significantly degraded or unavailable. For overcoming the aforementioned navigation challenges, research has been very active for decades for finding a suitable set of other methods for augmenting or replacing the use of GNSS in positioning for urban traffic.

The Working Group has a major focus on:

- Specification and characterization of the system requirements, especially from the environmental and safety viewpoints,
- Evaluation of the usability of emerging technologies for the urban traffic navigation, including vision-aiding and collaborative driving systems,
- Selection of best set of technologies fulfilling the system requirements,
- Performance analysis of the selected system both for vehicles and pedestrians in urban areas,
- Selecting the most suitable algorithms for map matching and routing.

The focus of the WG was on navigation challenges in urban environments for greener and safer traffic. At present, navigation is mainly based on the use of Global Navigation Satellite Systems (GNSS), providing good performance in open outdoor environments. However, navigation solution with sufficient accuracy and integrity is needed in urban canyons, where GNSS is significantly degraded or unavailable. The Work Group has addressed the development of seamless positioning methods for assuring accurate and reliable navigation solution in urban areas during GNSS outages. A loosely-coupled Kalman filter was implemented to fuse measurements provided by a GNSS receiver, Inertial Measurement Unit (IMU), magnetometer, barometer and optionally a camera to provide a low-cost solution for urban navigation. The system was tested in multiple test campaigns in Finland in 2017. Assessment of GNSS performance in challenging navigation environments through analytical models and simulators is not effective in terms of cost, complexity, and scalability of the results. A record-and-replay approach was developed as an efficient solution to grant the flexibility of the test environment and the fidelity to a realistic scenario. The method was tested via collecting data in multiple test campaigns in Finland (2016, 2017) and Italy (2017, 2018).

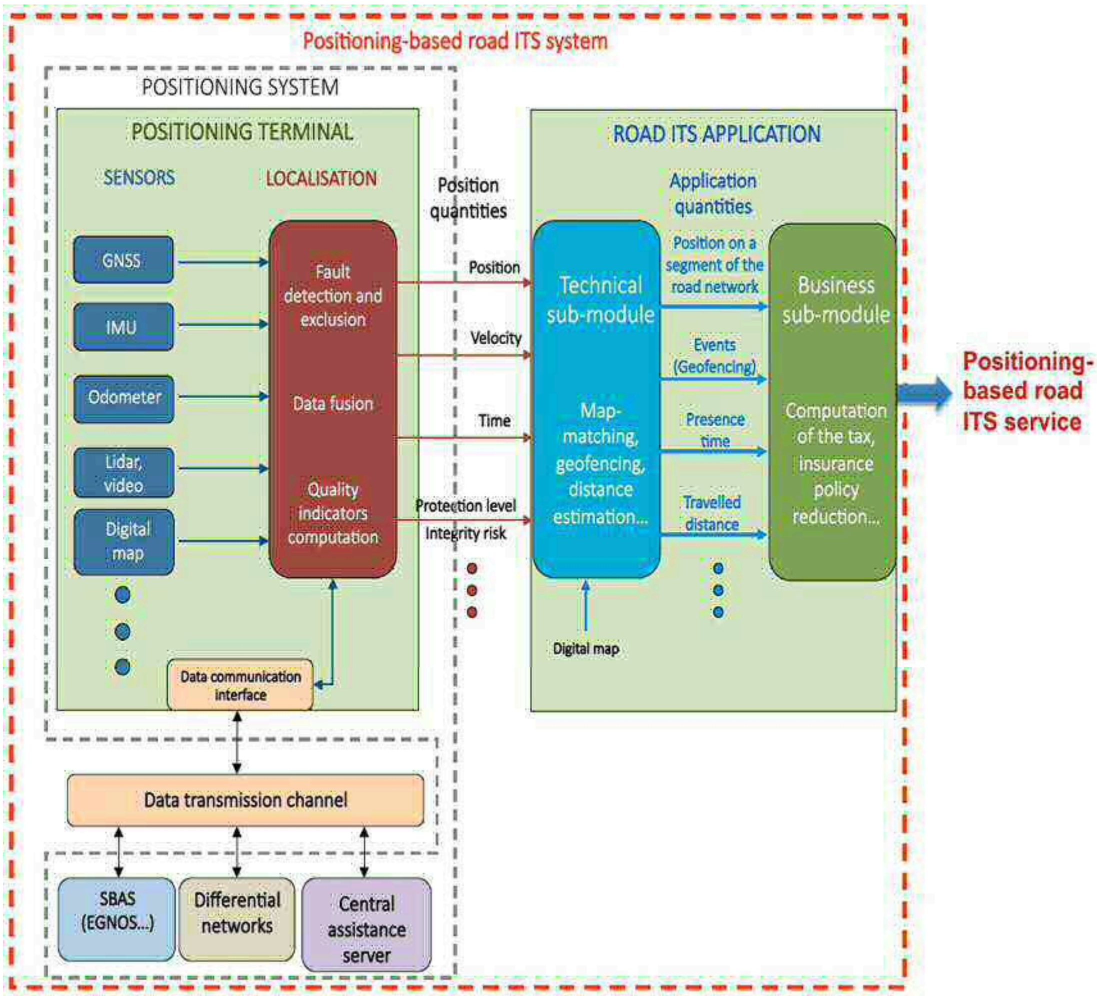

Fig. 4.1.4-1 Working principle of GNSS performance assessment for ITS applications adopted in SaPPART COST Action with the participation of WG 4.1.4 members [www.sappart.net]

The core of autonomous vehicle navigation is based on GNSS / IMU and optical systems fusion. The accuracy and reliability requirements are much higher than for traditional road traffic and they cannot afford gaps in positioning service provision. Therefore, a novel method providing good performance position solution in deep urban areas with heavily degraded and partially denied satellite positioning was developed, based on deeply-coupled fusion of GNSS/IMU and computer vision. The method was tested for urban navigation via collecting data in multiple test campaigns in Finland and Italy (2017, 2018). Use of optical systems in snow and ice conditions is problematic. An extensive literature survey was made about most relevant navigation technologies and their feasibility in Arctic. The work identified the open research questions to obtain sufficient performance for autonomous vehicles. Also, a Special Issue (SI) “Recent advancements on the use of GNSS- based positioning for Intelligent Transport System” was established for IEEE ITS Magazine.

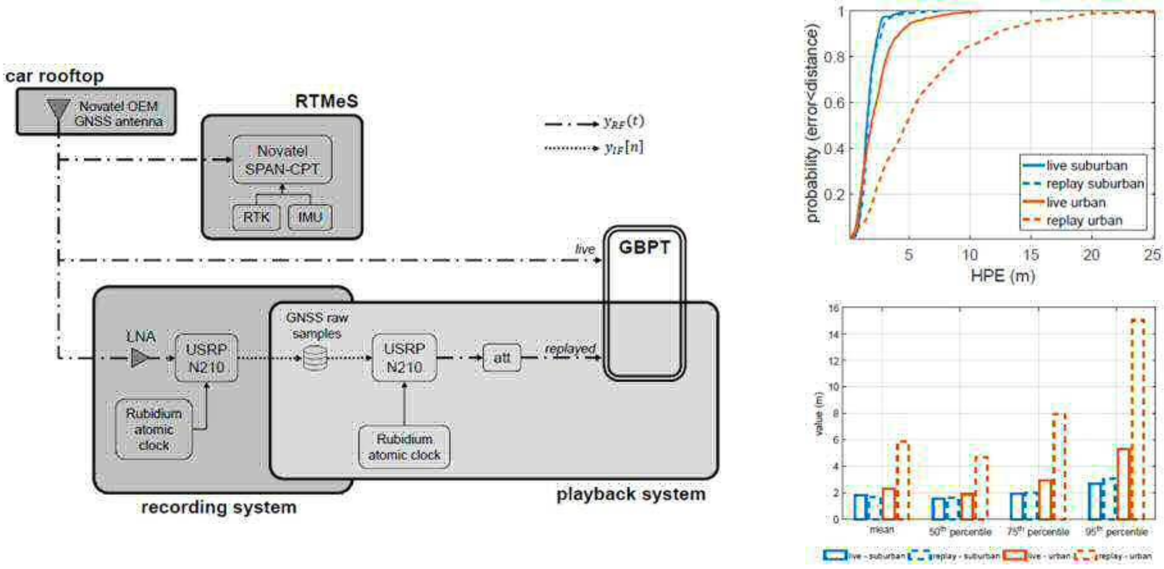

Fig. 4.1.4-2 GNSS record and replay system setup analyzed for vehicular positioning applications RTMeS: Reference Trajectory Measurement System, RTK: real time kinematic (left), statistical characterization of the Horizontal Position Error (HPE), cumulative distribution function (top right) and additional metrics (bottom right) [Cristodaro *et al*, Sensors 2018, 18, 2189]

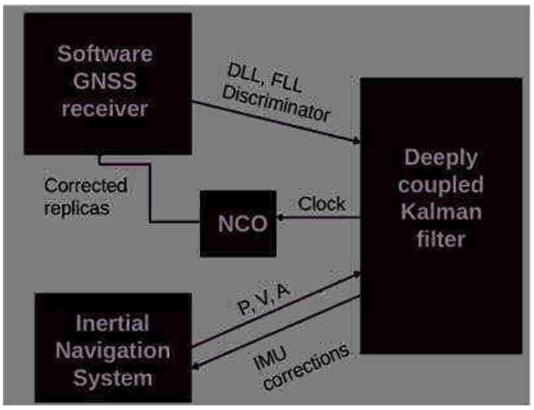

Fig. 4.1.4-3 Deeply-coupled Kalman filtering for GNSS/IMU/Vision fusion

Research visits

Valerie Renaudin, IFSTTAR, France hosted by Laura Ruotsalainen, Finnish Geospatial Research Institute, Finland

Laura Ruotsalainen, Finnish Geospatial Research Institute, Finland hosted by Fabio Dovis, Politecnico di Torino, Italy

Andrea Della Monica, Politecnico di Torino, Italy hosted by Laura Ruotsalainen, Finnish Geospatial Research Institute, Finland

Calogero Cristodaro, Politecnico di Torino, Italy hosted by Laura Ruotsalainen, Finnish Geospatial Research Institute, Finland

Journal publications

C Cristodaro, L Ruotsalainen, F Dovis (2018). Benefits and Limitations of the Record and Replay Approach for GNSS Receiver Performance Assessment in Harsh Scenarios, Sensors 18 (7), 2189.

L Ruotsalainen, V Renaudin, L Pei, M Piras, J Marais, E Cavalheri, S Kaasalainen (2019) Towards Autonomous Driving in Arctic Areas, submitted to IEEE ITS Magazine

Conference Publications

A. Della Monica, L. Ruotsalainen and F. Dovis (2018) "Multisensor navigation in urban environment," IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, 2018, pp. 730-738

C Cristodaro, F Dovis, L Ruotsalainen (2017): The Record and Replay Approach for GNSS Receiver Performance Assessment in Road Environment, In Proceedings of ION ITM, pp. January 30 - February2, Monterey, CA, pp. 1369-1375

Gikas V., Kealy A., Paffenholz J-A, Perakis H., Retscher G., Zhang K., Ruotsalainen L., Santos M. (2016), IAG SC 4.1 "Emerging Positioning Technologies and GNSS Augmentation" In Proceedings of European Navigation Conference (ENC), June 30 - July 2, Helsinki, Finland P.-Y.

Gilliéron, L. Ruotsalainen, F. Peyret, S. Feng, J. Engdahl (2016): The SaPPART COST Action: Towards positioning integrity for road transport, In Proceedings of European Navigation Conference (ENC), June 30 - July 2, Helsinki, Finland

Dovis F., Ruotsalainen L., Gikas L. (2016): Robust Positioning for Urban Traffic: Motivations and Activity plan for the WG 4.1.4 established within the IAG SC 4.1 Emerging Positioning Technologies and GNSS Augmentation. IAG Commission 4 Positioning and Applications Symposium, Wroclaw, Poland, September 6, 2016.

Meetings and Conferences

The WG presented the goals and actions of the group and had meetings in the following events:

- IAG Commission 4 Positioning and Applications Symposium" in Wroclaw, in September, oral presentation 2015
- ITS World Congress 2015, Bordeaux , Oct. 5-9 European Navigation conference 2016 in Helsinki, in May, poster presentation
- Institute of Navigation conferences GNSS+, PLANS and ITM 2015, 2016, 2017, 2018, 2019
- SaPPART final event in Brussels, October 2017
- European Navigation Conference (ENC) in Lausanne, May 2017
- Indoor Positioning Indoor Navigation (IPIN) Conference in Nantes, September 2018

Cooperation with other Organizations

The group has established links between the following stakeholders for improved dissemination of the action deliverables and input of different user needs for the work:

- EU COST SaPPART in SaPPART meetings
- Other IAG SC 4 WGs in Commission 4 Symposium in Poland 2016
- Different stakeholders participating the eKnot roadshow in Torino 2017

Sub-commission 4.2: Geopatial Mapping and Geodetic Engineering

Chair: *Jinling Wang (Australia)*
Vice-Chair: *Michael J. Olsen (USA)*
Secretary: *Hsiu-Wen Chang (China-Taipei)*

Overview

Geodesy provides foundations for geospatial mapping and engineering applications. Modern geospatial mapping as a massive point positioning process has been evolving towards automatic operations, and at the same time, various engineering areas are increasingly relying on highly developed geospatial technologies to deliver improved productivities and safety with minimised negative environment impact. This Sub-Commission (SC) 4.2 will therefore endeavour to coordinate research and other activities that address the broad areas of the theory and applications of geodesy tools in geospatial mapping and engineering, ranging from construction work, geotechnical and structural health monitoring, mining, to natural phenomena such as landslides and ground subsidence. The SC4.2 will carry out its work in close cooperation with other IAG Entities, as well as via linkages with relevant scientific and professional organizations such as ISPRS, FIG, ISM, ICA, IEEE, ION, OGC.

Major objectives of Sub-Commission (SC) 4.2 include:

- To develop and promote the use of new geospatial mobile mapping technologies for various applications;
- To develop and report the modelling and quality control framework for geo-referencing procedures;
- To monitor research and development into new technologies that are applicable to the general field of engineering geodesy, including hardware, software and analysis techniques;
- To study advances in geodetic methods for engineering applications, such as mining operations, and large construction sites;
- To study advances in monitoring and alert systems for local geodynamic processes, such as landslides, ground subsidence, etc.;
- To study advances in Structural Health Monitoring (SHM) systems and geospatial mapping applications in SHM;
- To study advances in Building Information Modelling (BIM) and geospatial mapping applications in BIM.

Major Sub-Commission 4.2 Activity

SC 4.2 is composed of 4 working Groups. While each working group has conducted various activities, the Sub-Commission 4.2 has successfully organised one major event: **The 9th International Symposium on Mobile Mapping Technology (MMT2015),** Sydney, Australia, December 9-11, 2015, see the program details at www.mmt2015.org.

The MMT Symposium is the primary event jointly sponsored by International Association of Geodesy (**IAG**), the International Society of Photogrammetry and Remote Sensing (**ISPRS**) and the International Federation of Surveyors (**FIG**). In addition, for the first time, another two major international organisations, the International Society of Mine Surveying (**ISM**) and the International Cartographic Association (**ICA**), Australian Surveying and Spatial Sciences Institute (SSSI), and Spatial Industries Business Association (SIBA), Australian Robotics and Automation Association (ARAA) as well as Australian Network of Structural Health Monitoring (ANSHM) have also offered the official sponsorships to the MMT2015.

MMT2015 attracted about 300 registered participants from 35 countries/regions, and received 156 full paper submissions for the conference proceedings, with topics ranging from new mapping concepts, the state of the art of technology, multi-disciplinary approaches, new applications, to future trends. The program included three keynote presentations, two panel discussions, 27 technical sessions, and pre-symposium workshops. Among the papers presented at the Symposium, a total of 26 selected papers have been published in 3 refereed journals: 7 papers published in *Geo-spatial Information Science* (as a Special Issue: Mobile Mapping with Ubiquitous Point Clouds, https://www.tandfonline.com/toc/tgsi20/19/3); 13 papers published in the *Journal of Surveying Engineering* (as a special collection https://ascelibrary.org/page/jsued2/mmt_2015); 6 papers published in *Photogrammetric Engineering & Remote Sensing* as a special issue, 82(12), 2016 https://www.ingentaconnect.com/content/asprs/pers/2016/00000082/00000012)

(L. to R: J. Wang, N. Haala, S. Guo, N. El-Sheimy, D.A. Grejner-Brzezinska, C. Toth)

One behalf of the Organising Committee of The 9th International Symposium on Mobile Mapping Technology (MMT 2015), General Chair Jinling Wang (Australia), Scientific Committee Chair Norbert Haala (Germany), Program Chair Charles Toth (USA) presented the "Outstanding Achievement Award" to Dorota A. Grejner-Brzezinska(USA), Naser El-Sheimy (Canada), Sheng Guo (China) in recognition of their pioneering contributions in developing and promoting mobile mapping technology.

Working Groups of Sub-commission 4.2:

WG 4.2.1: Mobile Mapping Technologies and Applications

Chair: J. Skaloud (Switzerland)
Vice-Chair: K.-W. Chiang (China-Taipei)

Members

Hsiu-Wen Chang (Taiwan)
Ismael Colomina (Spain)
Davide Cucci (Switzerland)
Michael Cramer (Germany)
Craig Glennie (USA)
Jen-kai Liao (Taiwan)
Martin Rehak (Switzerland)
Philipp Schaer (Switzerland)
Guang-Je Tsai (Taiwan)
Yi-Hsing Tseng (Taiwan)
Julien Vallet (Switzerland)
Jinling Wang (Australia)
Ming Yang (Taiwan)

Working Group Activities and Publications

Working Group 4.2.1 focuses on mobile mapping technology and applications. Mobile mapping technologies have been widely used to collect geospatial data for a variety of applications, for example, navigation and online geospatial information services. As mobile mapping sensors are becoming cheaper and easier to access, modeling and quality control procedures for major steps of mobile mapping should be further developed to ensure the reliability of geospatial data from mobile mapping systems. This working group conducts its work through coordinated activities among the members of the group as well as in collaborations with other professional organizations, such as ISPRS/FIG. Over the past two years, the following major activities are conducted:

EuroCOW 2016
The European Calibration and Orientation Workshop, 10-16 February 2016

The Chair and the some members of the Working Group 4.2.1 organised the EuroCOW, the European Calibration and Orientation Workshop which was held from February 10th to February 12th, 2016 on the EPFL campus, located in Lausanne, Switzerland. This biennial meeting brought together the world experts, both from public and private sectors, to present and discuss the recent findings and developments on Sensor Calibration and Orientation. With the recent development of autonomous platforms, this traditional field of photogrammetry and geodesy integrates with robotics, computer vision and system control. The full papers from submitted to the EuroCOW 2016 are published in International Archive of Photogrammetry, Remote Sensing and Spatial Information Science at
http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-3-W4/index.html

EuroCOW 2017
Jointed held with ISPRS as a part of Hannover workshop, 6–9 June 2017, Germany

In mobile mapping related research on sensor calibration, image orientation, object extraction and scene understanding from images and image sequences*, both geometry and semantics play an important role, and high quality results require appropriate handling of all these aspects. While individual algorithms differ according to the imaging geometry and the employed sensors and platforms, all mentioned aspects need to be integrated in a suitable workflow to solve most real-world problems (http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-1-W1/1/2017/isprs-archives-XLII-1-W1-1-2017.pdf).*

Under such observations, EuroCOW - European Calibration and Orientation Workshop, collaborating with other meetings (HRIGI - High-Resolution Earth Imaging for Geospatial Information, CMRT - City Models, Roads and Traffic, ISA - Image Sequence Analysis), co-organised a special event "Hannover workshop 2017". A total of 30 full papers were accepted for the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences at http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-1-W1/index.html; while 99 papers are published in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-1/W1, 2017 (http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-1-W1/index.html)

The European Calibration and Orientation Workshop, 13-14 June 2019

This one and half-day 'single-track' meeting strives to be practical, informative and informal where the experts with theoretical and hands-on experience discuss in a relax atmosphere. The workshop will be part of the ISPRS Geospatial Week 2019 and is hosted by the University of Twente, Enschede, The Netherlands.

About two dozen of publications were reviewed and will be presented. The primary theme focuses on tighter integration between sensors and platforms that remains an open challenge both algorithmically and practically for a number of applications that requires higher measures for reliability, integrity as well as accuracy both in navigation and mapping. Also, calibration revamped calibration procedures are presented for new (and often small) optical sensors as well as their integration with navigation devices.

Selected Publications

1. Lin, C.-A.; Chiang, K.-W.; Kuo, C.-Y. *Development of INS/GNSS UAV-Borne Vector Gravimetry System*, IEEE Geoscience and Remote Sensing Letters (Volume: 14, Issue: 5, May 2017), pp. 759 – 763
2. Chiang, K.-W.; Liao, J.-K.; Huang, S.-H.; Chang, H.-W.; Chu, C.-H. *The Performance Analysis of Space Resection-Aided Pedestrian Dead Reckoning for Smartphone Navigation in a Mapped Indoor Environment*. ISPRS Int. J. Geo-Inf. 2017, 6, 43.
3. Lai, Y.-C.; Chang, C.-C.; Tsai, C.-M.; Huang, S.-C.; Chiang, K.-W. *A Knowledge-Based Step Length Estimation Method Based on Fuzzy Logic and Multi-Sensor Fusion Algorithms for a Pedestrian Dead Reckoning System*. ISPRS Int. J. Geo-Inf. 2016, 5, 70.
4. Liao, J.-K.; Chiang, K.-W.; Zhou, Z.-M. The Performance Analysis of Smartphone-Based Pedestrian Dead Reckoning and Wireless Locating Technology for Indoor Navigation Application. Inventions 2016, 1, 25.
5. Kai-Wei Chiang, Jhen-Kai Liao, Guang-Je Tsai, Hsiu-Wen Chang (2015, Dec). The Performance Analysis of the Map aided Fuzzy Decision Tree based on Pedestrian Dead Reckoning Algorithm in Indoor Environment. Sensors, 16(1), 34. 4.
6. Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. (2015, Mar). New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors, 15, 6560-6585.
7. M. Rehak and J. Skaloud. *Time synchronization of consumer cameras on Micro Aerial Vehicles,* in Isprs Journal of Photogrammetry and Remote Sensing, vol. 123, num. 1, p. 114-123, 2017.

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Working Group 4.2.2 Applications of Geodesy in Mining Engineering

Chair: Jian Wang (China)
Co-Chair: Frederick Cawood (South Africa)

Members

- *Abelardo Bethencourt Fernandez (Spain)*
- *Agrim. Diego Alejandro Piñón (Argentina)*
- *Alberto Hernández Moraleda (Spain)*
- *Aiguo Li (China)*
- *Afeni Thomas (Nigeria)*
- *Binghao Li (Australia)*
- *Dai Zhen (Germany)*
- *Fang Yang (China)*
- *Jinyun Guo (China)*
- *Kefei Zhang (Australia)*
- *Luciene Delazari (Brazil)*
- *Nesreen I Ziedan (Egypt)*
- *Vagner G. Ferreira (China)*
- *Vladimir Tikunov (Russia)*
- *Xiaolin Meng (UK)*

Activities and publications during the period 2015-2019

This study group aims at providing a platform for communicating the current research of the geospatial mapping, modern navigation and guidance technologies used in mining operations. The main focus in the past 4 years has been on several points that include underground/indoor positioning technology, new generation of positioning system for underground mine environments and GNSS and its synergized hazard monitoring. The group also aims to boost education and training of the geospatial technology used in mining operation for backward mine to increase safety. Hereafter, some of the work completed by individual group members in their research groups are summarized.

(1) Positioning in degenerated environment

In one study, a method based on the control points is used to determine the coordinates in advance in roadways of underground mine vehicles is proposed. the method, is necessary to correct the error state in INS / odometer integrated navigation system, which can increase the navigation accuracy. This method include three steps: i) to build a system dynamic model and observation model of INS /odometer integrated navigation system; ii) to propose a position modification filter equation based on known points; and iii) to produce a Parallel-Kalman filter to realize the dual filter of integrated navigation and INS/odometer integrated navigation system based on position modification for underground mine vehicle Overall, the results of the experiment indicated that the INS /odometer integrated navigation performance increased substantially by position modification of known points in roadways. Furthermore, the planimetric precision of real-time navigation increased from dozens of meters to meter scale which is able to meet the needs of navigation for underground mine vehicles.

In a second study, a tightly-coupled Global Position System (GPS)/Ultra-Wideband (UWB)/Inertial Navigation System (INS) cooperative positioning scheme using a Robust

Kalman Filter (RKF) supported by V2I communication was developed and tested in degenerated environment. The scheme can provide ubiquitous location to be used in open-pit mine for miner navigation, trucker guidance and machine operating. An adaptive Robust Kalman Filter(RKF) was developed to further improve the reliability of the solution and the result proves that the RKF can eliminate the effects of gross errors. Additionally, the internal and external reliabilities of the system are enhanced when the UWB observables received from the moving terminals are involved in the positioning algorithm.

In the third study, a method is presented to predict the location using RSS. A study on the effects of walls and floors on the RSS is provided, and a localization technique that utilizes the finding of the effects of obstructions on the RSS is investigated. The investigated technique uses multi walls and floors model in the estimation. The system model showed the major difficulty in indoor localization algorithm, especially the difficulty of location estimation using the storage of building layout, the algorithm has been used to estimate location using three or more reference nodes, and in special cases, by using two reference nodes. Experimental results show that the position estimation error is less than 2 meters for most locations. It is suitable for indoor environments with multiple floors and multiple walls.

The fourth method proposes a less environment-dependent and a priori knowledge-independent NLOS identification and mitigation method for ranging which is able to determine the specific NLOS channel. Based on the identified channel information, a rule is developed to select appropriate NLOS ranges for location estimation. Meanwhile, an equality constrained Taylor series robust least squares (ECTSRLS) technique is proposed to suppress residual NLOS range errors by introducing robustness to Taylor series least squares method. All these constitute our FCE-ECTSRLS NLOS mitigation algorithm. The performance of the proposed algorithm is compared with four existing NLOS mitigation algorithms by both static and mobile localization experiments in a harsh indoor environment. Experimental results have demonstrated that the proposed FCE-ECTSRLS algorithm outperforms the other four algorithms significantly.

(2) Map aided underground/indoor positioning

An Improved PDR/ Magnetometers/Floor Map Integration Algorithm for Ubiquitous Positioning Using Adaptive Unscented Kalman Filter was proposed. Additionally, a scheme using a foot-mounted Inertial Measurement Unit (IMU) and a floor map to provide ubiquitous positioning in a number of settings, like in a supermarket as a shopping guide, for a fire emergency service for navigation, or a miner to be tracked was put forward. Firstly, several Zero-Velocity detection (ZDET) algorithms are compared and discussed when used in static detection of a pedestrian. By introducing the Zero-Velocity knowledge of the pedestrian, fusing magnetometers measurement, an improved Pedestrian Dead Reckoning (PDR) model is developed to constrain the accumulating errors of the PDR positioning. Secondly, the Correlation Matching Algorithm based on map projection (CMAP) is presented and zone division of a floor map is demonstrated for fusion of the PDR algorithm. At last, in order to use the knowledge of dynamic characteristics of a pedestrian trajectory, the Adaptive Unscented Kalman Filter (A-UKF) is applied to tightly integrate IMU, magnetometers and floor map for the ubiquitous positioning. The performance observed in a field experiment confirms that the proposed scheme can reliably achieve meter-level positioning.

Another scheme for indoor positioning by fusing floor map, WiFi and smartphone sensor data to provide meter-level positioning without additional infrastructure was advanced. A topology-constrained KNN algorithm based on a floor map layout provides the coordinates required to integrate WiFi data with pseudo-odometry (P-O) measurements simulated using a pedestrian dead reckoning (PDR) approach. One method of further improving the positioning accuracy is to use a more effective multi-threshold step detection algorithm, as proposed by the authors. The performance observed in a field experiment performed on the fourth floor of the School of Environmental Science and Spatial Informatics (SESSI) building on the China University of Mining and Technology (CUMT) campus confirms that the proposed scheme can reliably achieve meter-level positioning.

The third research investigates subjective user preference for using Floor Plans and Schematic Maps in an indoor environment, and how users locate and orient themselves when using these representations. We sought to verify the efficiency of these two kinds of digital maps and evaluate which elements found in physical environments and which elements found in the representations influence the user spatial orientation process. Users answered questions and performed orientation tasks which indicated their level of familiarity with the area being studied, their understanding of the symbology used, and their identification of Points of Interest (POI) in the environment. The initial results indicated a preference for the Schematic Map, because users thought that the symbology used on the map adopted was easy to understand.

(3) New generation of positioning system for Underground Mine Environments

On 19 April 2017, a meeting on the study of the new generation of positioning system for Underground Mine Environments was held at Xuzhou, China, experts from the China University of Mining and Technology, the University of New South Wales and the RMIT University come to a conclusion that the new generation underground positioning system should include multi-sensors such as: accelerometer, magnetometer and gyroscope. In which the fusion algorithm should consider intelligence algorithm. The meeting also discussed a prototype for meter level accuracy positioning for persons and machines, to locate and manage the persons and machines, to navigate the persons in emergency in mine environment.

(4) Effort on building an international platform for geoinformatics communications

The chair and vice chair of this working group are working for building an international platform for communicating in related research and education area. The purpose is to involve several Universities and research institutes. As a starting point, Wits University and CUMT sponsored a joint research lab on 27 October 2016 at CUMT Nanhu Campus, Xuzhou, Jiangsu Province, China.

Eleven African scholars from nine African countries, namely, Liberia, Sudan, Gabon, Cameroon, Namibia, Madagascar, Togo, Zambia and Mozambique, participated in the opening ceremon.

For the moment, the core content of the lab include: (i) Geospatial positioning, GNSS system and equipment use(Including China BeiDou system) indoor positioning systems, real-time underground positioning systems linked to mine plan, remote sensing and positioning of mine hazards, hardware and software development and manufacturing of world-first technologies for underground mining; (ii) mobile and underground platforms, SLAM technology systems, mobile and underground platforms - Position, Navigate and Time (PNT) ,laser scanning for ground movement risk monitoring and modelling, autonomous rail systems with robotics; (iii) digital/smart mining, remote sensing technologies detecting risks, environmental monitoring and climate control underground, security video analytics, cloud computation, hazard/risk maps; (iv) education and training for African countries, training and education on GNSS , 21st century mining skills, skills to manufacture new technologies, installation and maintenance of technology systems designed in the joint laboratory, education and skills development for technicians and professionals of technology systems designed in the joint laboratory, mining law and policy unit covering African countries. This is only the first step. More efforts should be made by the members in future to boost the development of the platform.

The Digital Mining research laboratory at Wits University is also collaborating on digital mining technologies with NUST University in Pakistan on 21st century mining, including some research on national mineral policy and mining cadastre development.

In 2018, A tunnel for testing coal mine positioning and navigation system is built in WITS university and BDS coal mine CORS system is provide to get the PNT position by CUMT (China University of Mining and Technology) and Hi-Target Surveying Instrument Co. Ltd.
To further enhance the reliability and availability of GPS/INS integrated navigation in GPS challenging environment, range observation through ultra-wideband (UWB) is introduced in PPP/INS tightly coupled navigation. Comparison of precise point positioning/inertial navigation system/ultra wideband (PPP/INS/UWB) tightly coupled positioning among different precise satellite ephemeris and clock products is made and corresponding data analysis is provided. Rapid and ultra-rapid products are applied in PPP/INS/UWB integrated system to assess the impact of ephemeris and clock accuracy on tightly coupled positioning.

The ultimate objective is to use technology to put distance between mine workers and the typical risks they are exposed to on a daily basis. This objective is achieved by transferring surface digital technologies into the underground environment. Recently completed and existing research projects include: (i) Extension of surface real-time wireless communication systems into the underground environment. The challenge is for wireless systems to work reliably – all the time and for the system to cope with live streaming of data; (ii) On positioning, mapping and navigation, significant work includes test work that proves that sidewall survey stations meet the accuracy and other legal geospatial requirements for safe mining; research and installation of indoor positioning systems that include both relative and absolute (geodetic) coordinates systems, and a testing facility for scanning and positioning from a moving platform; (iii) Action recognition and detection of abnormalities through combining positioning, video analytics and biometric information; (iv) Remote, visual, inspections through the development of an underground UAV with the capability to position, map, navigate and detect harmful volatile compounds and gases.

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WG 4.2.3: Mobile Structural Health Monitoring Systems

Chair: *Christian Eschmann (Germany)*
Vice Chair: *Johnson Shen (Australia)*

Members

Matthias Bartholmai (Germany)
Edouard Burrier (France)
João Caetano (Portugal)
Hui Deng (China)
Fuyang Ke (China)
Patrick Neumann (Germany)
Ralf M. Moryson (Germany)
Björn Schäfer (Germany)
Ali Al-Shaery (Saudi Arabia)
Alexander Velizhev (Switzerland)
Jinling Wang (Australia)

Activities and publications

Working Group 4.2.3 focuses on structural health monitoring (SHM) which is an issue of increasing importance when looking at more and more aging and critical infrastructure around the world. Both traditional and emerging geodetic techniques may be considered to carry out SHM tasks. In order to perform safety-related infrastructure inspections, robotic solutions are required to allow an automatic and reliable geospatial data acquisition for a comprehensive building database suitable for SHM analysis. Here the investigation of new mapping and navigation methods as well as non-destructive testing (NDT) sensors forms the basis for these mobile SHM systems. To develop such reliable autonomous systems, this working group will focus on current challenges such as the reproducibility and traceability of mobile NDT sensor data as well as the precise localization and navigation operations inside and/or in the areas close to infrastructures. Over the past two years, the working group members have conducted the following research activities:

(1) Studies on the possible usage of highly automated systems in the field of SHM

Due to the recent technological progress in robotics and sensor engineering, automated remote sensor systems finally are more and more accepted as an appropriate means even for critical investigations such as infrastructural inspection and monitoring. Regarding the usage of mobile – especially unmanned – systems in terms of future structural health monitoring applications, the requirements for those systems clearly point out important criteria concerning commercial implementation. Comprehensive studies have shown that both ground vehicle systems and their flying counterparts can be useful tools when it comes to optimizing monitoring processes. The automation of those systems is particularly difficult with regard to safe use with less as well as specially trained personnel. In addition, the integration of applications into common processes, e.g. in the case of remotely-piloted aircraft systems (RPAS) their integration into national or sovereign airspace, is still being limited due to national regulations.

Our conclusions are:
a) Redundancy of safety-related functions of unmanned systems (e.g. data link, power supply, communication) is an important basis for everyday economic use.

b) High degree of automation is necessary for any kind of SHM system with respect to user friendliness and safe usage in terms of urban applications.
c) Continuing R&D activities as a kind of lobbying for the establishment of a widespread acceptance on the official level of mobile systems as a comprehensive means for assessment purposes.

(2) Cloud Platform for SHM and Warming based on Multiple Sensors

The cloud platform SHM and Warming consists of GNSS and vision sensors, Cloud Service Center and APP. The GNSS stations can monitor the structure surface deformation at mm level accuracy in real time. The sensors can acquire the hydrogeological and atmospheric parameters. The vision sensors can detect the environment around the monitoring objects by image recognition technology. Then GNSS measurements and images can be sent to cloud service center via optical fibre or wireless network. And the structural health state parameters will be obtained in real time based on the multi-sensors and vision fusion on Cloud service center. At the same time, the cloud service center will forecast the structural health state parameters based on intelligent forecast model and historical data. The health parameters and warming message can be achieved and sent to managers by Web, E-mail or App. The GNSS and Sensor Cloud Platform is developed by the team led by Dr. Fuyang Ke at Nanjing University of Science Information and Technology and has been applied in many national key projects in China. It will be continuously improved for an artificial intelligence system in future.


Sensor installation for Cloud Platform for SHM and Warming at engineering sites in China

(3) Conferences, meetings, other WG activities

Since the topic of mobile SHM systems is quite diversified, activities have been carried out in the field of robotics, automation, flight system dynamics, data fusion as well as remote sensing. In this context, the working group team members therefor attended a variety of conferences, e.g. IMAV 2015, MMT2015, CBA-UAS 2016 and 19th WCNDT 2016, as well as related workshops.

Selected publications

Caetano, J. V., Percin, M., van Oudheusden, B. W., Remes, B., De Wagter, C., de Croon, G. C. H. E., & de Visser, C. C. (2015). Error analysis and assessment of unsteady forces acting on a flapping wing micro air vehicle: free flight versus wind-tunnel experimental methods. Bioinspiration & biomimetics, 10(5), 056004.

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WG 4.2.4: Building Information Modelling

Chair: *Mohsen Kalantari (, Australia)*
Vice Chair: *Michael Olsen (USA)*

Members

- Behnam Atazadeh (Australia)
- Craig Hanock (University of Nottingham, China)
- Yelda Turkan (Oregon State University, USA)
- Josh Plager (BIM Earth Corporation, USA)
- Pingbo Tang (Arizona State University, USA)
- Shubhi Harbola (Indian Institute of Technology Kanpur, India)
- Zita Ultmann
- Jingling Wang (Australia)

Committee Activities in 2015-2019

This new working group was formed in December 2015. The focus of our activities have been to grow membership in the working group, collaborate and develop relationships with similar working groups in other organizations, and formulate the scope for the committee. The members have been active in publishing work related to the objectives of the working group within their individual research groups. They are also participating in organizing several workshop events in collaboration with other entities. The working group has been an excellent forum to share these results with one another.

1. **Mobile Mapping Technology Conference** (December 2015, Sydney Australia). Several working group members presented publications at this conference. Some of these publications evolved into peer-reviewed Journal publications that were published in a special collection of the Journal of Surveying Engineering.
2. **FIG Working Week** (May 2016, Christchurch, New Zealand). WG members were active in presenting relevant publications to the WG at this conference. In addition, the working group had an initial meeting at the conference to begin planning events such as the 2017 FIG "BIM for Surveyors" workshop as well as the "BIM and GIS Integration" workshop (described below).
3. **IAG Commission 4 Symposium: Positioning and Applications** (September 2016, Wroclaw Poland). Vice-Chair Olsen attended the IAG Commission 4 meeting in Wroclaw Poland to represent the Working Group as well as present a paper at the symposium.
4. **BIM for Surveyors,** Joint Workshop with FIG, 28 May 2017. WG Members Kalantari, Olsen, and Handcock all presented at the workshop. Several additional speakers were invited to participate.

   Scope of the Workshop:

   - Teaching theoretical background of the BIM method (concepts, workflows and standards)
   - Best practice presentations from large projects and SME (from surveyor's point of view)
   - Presentation of the latest software (surveying, integration and collaboration with BIM, CAD, GIS)

Audience:

- International professionals from AEC-companies (engineering surveyors) and land administration agencies (land surveyors).
- Young professionals interested in this new technology for own projects
- Academics from different countries (just a few universities teach BIM until now)
- Selected students and young professionals from the FIG Young Surveyors Network.

Proceedings were published online at the FIG website: https://www.fig.net/fig2017/bim.htm

5. **International Workshop on Computing in Civil Engineering (IWCCE, ASCE Computing Division)** (June 2017, Seattle Washington).
   Working group member Pingbo Tang is the Vice Chair of the organizational committee for this conference and WG members Olsen and Turkan are serving on the Technical Committee. These WG members will present research related to topics of BIM, 3D modelling, and structural monitoring. The workshop will be used to connect with and identify additional members for the IAG working group as well as identify possible collaborations with the ASCE Computing Division with the working group.

6. **BIM and GIS Integration Workshop** 25 Oct 2017
   This is the first workshop organised by the International Association of Geodesy (IAG) on Building Information Modelling (BIM) and Geographic Information Systems (GIS) integration as an emerging area of research and development. Our working group has been actively planning this workshop.

   The effective integration of BIM and GIS provides opportunity for application across many domains including architecture, urban planning, disaster management, infrastructure engineering, facilities management, construction, policy and decision making.

   This workshop focuses on integration challenges and considers the technical, legal and institutional barriers in bringing BIM and GIS together. Topics will include, but are not limited to:

   - Legal and institutional considerations
   - Integrated collaborative environments
   - Standards in BIM and GIS
   - Level of details and level of development
   - Interoperability and geo-referencing
   - Integration for Decision Science and Risks
   - Automatic change analysis between BIM and GIS models
   - 3D visualisation
   - Virtual design and construction
   - Virtual reality and augmented reality
   - Algorithms to generate BIM/GIS models from point cloud data
   - BIM and GIS integration with 3D point clouds

   Details are available http://3dgeoinfo2017.com

7. **BIM for Surveyors,** Joint Workshop with FIG, May 2018.
   Building Information Modeling (BIM) is changing the way how surveyors work, think, collaborate and make money. Using and sharing multidimensional digital representations of

buildings are the driving forces for the digitalization of our work. This affects many tasks surveyors and GIS professionals perform, e. g. cost estimation, GIS analysis, engineering surveying, construction work, land management and facilities management.

Scope of the Workshop:
- Teaching theoretical background of the BIM method (concepts, workflows and standards).
- Best practice presentations from large projects and SME (from surveyor's point of view).
- Presentation of the latest software (surveying, integration and collaboration with BIM, CAD, GIS).

Publications are accessible in https://www.fig.net/fig2018/bim.htm

8. **Special Issue of Journal of Spatial Sciences on Nexus of BIM and GIS: integrating building and geospatial data**

This special issue focuses on integration challenges and considers the technical, legal and institutional barriers in bringing BIM and GIS together. The special issue is edited by chair and co-chair of the working group and will be published in January 2020. Topics will include, but are not limited to:

- Legal and institutional considerations
- Integrated collaborative environments
- Standards in BIM and GIS
- Level of detail and level of development
- Interoperability and geo-referencing
- Integration for Decision Science and Risks
- Automatic change analysis between BIM and GIS models
- 3D visualisation
- Virtual design and construction
- Virtual reality and augmented reality
- Algorithms to generate BIM/GIS models from point cloud data
- BIM and GIS integration with 3D point clouds
- Decision making based on BIM and GIS integration
- Geospatial data analysis based on BIM and GIS integration

9. **BIM and GIS Integration Workshop** Sep 2019
This workshop follows from the 1st BIM and GIS Integration workshop organised as part of the 12th 3D GeoInfo Conference 2017 by the International Association of Geodesy (IAG) on Building Information Modelling (BIM) and Geographic Information Systems (GIS) integration. The effective integration of BIM and GIS provides opportunities for application across many domains including architecture, urban planning, disaster management, infrastructure engineering, facilities management, construction, policy and decision making. This workshop focuses on integration challenges and considers the technical, legal and institutional barriers in bringing BIM and GIS together.

Details are available in https://www.3dgeoinfo2019.com/bim-gis-workshop/

Selected Publications

1. Kalasapudi, V. S., Tang, P.*, and Turkan, Y. (accepted) "A Computationally Efficient Approach for Automatic Change Analysis of Large-Scale Building Systems." Elsevier Journal of Automation in Construction. accepted in March 2017, DOI:10.1016/j.autcon.2017.04.001.
2. Behnam Atazadeh, Mohsen Kalantari, Abbas Rajabifard, Serene Ho (2017). Modelling building ownership boundaries within BIM environment: A case study in Victoria, Australia 2017 Journal of Computers, Environment and Urban Systems 61(A), 24-38, http://dx.doi.org/10.1016/j.compenvurbsys.2016.09.001
3. Aien, A., Rajabifard, A., Kalantari, M., Williamson, I. (2017). Review and Assessment of Current Data Models for 3D Cadastral Applications, Advances in 3D Geoinformation -Lecture Notes in Geoinformation and Cartography, DOI 10.1007/978-3-319-25691-7_24
4. Nolan, J., Eckels, R., Olsen, M.J., Yen, K.S., Lasky, T.A., and Rvani, B. (In Press). "Analysis of the multi-pass approach for collection and processing of mobile laser scan data," *Journal of Surveying Engineering,* Special Issue on Mobile Mapping Technology. http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000224
5. Behnam Atazadeh, Mohsen Kalantari, Abbas Rajabifard, Serene Ho, Tom Champion (2016). Extending a BIM-based data model to support 3D digital management of complex ownership spaces, International Journal of Geographical Information Science, DOI: 10.1080/13658816.2016.1207775
6. Behnam Atazadeh, Mohsen Kalantari, Abbas Rajabifard (2016). Comparing Three Types of BIM-based Models for Managing 3D Ownership Interests in Multi-level Buildings, 5th International FIG Workshop on 3D Cadastres, 18-20 October 2016, Athens, Greece.
7. R Jin, C Hancock, L Tang, C Chen, D Wanatowski, L Yang, Empirical Study of BIM Implementation–Based Perceptions among Chinese Practitioners, Journal of Management in Engineering 33 (5), 04017025, 2017
8. R Jin, L Tang, C Hancock, L Allan, BIM-based Multidisciplinary Building Design Practice-A Case Study, 7th International Conference on Energy and Environment of Residential Buildings
9. Rahman, R. A., Alsafouri, S., Tang, P., Ayer, S. K. (2016) "Building Information Modeling Skills for Career Success." Academic Interoperability Coalition (AIC) 10th BIM Academic Symposium & Job Task Analysis Review, Gainesville, FL, USA, 4 – 5 April 2016.
10. Rahman, R. A., Alsafouri, S., Tang, P., Ayer, S. K. (2016) "Comprehending Building Information Modeling Skills of Project Managers based on Social Media Analysis." International Conference on Sustainable Design, Engineering and Construction, Tempe, AZ, USA, 18 – 20 May 2016
11. Mahmoudabadi, H., Olsen, M.J., & Todorovic, S., (2016). "Efficient point cloud segmentation utilizing computer vision algorithms." *Journal of Photogrammetry and Remote Sensing*, 119C, 135-150, doi: 10.1016/j.isprsjprs.2016.05.015
12. Roe, G.V., O'Banion, M.S., and Olsen, M.J. (2016). "Mobile Lidar Guidelines to Support Utility Asset Management Along Highways," Proc. UESI Pipelines Conference, 2016, Kansas City, Missouri.
13. Alomari, K., Gambatese, J., & Olsen, M.J. (2016). "The role of BIM and 3D laser scanning on jobsites from the perspective of construction project management personnel." Construction Research Congress, 2016, Puerto Rico.
14. Guo F., Jahren C.T., Turkan Y., Jeong D. (2016), Civil Integrated Management: An Emerging Paradigm for Civil Infrastructure Project Delivery and Management, ASCE Journal of Management in Engineering, 04016044.
15. Puri N., Turkan Y. (2016), Fusing 4D BIM and 3D Point Clouds for Dimensional Quality Control of Precast Concrete Slabs and Walls, Proc. of the 16th International Conference on Construction Applications of Virtual Reality (CONVR), Hong Kong.
16. Son H., Kim C., Turkan Y. (2015), Scan-to-BIM – An Overview of Current State of the Art and a Look Ahead, Proc. of 32nd International Symposium on Automation and Robotics in Construction (ISARC), Oulu, Finland.
17. Tang, P., Chen, G., Shen, Z., and Ganapathy, R. (2015). "A Spatial-Context-Based Approach for Automated Spatial Change Analysis of Piece-Wise Linear Building Elements." Computer-Aided Civil and Infrastructure Engineering, in press, DOI: 10.1111/mice.12174.
18. Alsafouri, S., Ayer, S., and Tang, P. (2015). "Mobile VDC Adoption in Practice." The 15th International Conference on Construction Applications of Virtual Reality (CONVR), October 5-7, 2015, Banff, Alberta, Canada.
19. Craig Hancock Llewellyn TangRuoyu Jin, H De Light, Luke Allan, (2016). Building Information Management and Modelling Teaching in Geospatial Engineering, Civil Engineering and Architecture, FIG Working Week 2016
20. Tashakkori, H., Rajabifard, A., Kalantari, M. (2015). A new 3D indoor/outdoor spatial model for indoor emergency response facilitation, Journal of Building and Environment Building and Environment, V. 89, pp 170-182
21. Sabri, S., Pettit, C. J., Kalantari, M., Rajabifard, A., Lade, O., & Ngo, T. (2015). What are Essential requirements in Planning for Future Cities using Open Data Infrastructures and 3D Data Models? 14th International Conference on Computers in Urban Planning and Urban Management, Boston, MA, July 2015, 314.1-314.17

Sub-commission 4.3: Atmosphere Remote Sensing

Chair: *Michael Schmidt (Germany)*
Vice Chair: *Jaroslaw Bosy (Poland)*
Secretary: *Mahmut O. Karslioglu (Turkey)*

Overview

The SC 4.3 is composed of one Study Group and nine Working Groups. Besides, several SC 4.3 members participate in other IAG Joint Study Groups (JSG) related to atmosphere remote sensing, for instance, the IAG-ICCT JSG 0.20: “Space weather and ionosphere” chaired by Klaus Börger (Germany) and the IAG JSG 1.3: “Troposphere Ties” chaired by Robert Heinkelmann (Germany).

The most important meeting of the SC 4.3 chairs and vice chairs within the reporting period 2015 - 2017 took place on Monday, September 5th, 2016, during at IAG Commission 4 Symposium, at the Wroclaw University of Environmental and Life Sciences. Further SC 4.3 meetings happened during the SGI Workshops at the Technical University of Berlin in 2015 and 2016. Many splinter meetings of the Study and Working Groups took place, for instance, during the European Geosciences Union General Assemblies (EGU-GA) held in Vienna, Austria, in the years 2016 to 2019. In addition, members of the SC 4.3 organized and chaired several sessions within these and other conferences and symposia.

Concerning the SC 4.3 topic “Space Weather” a new Focus Area (FA) was accepted by the GGOS Coordinating Board Meeting on April 22nd, 2017 in Vienna and installed in the GGOS structure. This FA is titled “Geodetic Space Weather Research” and is chaired by Michael Schmidt and Klaus Börger as the vice-chair. Information about the defined objectives of the FA and the work already performed in the period 2015-2019 will be presented in the GGOS part of this Final Report.

On the next pages the different (Joint) Study and Working Groups of the SC 4.3 give an overview about their work within the last four years, i.e. the reporting period 2015 to 2019.

Study Groups of Sub-commission 4.3: Atmosphere Remote Sensing

SG 4.3.1: Ionospheric and Atmospheric Coupling Processes and Phenomena: Modeling and Measurements

Chair: Lucie Rolland (France)
Vice Chair: Attila Komjathi (USA)

The Study Group was closed in Summer 2017

Working Groups of Sub-commission 4.3: Atmosphere Remote Sensing

WG 4.3.1: Real-time Ionosphere Monitoring

Chair: Alberto Garcia-Rigo (Spain)
Vice Chair: David Roma Dollase (Spain)

Members

Manuel Hernández-Pajares (Spain), Zishen Li (China), Ningbo Wang (China), Michael Terkildsen (Australia), German Olivares (Australia), Reza Ghoddousi-Fard (Canada), Eren Erdogan (Germany), Denise Dettmering (Germany), Haris Haralambous (Cyprus), Yannick Béniguel (France), Jens Berdermann (Germany), Martin Kriegel (Germany), Anna Krypiak Gregorczyk (Poland), Tamara Gulyaeva (Russia), Attila Komjathy (USA), Panagiotis Vergados (USA), Joachim Feltens (Germany), René Zandbergen (Germany), Tim Fuller-Rowell (USA), David Altadill (Spain), Estefania Blanch (Spain), Nicolas Bergeot (France), Jean-Marie Chevalier (France), Andrzej Krankowski (Poland), Loukis Agrotis (Germany), Ivan Galkin (USA), Raul Orus-Perez (The Netherlands)

Activities and publications during the period 2015-2019

The activities conducted in 2015-2019 within the International Association of Geodesy's Real Time Ionosphere Monitoring Working Group (IAG's RTIM-WG - Sub-Commission 4.3 Atmosphere Remote Sensing), have included multiple research lines/collaborations. In particular, the following ones have implied the collaboration of multiple entities within RTIM-WG or are recent analysis by its members relevant to RTIM-WG:

(1) RT combination/validation of Global Ionospheric Maps (GIMs) from UPC, CAS and CNES (RTCM message 1264)

A study, definition, implementation and continuous operation of a first version of the real-time combination of Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC) has been conducted in the context of the International GNSS Service (IGS).

Labelled as IRTG, it is being obtained by computing, each 20 minutes, a new global weight for each one of the three independent RT-GIMs: from CAS (CAS05), CNES (CLK91) and UPC (URTG). The weights are given by the inverse of the squared RMS of the dSTEC error, taking as reference observation the first one of each given phase-continuous-transmitter-receiver arc during the last hour with elevation higher than 10º, and with a difference of at least 25º with the first one, and a minimum of 50 obs. per arc. The results in Fig. 3.1.1 on dSTEC RMS of common worldwide receivers in the first Real-Time operative implementation, show that RT runs CLK91 and URTG show similar results, slightly better than CAS05, similarly to the external assessment with JASON3.

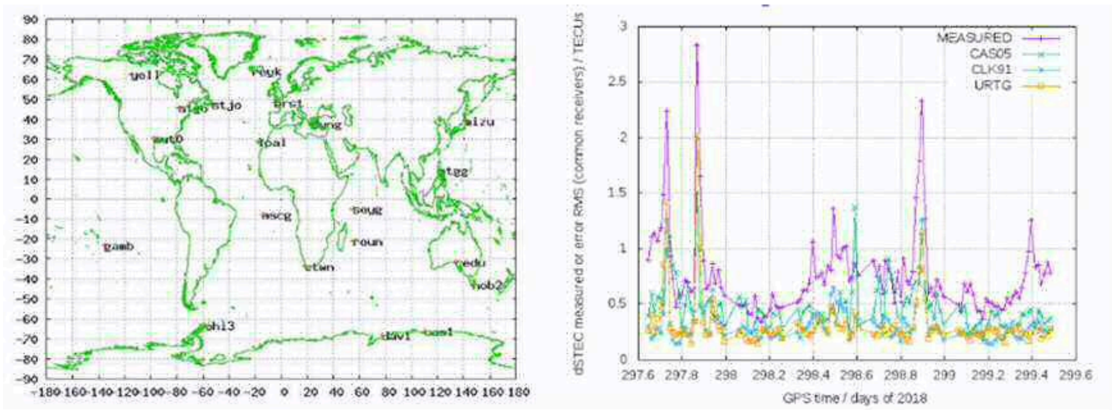

Fig. 3.1.1: Common worldwide receivers and first RT dSTEC assessment

The performance of the first RT combinations against external VTEC obtained from altimeter JASON-3. In this context, the RT combined GIM is performing slightly better (2.85 TECUs St.Dev. vs JASON3 VTEC) than the three RT-GIMs, and only 0.6 TECU worse than the rapid UQRG GIM. The weights, derived from the normalized inverse of the dSTEC RMS over the same measurements of the common receivers (global time-varying weight for each RT-GIM), each 20 minutes, are shown in Fig. 3.1.2. CLK91 shows typically a similar weight than URTG during these very first common RT results.

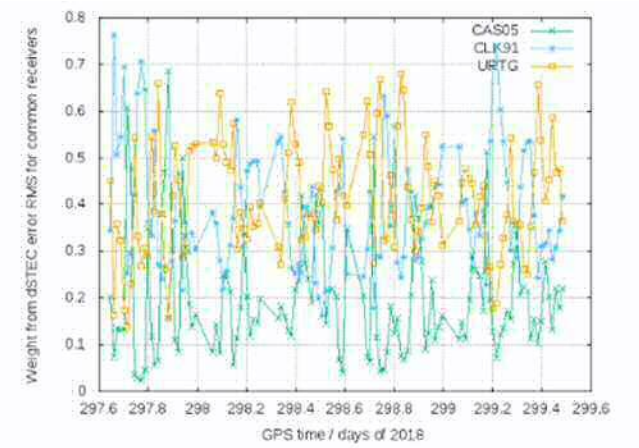

Fig. 3.1.2: RT-GIM weights in the first RT operational implementation

At the moment, a first combination of RT GIMs (IRTG) is continuously and consistently working at UPC facilities. As for the future, the potential performance improvement after adding a geographical variability in the weight, including the spectral domain, can be studied. Also note that NRCan is also interested in joining this IRTG combined product.

(2) Analysis of St. Patrick's Day 2015 storm from complementary ionospheric RT/NRT parameters

Results on the RT/NRT products for the days surrounding St. Patrick storm (doy 76, 2015) were merged considering different approaches within the RTIM-WG to have a global overview of the impact on ionosphere. Additional data (also in post-processing) were also added for further analysis. As shown in next figures, the following products provided by RTIM-WG members were considered: Geomagnetic indices (Kp, Dst, SYM-H), Global Electron Content from UQRG GIMs, global Vertical TEC maps from DGFI-TUM, UPC-IonSAT and regional ones from ROB, IRI-based RT Assimilative Modeling (IRTAM’s foF2, hmF2, B0 from University of Massachusetts Lowell, W-index from IZMIRAN, Global RT ROTI from UPC-IonSAT, Scintillations from IEEA, among others. Some of the corresponding figures can be found below (also refer to Garcia-Rigo et al. 2017) (Figs. 3.1.3 to 3.1.8)

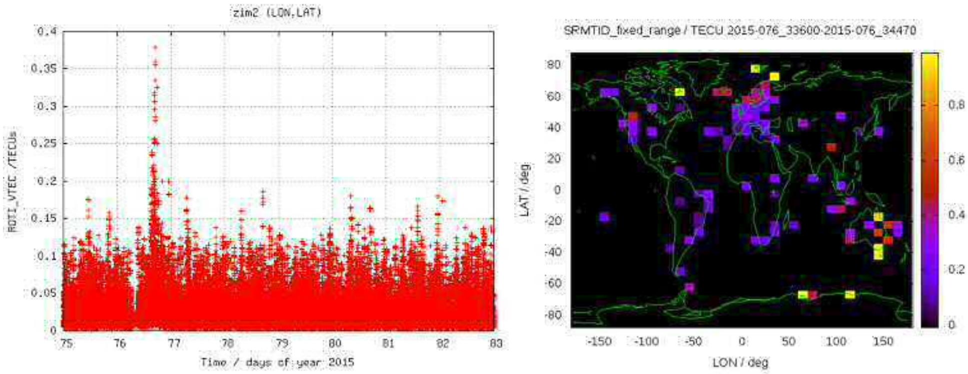

Fig. 3.1.3: UPC-IonSAT's RT ROTI for ZIM2 receiver on days surrounding St. Patrick storm ; SRMTID RT index on Medium Travelling Ionospheric Disturbances

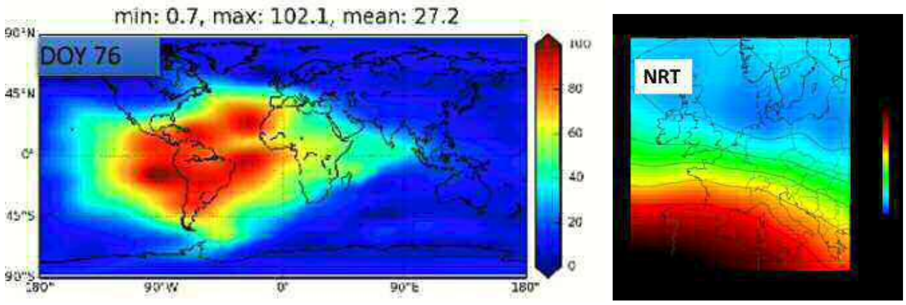

Fig. 3.1.4: DGFI-TUM's VTEC global Map on DOY 76, 2017, around 18h00 (on the left) and ROB's 15-min VTEC RT maps from EUREF Network (on the right).

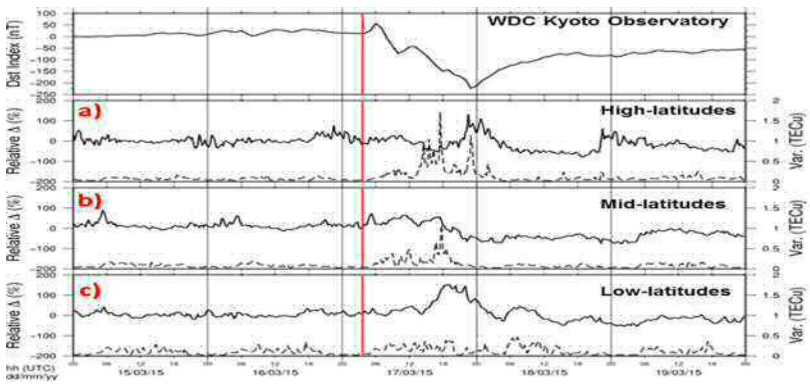

Fig. 3.1.5: ROB's relative VTEC (wrt 15 previous days mean) and Variability in TECUs for European Latitudes close to 35, 50 and 60 degrees (labelled a), b) and c)). March 17, 2015 storm onset is highlighted in red.

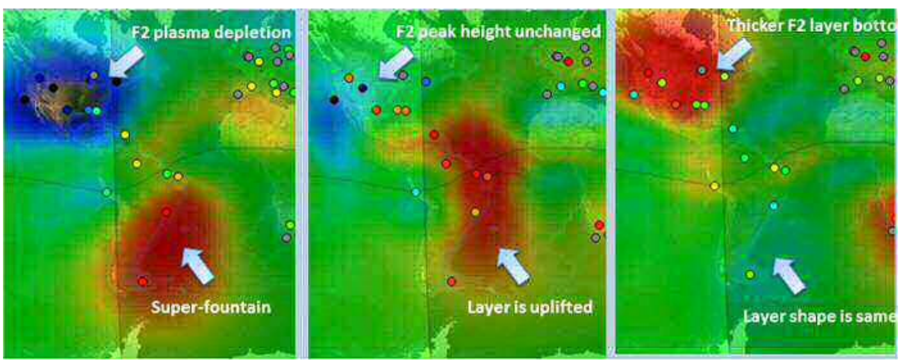

Fig. 3.1.6: Univ. Massachusetts Lowell's IRTAM - IRI-based RT Assimilative Modeling based on GIRO (Global Iono. Radio Obs.) + IRI + NECTAR assimilative algorithm. Global nowcasting at 15 min. time resolution.

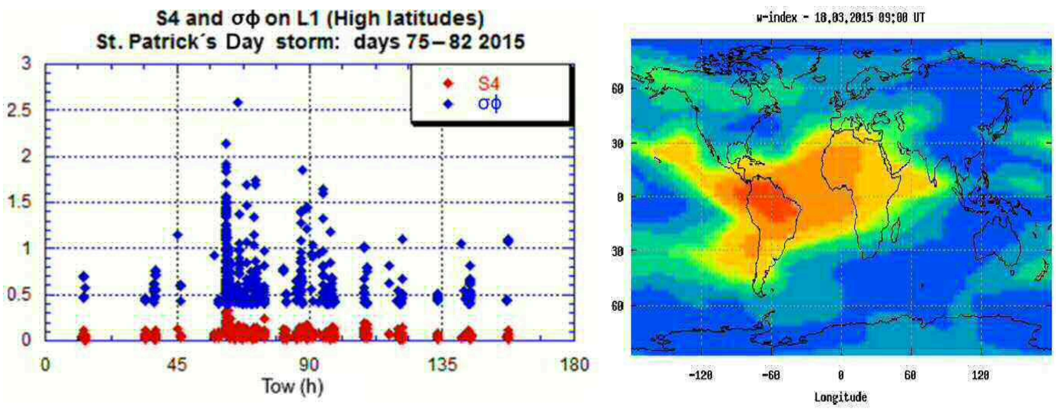

Fig. 3.1.7: IEEA's Scintillations at Sodankylä (left plot) IZMIRAN's Global maps of W-index based on JPL GIMs.

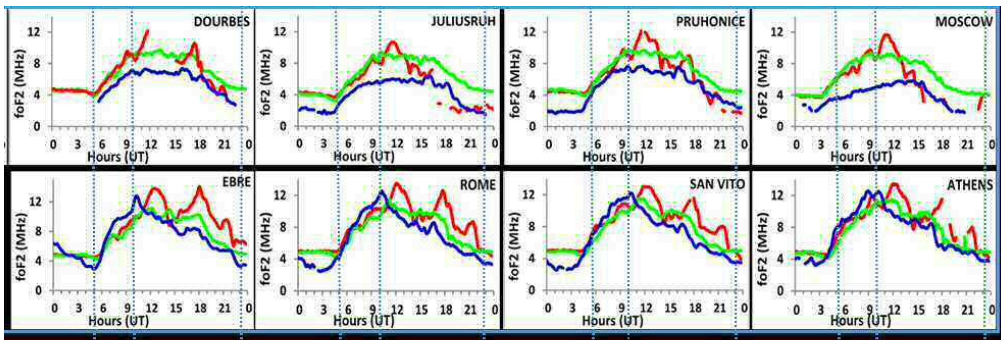

Fig. 3.1.8: Frederick University Cyprus. Digisonde measurements obtained in Europe between 75-77, 2017

(3) Comparison of the performance of six different RT/NRT Global VTEC products in IONEX format

Three RT GIMs from CAS (aoeg), CNES (cnsg) and UPC (urtg); one NRT from DGFI-TUM and two traditional GIMs for reference, from UPC (UQRG) and IGS (IGSG) have been considered. Their performance has been assessed against JASON altimeter VTEC data and GNSS dSTEC test. Results are summarized below in Fig. 3.1.9 and Table 3.1.1 for the period between day of year 45 to 59 in 2016

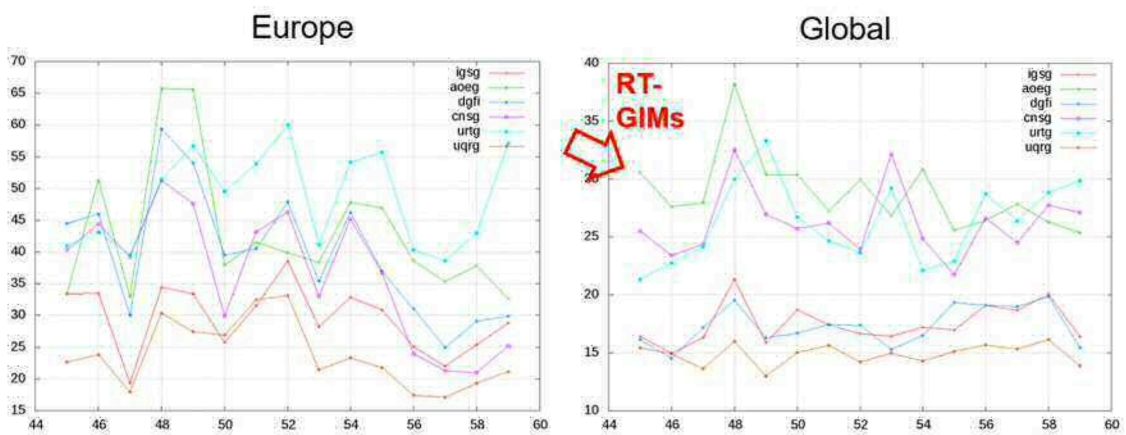

Fig. 3.1.9: Relative RMS error (%) for days of year 2016 from 45 to 59

Table 3.1.1: From left to right: GIM, square root of the arithmetic mean of the RMS for all stations and days; maximum and minimum RMS for all 35 stations; bias for all stations and days.

	GIM	RMS [TECU]	RMS max [TECU]	RMS min [TECU]	BIAS [TECU]
RT-GIMs	AOEG	11.8	22.6	4.8	-1.43
	CNSG	9.2	18.8	3.0	0.21
	URTG	8.2	14.9	3.4	0.30
	DGFI	5.6	10.8	1.8	-0.57
	IGSG	6.2	11.6	1.9	-1.01
	UQRG	4.6	9.1	1.1	-0.61

CAS members have also validated their RT maps by means of GPS dSTEC assessment and JASON-3 altimeter data for the period 08/2017 till 12/2018. As shown in next Fig. 3.1.10 Bias and Std of the differences between RT/final GIMs and GPS dSTECs and JASON VTEC, respectively, have been plotted.

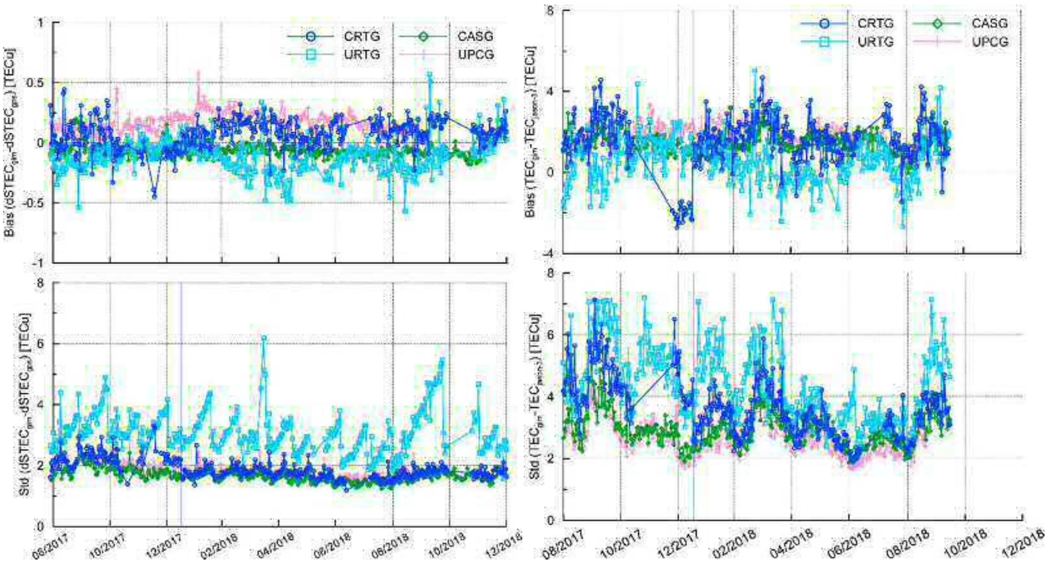

Fig. 3.1.10: Assessment of CAS RT maps by means of GPS dSTEC (left) and JASON3 VTEC (right).

DGFI-TUM's members have also performed evaluations of their new Near Real-Time GIMs (labelled DFRG) based on both dSTEC analysis and Jason-2 altimeter data for test period: 1-28 March 2015. Regarding dSTEC analysis, the following statistical measures have been obtained by DGFI-TUM: the average mean values, the average standard deviations and the average RMS deviations are presented for each of the stations and analysis centres covering the entire test period. In conclusion, DGFI-TUM product DFRG and UPC product UQRG show the smallest RMS errors in terms of dSTEC analysis.

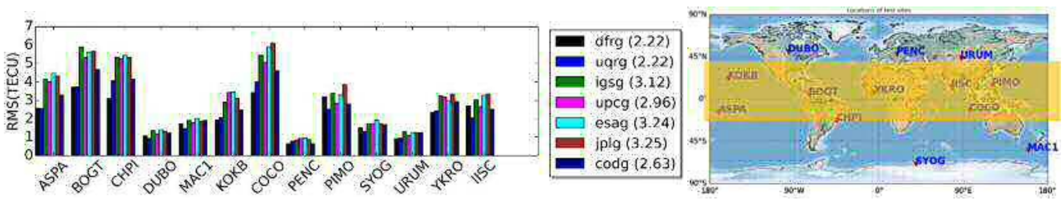

Fig. 3.1.11: Low-latitude dSTEC analysis, only for the highlighted test stations on the right-hand map (instead of all, as in the above plots)

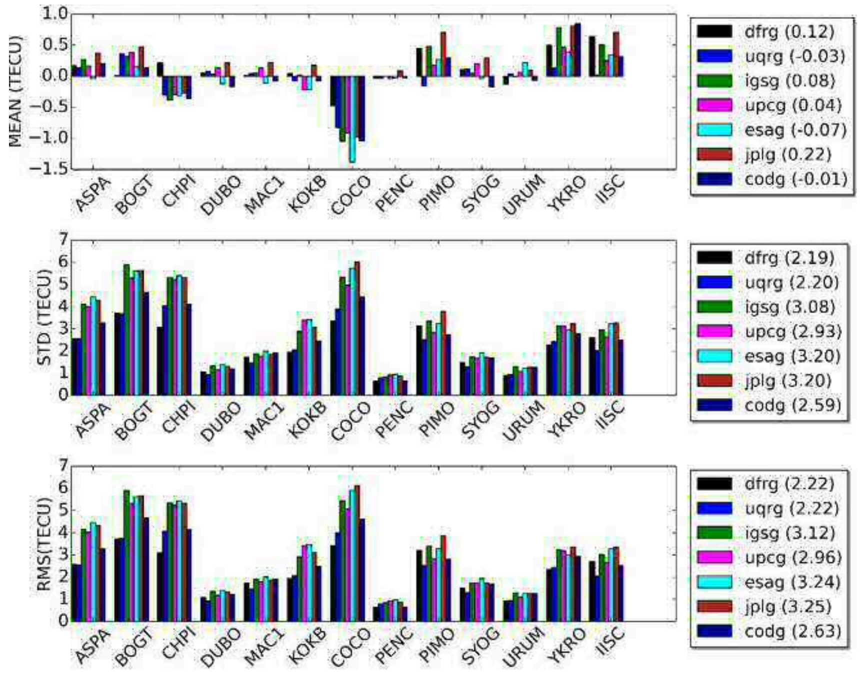

Fig. 3.1.12: World-wide dSTEC analysis. The average mean values, the average standard deviations and the average RMS deviations are presented for each of the stations and analysis centres covering the entire test period. The values in parentheses on the legend show overall average values computed from all the receivers

Regarding JASON analysis, comparing with altimeter VTEC reveals that the UPC product UQRG has the smallest RMS deviation compared to VTEC values derived from Jason-2 and DGFI-TUM product DFRG shows a very close agreement to the UPC product.

(4) A new methodology has been implemented by Observatori de l'Ebre to detect Large Scale Travelling Ionospheric Disturbances (LSTIDs) for monostatic measurements of a network of HF sensors, using NRT data from Digisondes within Europe and South Africa

The method (HF Interferometry) detects quasi-periodic oscillations of ionospheric characteristics, identifies coherent oscillation activity at different measuring sites of the network and sets bounds to time intervals for which such activity occurs into a given region. It provides the dominant period of oscillation and amplitude and the vector velocity of propagation of the LSTID. The HF Interferometry method uses near real time data from the Digisonde sites within

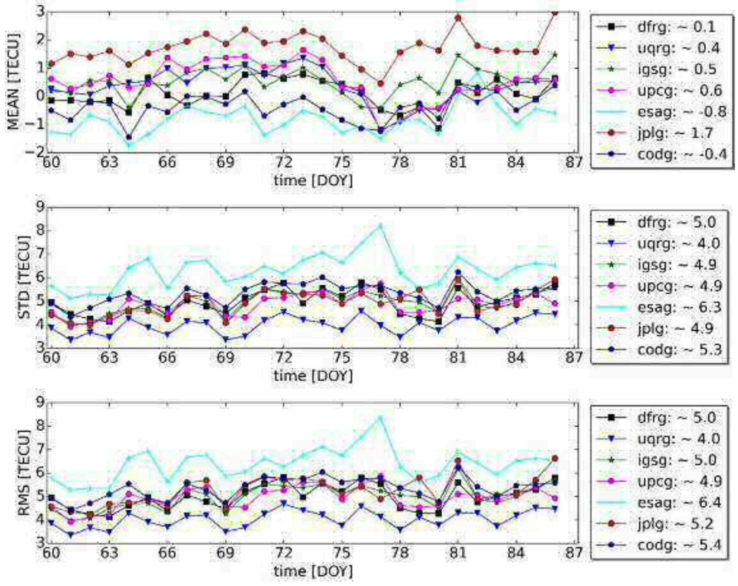

Fig. 3.1.13: JASON analysis based on the following statistical measures: the daily mean values (top), the daily standard deviations (middle) and the daily RMS deviations (bottom) are presented for each analysis centres covering the entire test period. The values in the parentheses show the average values for the measures

Europe and South Africa and it allows the identification of LSTIDs which are associated with auroral and geomagnetic activity, directly related to Space Weather. This method is running in near real time from the TechTIDE project website http://techtide.space.noa.gr/?page_id=3766 since 16th April 2019. Since then, the methodology has detected several periods of activity. As an example, we show you the TID activity that was detected during the night of 23-24 April 2019. Although no significant auroral activity was detected and kp index reached values of 3, a clear TID of auroral origin was detected.

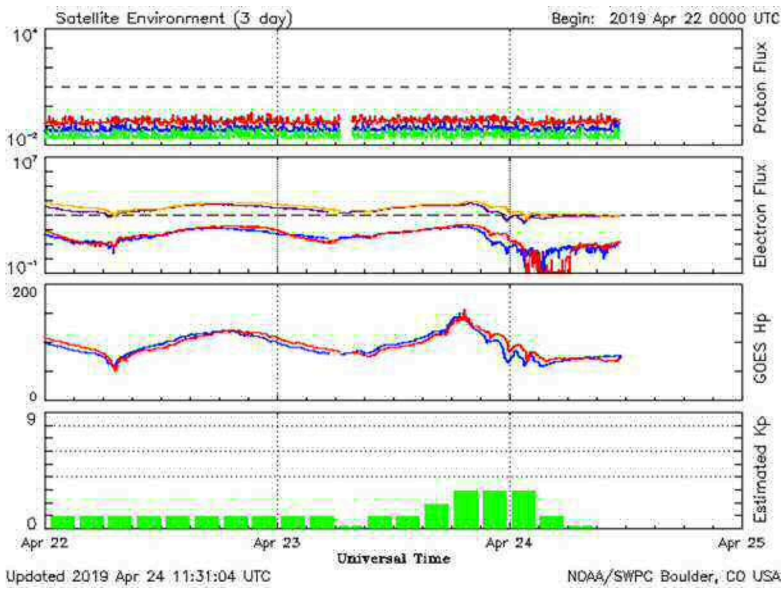

Fig. 3.1.14: TID activity beginning at April 22, 2019.

The next Figure shows the velocity, azimuth, period and spectral contribution of the perturbation for 24 April 2019 over Ebro station. EB040_20190423.png is a similar figure for 23 April. The methodology detected a perturbation that started at about 22:00 UT on 23 April and ended at 4:00 UT on 24 April. From the figures we can see that it propagates at about 600m/s with an azimuth of 180° with a period of about 110 min.

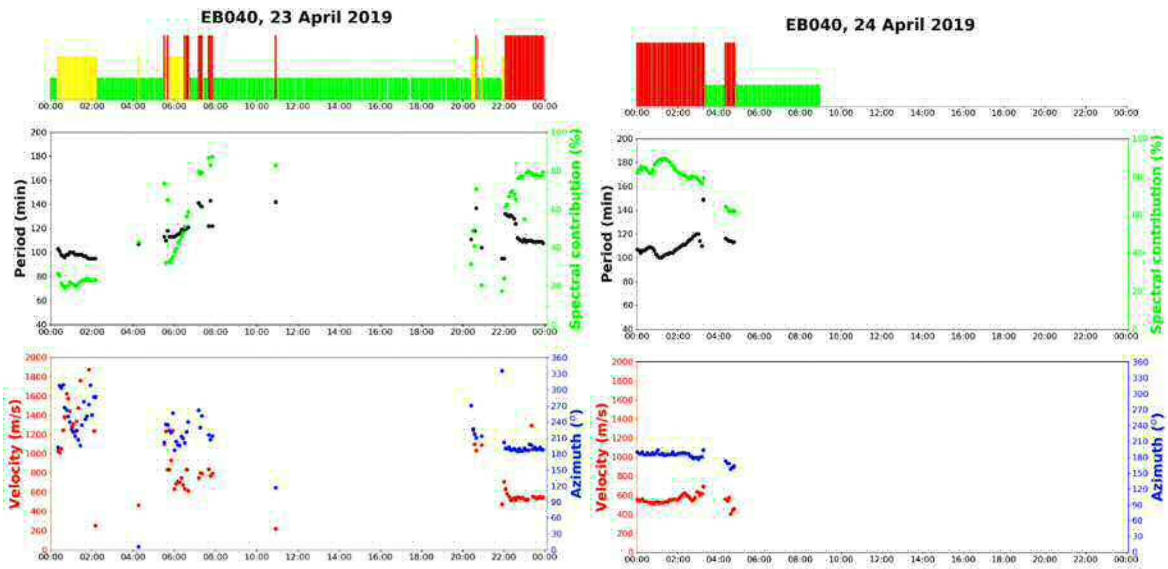

Fig. 3.1.15: Velocity, azimuth, period and spectral contribution of the perturbation for 24 April 2019 over Ebro station

(5) CAS's RT Ionospheric irregularity monitoring and the new ROT change index (RROT)

For ionospheric irregularity monitoring, ROTI (Rate Of ionospheric TEC change Index), AART (along arc vertical TEC rate) and SRTI (Single Receiver TID Index) are employed to characterize the irregularity degree of the ionosphere. Additionally, a new ionospheric activity indicator, rate of ROT change index (RROT), was proposed based on the single-differenced rate of ionospheric TEC change (ROT). The ionospheric activity indicators ROTI, AART, SRTI and RROT can be easily computed from dual-frequency GNSS signals (like GPS L1 and L2 carrier phase measurements) in real-time mode. In our analysis, AART and SRTI indicators are used to generate the station-based ionospheric irregularity monitoring products, while ROTI and RROT indicators are preferred to reconstruct global maps with a temporal resolution of 15 minutes and a spatial resolution of 5 and 2.5 degrees in longitude and latitude, respectively, and regional maps with high spatial resolution (2x2 degrees) for European, Australia and North American regions. These maps are currently provided in an IONEX-like format, and freely downloadable from CAS ftp (ftp://ftp.gipp.org.cn/product/).

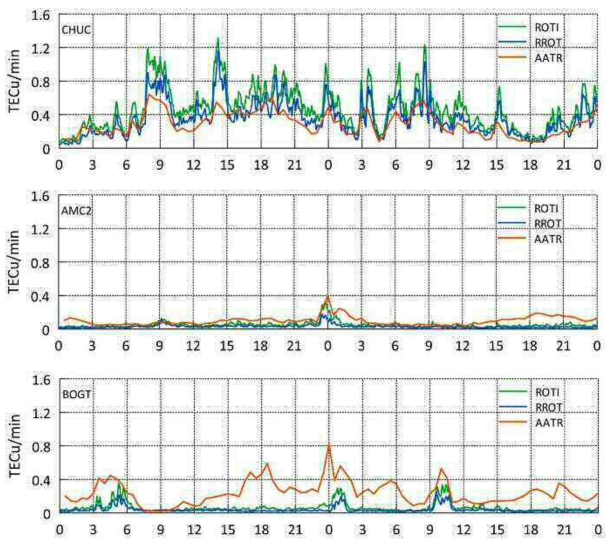

Fig. 3.1.16: Comparison of ROTI, RROT and AATR at high (CHUC), middle (AMC2) and low (BOGT) latitude stations (March 17-18, 2015)

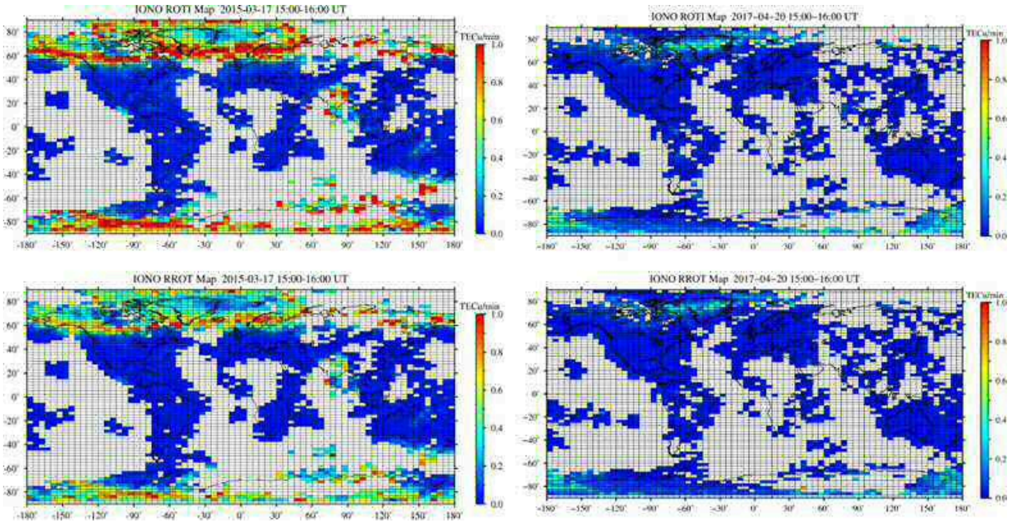

Fig. 3.1.17: Global ROTI and RROT maps on 2015-3-17 (stormy day) and 2017-4-20 (quiet day)

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WG 4.3.2: Ionosphere Predictions

Chair: *Mainul Hoque (Germany)*
Vice Chair: *Eren Erdogan (Germany)*

Members

Claudia Borries (Germany), Nada Ellahony (Egypt), Adria Rovira Garcia (Spain), Abraham Stern (USA), Mahdi Alizadeh (Iran), Marta Cueto Santamaría (Spain), Aliaa Abd-Elnasser (Egypt), Alberto Garcia-Rigo (Spain), Manuel Hernandez Pajares (Spain), Norbert Jakowski (Germany), Jens Berdermann (Germany), Michael Schmidt (Germany), Enric Monte (Spain), Lung-Chih (Taiwan, China), Wijaya Dudy (Indonesia)

Activities and publications during the period 2015-2019

To realize the WG 4.3.2 objectives and goals, group members accomplished individual activities as well as worked in cooperation with other group members. The work done during the period 2015-2019 is briefly described below.

Comparison among different TEC prediction approaches:

As an initiative from the working group WG 4.3.2, Hoque et al. (2017a), Erdogan et al (2018), Hoque et al. (2019c) compared total electron content (TEC) prediction approaches/results from different centers contributing to this WG 4.3.2 such as German Aerospace Center (DLR), Universitat Politècnica de Catalunya (UPC), Technische Universität München (TUM) and GMV (see Table 3.2.1).

Table 3.2.1: Comparison among different TEC prediction approaches (reprinted from Hoque et al. 2017a)

Center	TEC	TEC prediction approach	TEC prediction performance
DLR	NTCM	model-assisted (27-day median) TEC forecast algorithm taking benefit from actual trends of the TEC behavior at each grid point	over Europe,1 hour forecast, RMS error is below 4 and 5 TECU during quiet (20 May – 3 Jun 2015) and perturbed period (12-26 Mar 2015), respectively
UPC	TOMION	linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain	global, up to 48-hour forecast, RMS discrepancy of U2PG wrt IGSG below 6 and 8 TECU during quiet & perturbed period, resp., considering JASON2 data as reference
DGFI-TUM	B-splines	Fourier series analysis of the B-spline coefficients using the last 5 days data sets	global, RMS deviations of the forecasted maps with respect to IGS final products exhibit around 5 and 7 TECU for the quiet and perturbed periods, respectively
GMV	--	ionospheric delay estimated from previous epochs using GNSS data and the main dependence of ionospheric delays on solar and magnetic conditions	over Europe, 0.5 hour forecast, RMS error below 3 TECU and over Latin American & Africa, 0.5 & 1 hour forecast, RMS error below 8 TECU

The presented work enables the possibility of comparing TEC prediction approaches/results from different centers. Different TEC prediction approaches outlined in the study will certainly help to learn about forecasting ionospheric ionization.

Besides above mentioned work, there are other specific tasks accomplished and published by the group members. These are briefly explained below.

TEC forecasting based on manifold trajectories:

The group members working at UPC-IonSAT developed a forecast method taking into account the possible deformations of the post-processed and real-time vertical Total Electron Content (VTEC) Global Ionospheric Maps, as trajectories on a tangent space. The origin of the method comes from the fact that most of the forecast error of former techniques (see García-Rigo et al., 2011) is concentrated on the borders of the most ionized regions of the maps, such as it is shown in Fig. 3.2.1.

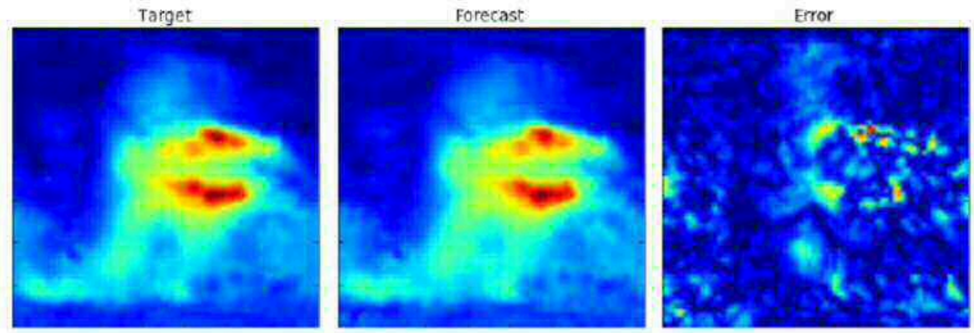
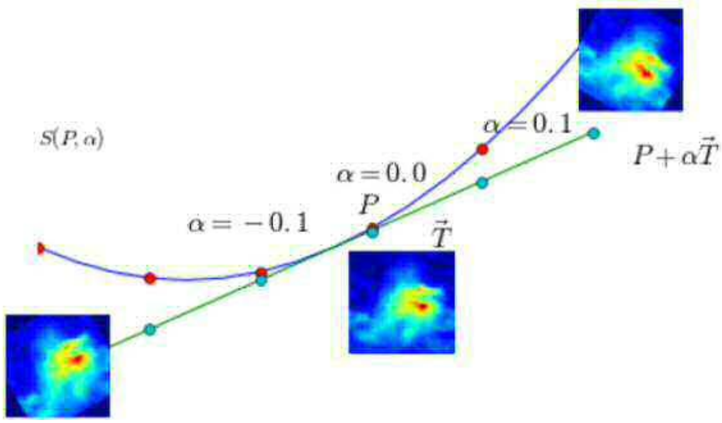


Figure 3.2.1: Target TEC map to be forecast (left), the resulting forecast at a horizon of 3 hours (center), and the forecast square error (right), on 2016-01-19 at 10:30:00

Therefore, the modeling of the time evolution of the maps is considered as trajectories in the space of pixels. These trajectories are restraint to be on the surface of manifolds, thus each ionospheric map of NxM pixels is taken as a point in a space R^(NxM), and selected eight local deformations, such as translation, stretching, diagonal deformations etc. These deformations were modeled by a first order Taylor series, i.e. a tangent space, which was used as a linear base that spans the possible points of the time trajectory of the ionospheric maps. Thus, the forecast was done by combining linearly a set of near past VTEC maps in local-time sun-fixed reference frame, along with their tangent maps, in order to create the VTEC forecast map. The method is shown in the diagram of Fig. 3.2.2, where the tangent space corresponds to a slight rotation of the image, along the direction of rotation in the tangent space.

Figure 3.2.2: Tangent space to the Manifold of the map at '2016-01-19 10:30:00



As an example of the deformations in the time trajectory of the maps that are modeled by means of the tangent space as shown in Figs. 3.2.3 and 3.2.4, the cases of scale, translation and hyperbolic deformations.

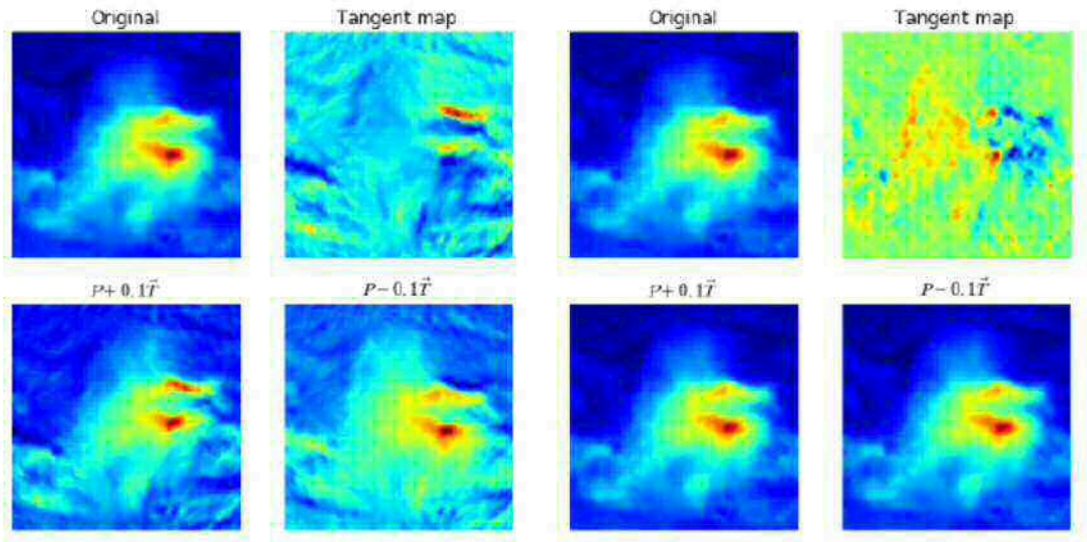


Figure 3.2.3: Scale transform (left group) and Y-translation (right group) at '2016-01-19 0:30:00'

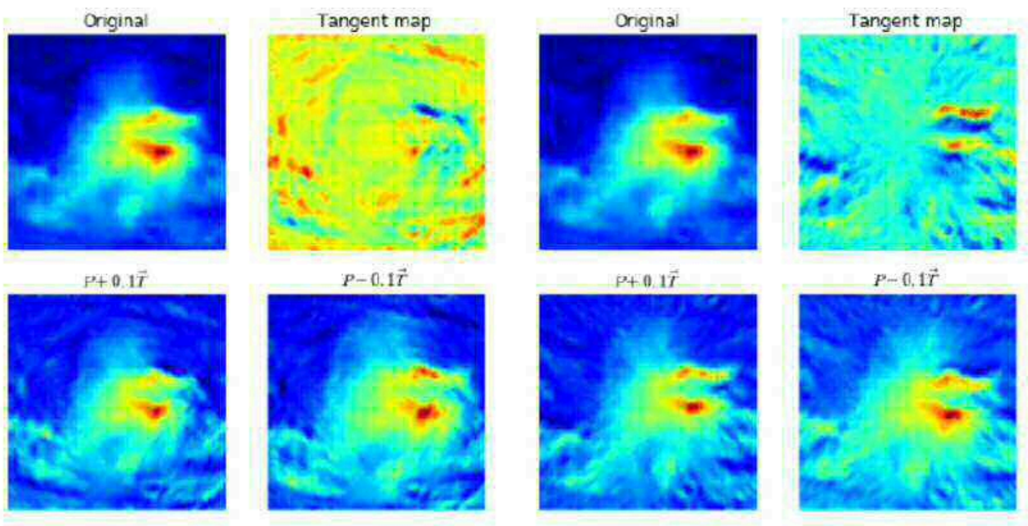


Figure 3.2.4: Diagonal Hyperbolic transform (left group) and Parallel Hyperbolic transform (right group) at '2016-01-19 10:30:00'

The forecast consists of a linear combination of previous maps, along with the corresponding tangent space associated with each map, which is explained in detail in section 4 of Monte-Moreno et al. 2018.

As for the performance in Fig. 3.2.5, the comparison of the time evolution of the TEC RMSE is shown for the case of forecasting, by means of the tangent space method and the case of a persistive (frozen) map as forecast. The performance is shown at 4 time horizons: 30 minutes, 1 hour, 3 hours, and 1 day, during a one-month period.

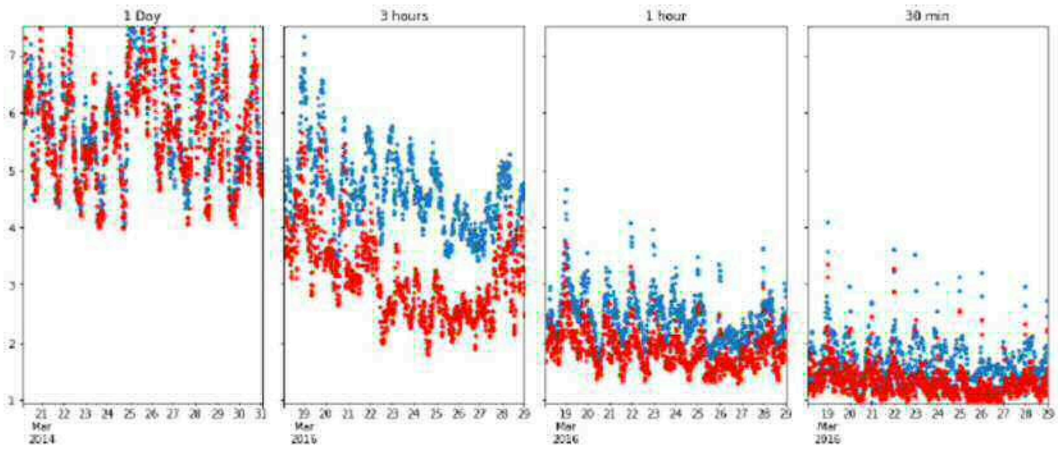


Figure 3.2.5: Time evolution of the TEC RMSE, for the case of forecast with the tangent space method (red), and persistive map method (blue) for different horizons (see annotation on the upper part of the figures)

The relative performance is shown as ratio in the following table:

Horizon	1/2h	1h	2h	3h	6h	24h
Ratio	84.99 %	77.65%	71.35%	69.34 %	87.23 %	95.76%

Where it can be seen that there is an improvement of about a 30% over not performing the forecast. Nevertheless, this hides the fact that most of the forecast errors are concentrated at very specific moments, as it can be seen in Fig. 3.2.5. In this context, a better comparison is shown in the box plots of Fig. 3.2.6.

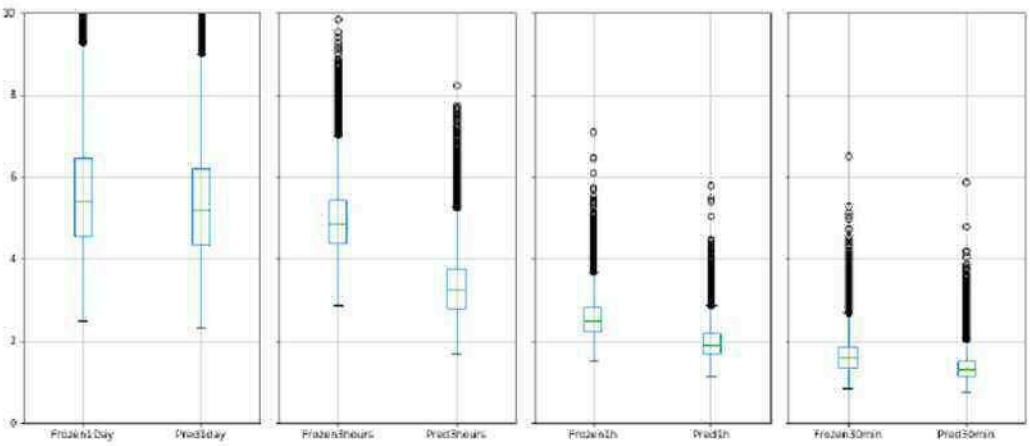


Figure 3.2.6: Box plots of the TEC RMSE, for the case of forecast based on persistive frozen value (left) and the tangent space forecast (right), for each horizon (1 day, 3 hours, 1 hour and 30 minutes, left to right; see the tick labels of each figure)

In Fig. 3.2.7, we show the comparison of both forecasting methods during a whole year for the case of the forecast at a horizon of 3 hours.

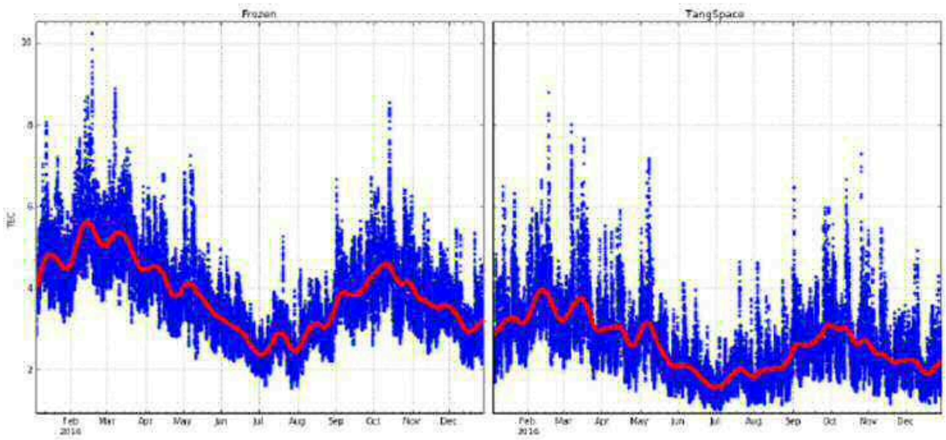


Figure 3.2.7: Time evolution during a whole year of the total RMSE in TECUs for a horizon of 3 hours. Right, the persistive (frozen) forecast, in red the time series low-pass filtered. Left, the forcast by means of the tangent space method.

Ionosphere prediction using B-splines in a Kalman filter:

At DGFI-TUM, the focus for VTEC forecasting is on setting up a harmonic analysis based on Fourier series expansion extended by an Autoregressive Moving Average (ARMA) model as illustrated in Fig. 3.2 8. To be more specific, the VTEC is represented by a series expansion in tensor products of polynomial B-splines $N_{k_1}^{J_1}(\varphi)$ in latitude and trigonometric B-splines $T_{k_2}^{J_2}(\lambda)$ in longitude (Schmidt et al. 2015). The corresponding series coefficients $d_{k_1,k_2}^{J_1,J_2}$ are estimated by Kalman filtering running in near-real time (Erdogan et al. 2017). For the forecasting of the VTEC values the approach is based on the extraction of important signal components by using a Fourier series representation of the BS coefficients. The approach is extended by an ARMA model to take into account the stochastic part. The unknown coefficients a_0, C_i, S_i of the Fourier series and the ARMA model parameters for each BS coefficient are computed at the end of every hour using a time series in a moving window consisting of estimated BS coefficients from the last 5 days. Finally, the extrapolated series coefficients provide the forecasted VTEC values.

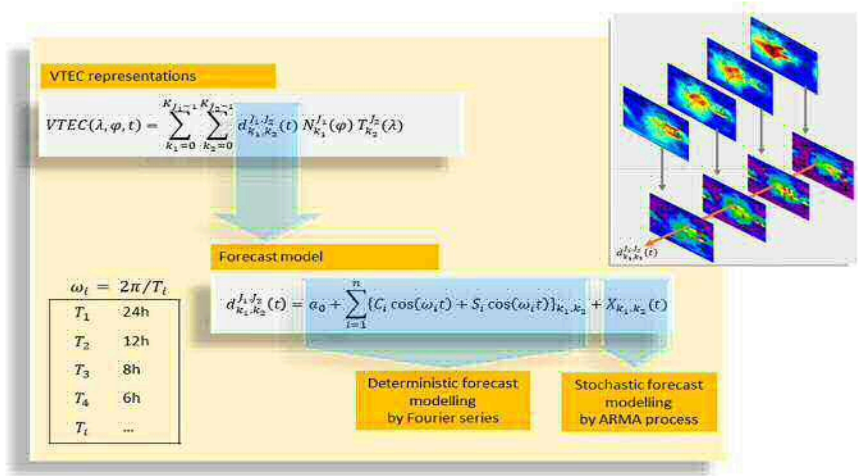


Figure 3.2.8: Overall concept for the forecasting approach at DGFI-TUM

Figure 3.2.9 shows the comparison of performance of the forecasting approaches based on using only Fourier series and Fourier series extended with ARMA model. In the current implementation, effect of ARMA model vanishes after few hours.

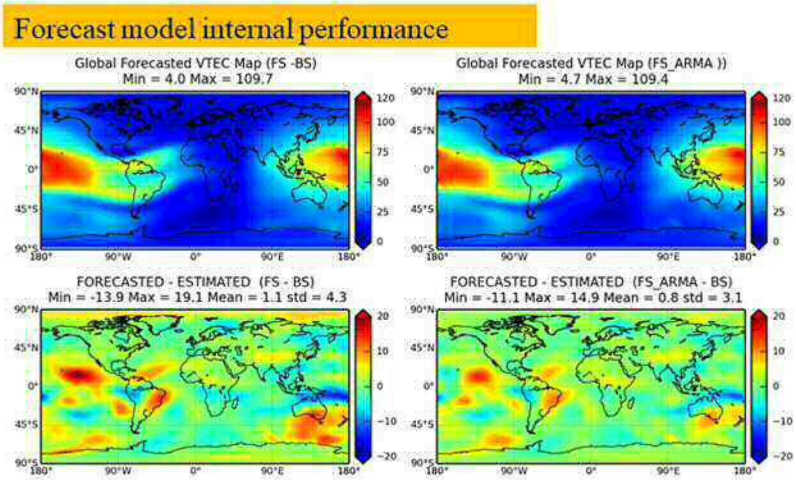


Figure 3.2.9: Two hour ahead performance of the forecast models; left: using Fourier series approach only; right: Fourier series and ARMA model approach.

In addition to provide forecasted VTEC maps for the next days, the approach was recently used to provide a background information to a regional real-time ionosphere modelling study covering the European region (Schmidt et al. 2015). The concept is illustrated in Fig. 3.2.10. The left section of the image shows the steps of the RT modelling supported by the forecast approach and the right section shows the corresponding VTEC maps for each step. The real-time modelling approach attempts to generate VTEC products by updating the forecasted products with GPS data collected in real-time (using RTCM data streams) over European region.

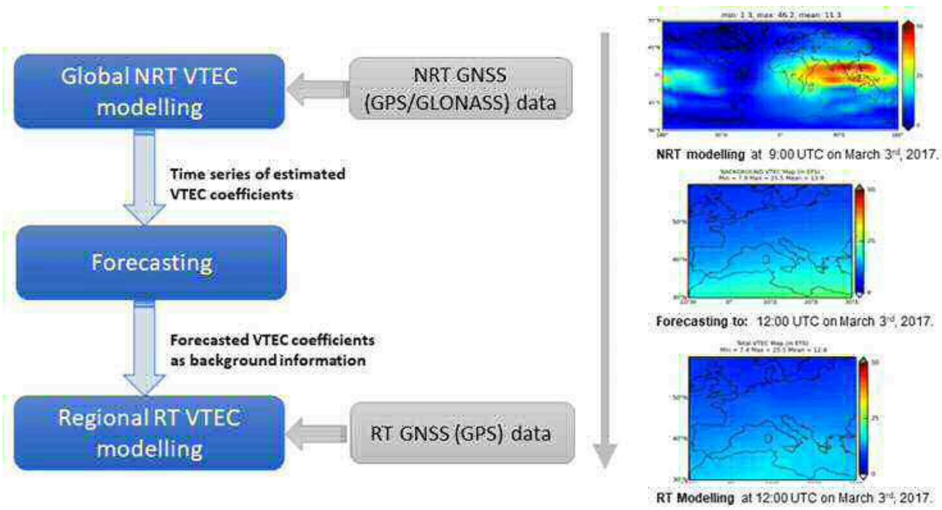


Figure 3.2.10: DGFI-TUM's concept for regional RT modelling supported by the forecast model

TEC prediction at a GPS station

An important characteristic of the GPS constellation is that the same satellite appears in the same part of the sky with a period of approximately 4 minutes less than one day. This brings the same ray path geometry when looking to the same satellite from a location on Earth. Hoque et al. (2016a, b) found that this repetition can be successfully used for predicting TEC along a receiver-satellite link. They proposed a new approach for predicting TEC at a GPS station assuming that looking to a satellite in the same part of the sky from the same location on Earth brings nearly the same geophysical conditions for link related TEC estimation. They found that during quiet ionospheric condition the approach can predict slant TEC at a mid-latitude station with mean and standard deviations from reference values of about 0 and 1.5 TECU (1 TECU = 1.e+16 el/m^2), respectively. During perturbed condition the mean and standard deviations are found as about 0 and 3.9 TECU, respectively. They found that the new approach can successfully predict slant TEC several hours in advance if severe ionospheric storms are excluded. The following Fig. 3.2.11 shows prediction performance at gope and adis stations during quiet and perturbed ionospheric condition.

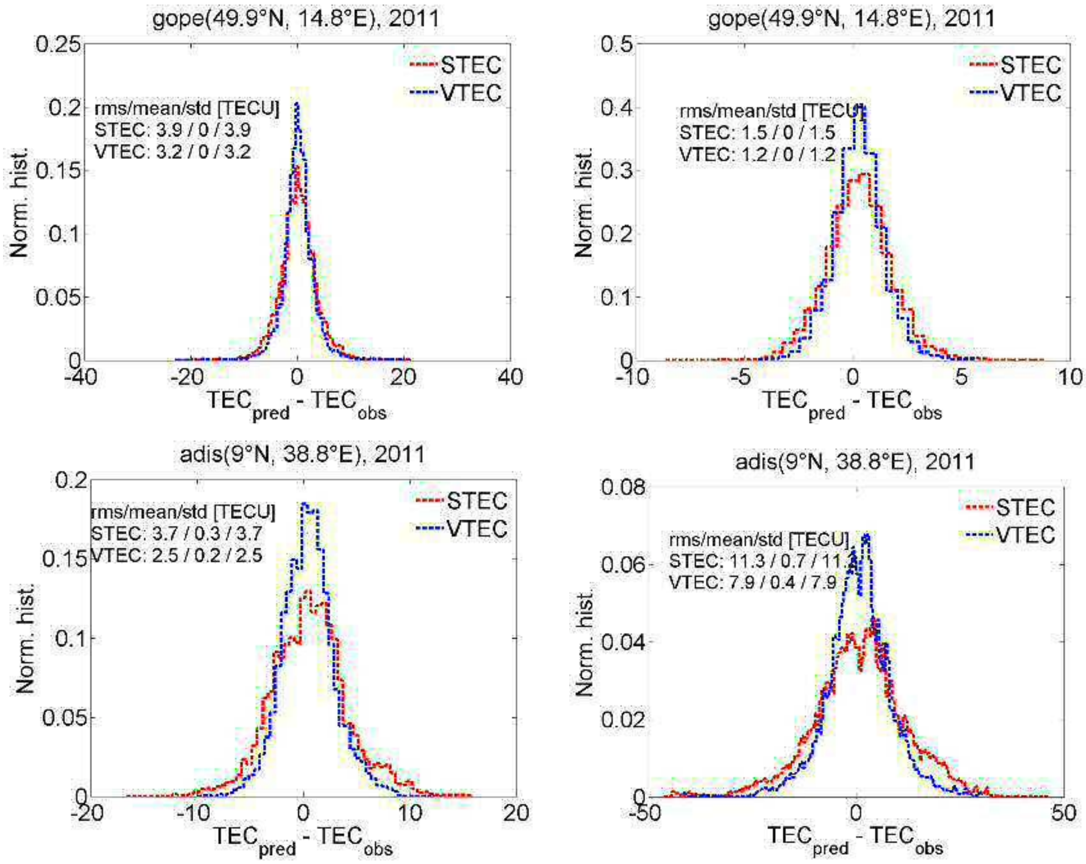


Figure 3.2.11: Prediction performance at gope and adis stations during quiet (left panels) and perturbed ionospheric period (right panels) (reprinted from Hoque et al. 2016b)

TEC prediction during solar eclipse:

Hoque et al. (2016c) investigated the possibility of modelling the TEC response and subsequent prediction during a solar eclipse. GNSS users can benefit from TEC depletion modelling during a solar eclipse. If the TEC depletion can be predicted in advance from such modelling activities, GNSS operators can either improve their broadcast delay/TEC information or inform users about the TEC depletion estimate depending on their location with respect to the eclipse path. Hoque et al. (2016c) found up to 6 TECU depletion in the vertical TEC estimate around the shadow spot which can be 2-3 times higher in slant TEC estimates at low elevation angles, indicating range errors of up to 2 – 3 meter in single frequency GNSS positioning.

Improved TEC prediction model for the modernized GPS

Hoque et al. (2017b, 2018) investigated the possibility of driving Neustrelitz TEC Model (NTCM) by the GPS Klobuchar coefficients. Since Klobuchar model coefficients are estimated based on GNSS TEC data obtained during previous day, it is indeed a prediction model 24 hours ahead. Therefore, NTCM driven by Klobuchar parameter will predict TEC 24 hours ahead. They found that the NTCM driven by Klobuchar model parameters can perform significantly better than the mother Klobuchar model. Using post processed reference total electron content (TEC) data from more than one solar cycle, they found that on average the RMS modelled TEC errors are up to 40% less for the proposed NTCM model compared to the Klobuchar model during high solar activity period, and about 10% less during low solar activity period. Such an approach does not require major technology changes for GPS users rather requires only introducing the NTCM approach a complement to the existing ICA algorithm while maintaining the simplicity of ionospheric range error mitigation with an improved model performance.

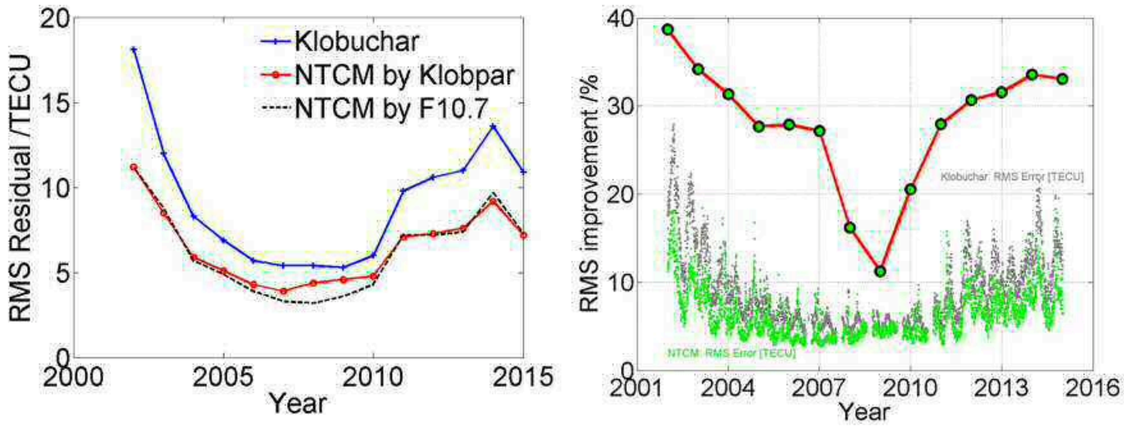


Figure 3.2.12: Left panel shows yearly average of RMS residual and right panel gives percentage improvement whereas daily RMS residuals are shown in the background. The RMS TEC errors for NTCM are up to about 40% and 10% less than the Klobuchar model during high and low solar activity period, respectively (Hoque et al. 2017b)

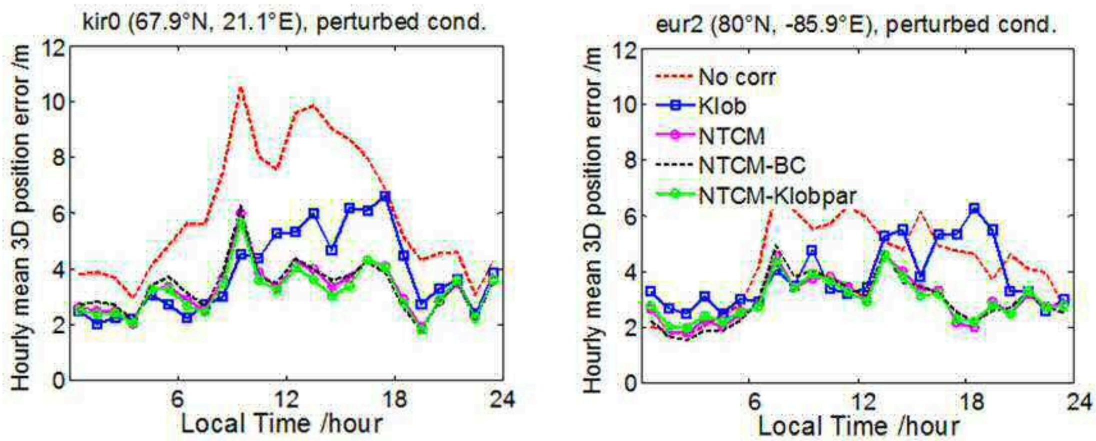


Figure 3.2.13: While estimating positioning accuracy, an improvement in the order of 0.5 m and 1.0 m for unperturbed low solar activity and perturbed medium solar activity conditions, respectively is obtained (Hoque et al. 2018).

Fast and improved TEC prediction model for the Galileo satellite navigation system:

Very recently Hoque et al. (2019a, 2019b) proposed an alternative ionospheric correction approach for single frequency Galileo users. In the proposed approach, the broadcast coefficients are used to drive another ionospheric model called the Neustrelitz Total Electron Content Model (NTCM) instead of the NeQuickG. The proposed NTCM is driven by Galileo broadcast parameters and the investigation shows that it performs better than the NeQuickG when compared with the reference VTEC data. It is found that the RMS and Standard Deviations (STD) of residuals are approx. 1.6 and 1.2 TECU (1 TECU = 10^{16} electrons/m^2) less for the NTCM than the NeQuickG. A comparison with the slant TEC reference data shows that the STD, mean and RMS residuals are approx. 9.5, 0.6, 10.0 TECU for the NeQuickG whereas for the NTCM, they are 9.3, 2.5, 10.1 TECU respectively. A comparison with Jason-2 altimeter datasets reveals that the NTCM performs better than the NeQuickG with RMS/STD deviations of approx. 7.5/7.4 and 8.2/7.9 TECU respectively. The investigation shows that the Galileo broadcast messages can be effectively used for driving the NTCM.

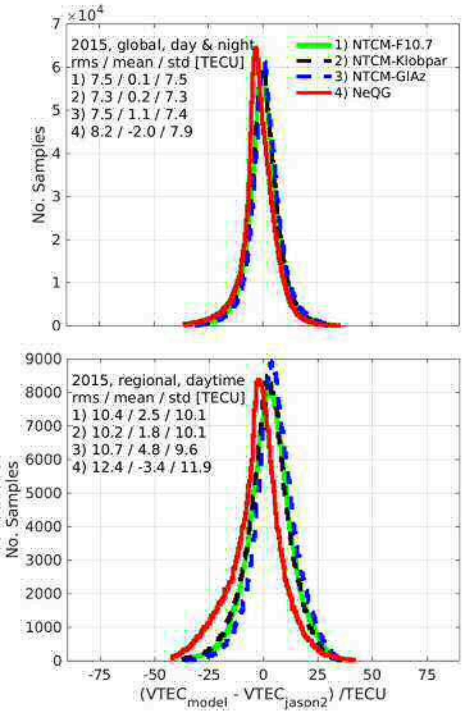


Figure 3.2.14: Histograms of the NeQuickG and NTCM residuals with respect to the reference Jason-2 data showing their performances for global day and nighttime (top panel) and low latitude daytime analysis (bottom panel) (Hoque et al. 2019a**)**.

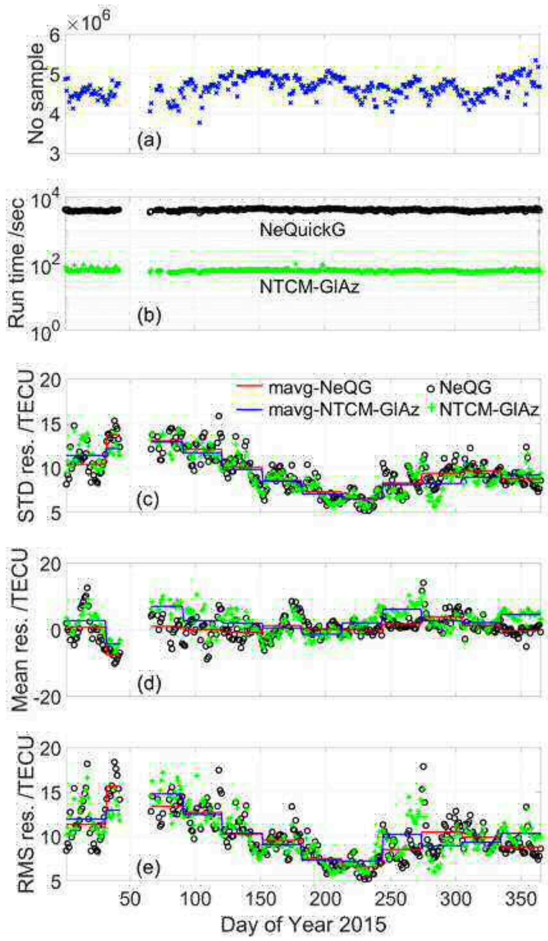


Figure 3.2.15: A performance comparison of NeQuickG and NTCM with global STEC observations. Panels (c), (d), (e) show the daily STD, mean and RMS of STEC residuals, and corresponding monthly average values are plotted in red and blue lines. The number of samples and a comparison of computation time are shown in panels (a) and (b) (Hoque et al. 2019a).

When comparing the computation time it is found that the NTCM is in average 65 times faster than the NeQuickG. This means that the NTCM is very fast running in operational applications and performs well when fed with the Az parameter. The Safety of Life (SoL) applications would certainly benefit from the reduced complexity of the algorithm that greatly facilitates certification for aviation users. The compact NTCM algorithm is also favorable for "standard" users. It is assumed that most mass market and geodetic receiver manufacturers would favor a compact algorithm.

TEC prediction model for future GNSS:

Hoque and Jakowski (2015) and Hoque et al. (2015) proposed an alternative ionospheric correction algorithm called Neustrelitz TEC broadcast model NTCM-BC to be used as an ionosphere prediction model in future global satellite navigation systems. Like the GPS ICA or Galileo NeQuick, the NTCM-BC can be optimized on a daily basis by utilizing GNSS data obtained at the previous day at monitor stations. Their investigation using GPS data of about

200 worldwide ground stations shows that the 24 hour ahead prediction performance of the NTCM-BC is better than the GPS ICA and comparable to the Galileo NeQuick model. They found that the 95 percentiles of the prediction error are about 16.1, 16.1 and 13.4 TECU for the GPS ICA, Galileo NeQuick and NTCM-BC, respectively, during a selected quiet ionospheric period whereas the corresponding numbers are found about 40.5, 28.2 and 26.5 TECU during a selected geomagnetic perturbed period. However, in terms of complexity the NTCM-BC is easier to handle than the Galileo NeQuick and in this respect comparable to the GPS ICA.

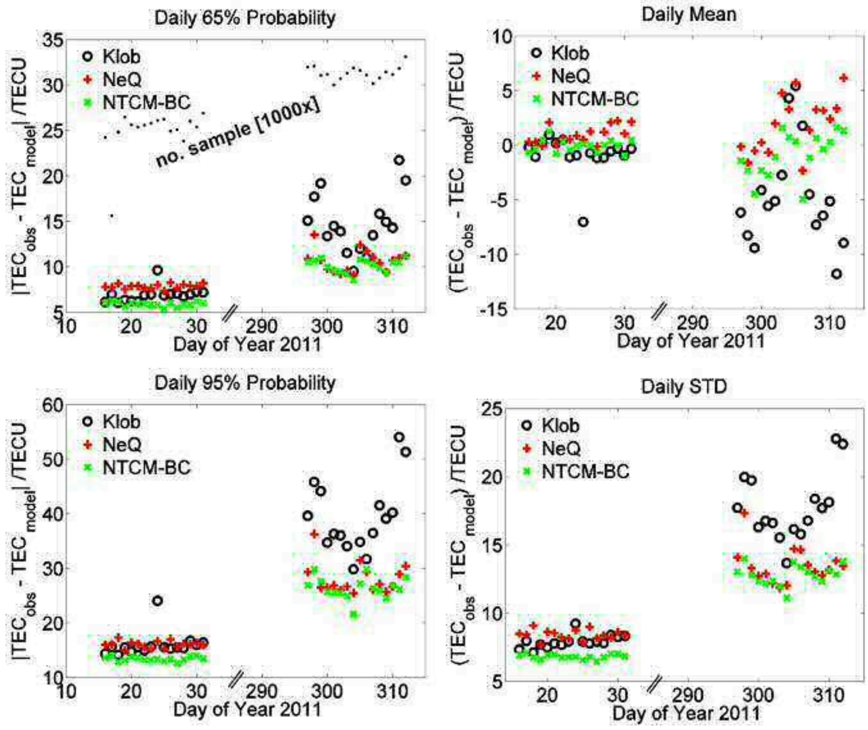


Figure 3.2.16: The top- and bottom-left plots show daily 65% and 95% probability of TEC prediction error, respectively, during quiet and perturbed days. The top- and bottom-right plots show corresponding daily mean and std values. The number of samples and corresponding scale are given in the top-left plot. (Reprinted from Hoque and Jakowski 2015)

Recently Badeke et al. (2016) compared four empirical models such as 27-day median model, Fourier series based approach, NTCM and NeQuick 2 for a reliable 24 hour ahead forecast of the TEC over Europe. Their investigation shows that the 27-day median model performs better than other approaches during geomagnetically quiet conditions.

Rovira-Garcia et al. (2015, 2016) worked on extending ionosphere model to provide a world-Wide coverage, showing that it is able to reduce the convergence of Precise Point Positioning and its agreement with observations from Low Earth Orbit (LEO) satellites.

Atabati and Alizadeh (2018) investigated possibility of predicting ionospheric scintillation activities. They implemented an Artificial Neural Network (ANN) technique for detecting ionospheric scintillation. The ANN is a data-dependent method that its performance improves with the sample size. Due to the advantages of ANN for large datasets and noisy data, the ANN model has been implemented for predicting the occurrences of amplitude scintillations. In this paper, the Genetic Algorithm (GA) technique is considered to obtain primary weights of the ANN model. This procedure is applied to GPS observations at GUAM station in order to predict amplitude scintillation index S4. Their investigation shows that the designed model can predict daily ionospheric scintillation with the accuracy of about 86% for selected days.

Several members of the "WG 4.3.2: Ionosphere Predictions" were actively involved in organizing the International Workshop on GNSS Ionosphere (IWGI) in 2018 and 2019 in Shanghai and Neustrelitz, respectively. Special sessions were organized for ionospheric modelling and prediction activities. The IWGI (https://iwgi2019.besl-eventservice.de) provides a platform for scientists and engineers to communicate and exchange their views on ionospheric theory, methods, technologies, applications and future challenges. The workshop is open to all scientists who are interested to present and discuss latest results and developments in ionospheric scintillation, reconstruction, modelling, monitoring techniques and prediction methodologies as well as ionospheric propagation effects on microwave space-based geodetic techniques such as the GNSS, SLR, VLBI, DORIS etc. and their mitigation using multi-frequency, multi-sensors observations.

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WG 4.3.3: Combination of Observation Techniques for Multi-dimensional Ionosphere Modelling

Chair: *Mahdi M. Alizadeh (Iran)*
Vice-Chair: *Dudy Wijaya (Indonesia)*

Members

Claudio Brunini (Argentina), Francisco Azpilicueta (Argentina), Robert Weber (Austria), Lyubka Pashova (Bulgaria), Mainul Hoque (Germany), Roman Galas (Germany), Jens Wickert (Germany), Robert Heinkelmann (Germany), Jens Berdermann (Germany), Eren Erdogan (Germany), Saeed Zare (Iran), Kinga Wezka (Poland), Andrzej Krankowski (Poland), Manuel Hernandez-Pajares (Spain), Lung-Chih Tsai (Taiwan), Mahmut O. Karslioglu (Turkey), Anthony Mannucci (USA), Chen Peng (USA), Chinh Nguyen Thai (Germany), T. Seun Oluwadare (Germany)

Activities during the period 2015-2019

Regional three-dimensional model of electron density

According to Schmidt et al. (2008) a multi-dimensional approach based on Euclidean quadratic B-spline wavelets can be used for representation of the ionospheric parameters characterized by an effective numerical algorithm. Due to the fact that these base functions are compactly supported, they provide a great advantage when used for regional modeling of the ionosphere or when the observations are unevenly distributed over the globe. In approach the parameters of the ionosphere, e.g. VTEC is separated into a reference part and a correction part. Following Dettmering et al. (2011b) ΔVTEC can be expressed by means of spline series expansion. The unknown coefficients of the expansion and should be estimated through a least-squares adjustment procedure. More details can be found in Schmidt (2007).

The two panels in Fig. 3.3.1 depict a regional model of maximum electron density (NmF2), and its corresponding height (hmF2) over Iran's region for 1st March 2013, 11 UT, using quadratic B-spline wavelets (Zare et al., 2018).

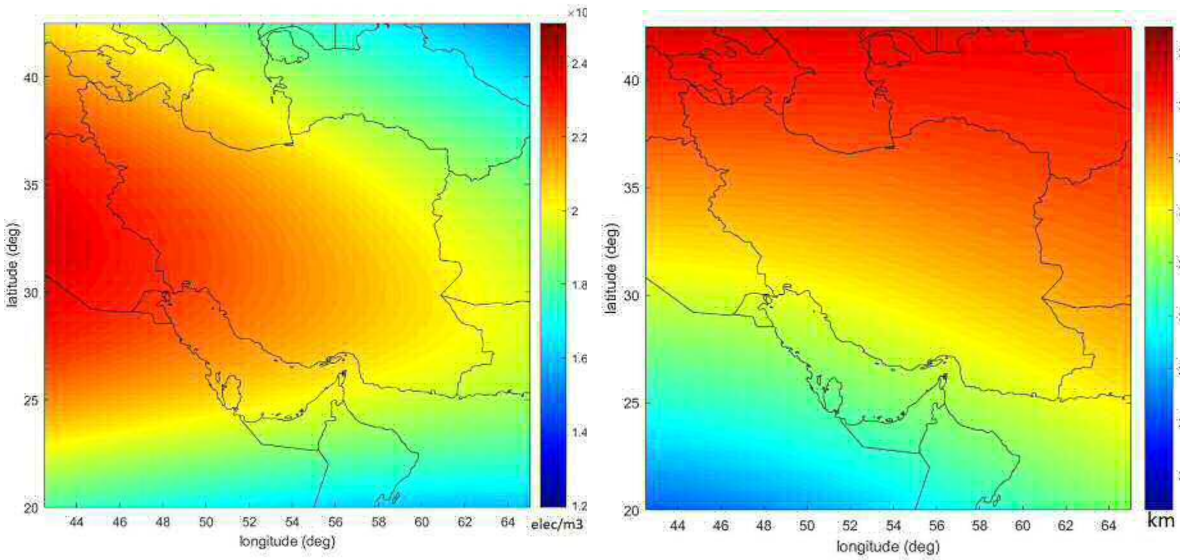

Figure 3.3.1: Regional model of the maximum electron density (NmF2) (left), and its corresponding height (hmF2) (right) over Iran at 1st March 2013, 11 UT (Zare et al., 2018).

SGI Workshops

During the past four years the JWG 4.3.3 was actively involved in holding several workshops. The Satellite Geodesy and Ionosphere Research (SGI) workshops were held yearly at the Technical University of Berlin, and aimed at bringing geodesists and other scientists dealing with geodetic sciences related to the ionosphere from all over the world to one meeting. The SGI Workshop:

- provided a great opportunity for geodetic scientists to meet and share their findings,
- provided opportunity for extended discussion about the presented topics,
- increased the visibility of space geodesy with respect to ionosphere research,
- offer an appropriate platform for further collaborations in the field of ionosphere research,
- initiated engagement with international community on data sharing, numerical modeling, and scientific research,
- tried to make available the possibility of common voice among the geodetic scientists dealing with the ionosphere, and
- contributed to the objectives of Global Geodetic Observing System (GGOS).

The Satellite Geodesy and Ionosphere research (SGI2015) workshop was held at the Technical University of Berlin during 7 and 8 July 2015. The workshop initially aimed at bringing together geodesists and other scientists from all over the world to one meeting, dealing with geodetic sciences and ionospheric research. The workshop was co-organized by Mahdi Alizadeh from the Institute of Geodesy and Geoinformation Science of the Technical University of Berlin and Department 1 'Geodesy and Remote Sensing' of the German Research Centre for the Geosciences (GFZ). Within this workshop Michael Schmidt, chair of the IAG Sub-Commission 4.3 "Atmosphere Remote Sensing" presented the ToR of the Sub-Commission and the intention of establishing ionosphere-related working and study groups within the Sub-Commission. Discussions were carried out about the topics of different study/working groups and the proposed chairpersons of each group (see IAG Newsletter – July 2015).

The second Satellite Geodesy and Ionosphere research workshop (SGI2016) was held at the Technical University of Berlin during 8 and 9 August 2016 as an activity of IAG Joint Working Group 4.3.3 "Combination of Observation Techniques for Multi-dimensional Ionosphere Modeling". The SGI2016 was organized by the Institute of Geodesy and Geoinformation Science of the Technical University of Berlin, K.N.Toosi University of Technology at Tehran, Iran and Department 1 'Geodesy and Remote Sensing' of the German Research Centre for the Geosciences (GFZ) Potsdam. The workshop provided a great opportunity for scientists to meet in a friendly atmosphere and to share their research and latest findings. In the discussion session Michael Schmidt presented the activities of the IAG Sub-Commission 4.3: "Atmosphere Remote Sensing" during the last year and explained the study, working, and joint working groups established during since last year. Some information was given about the GGOS-Days in Frankfurt in October 2015 and that GGOS has already developed three focus areas. Discussions were carried out about establishment of a fourth Focus Area related to Atmosphere, including impact of both troposphere and ionosphere on modern society, long term variations of the atmosphere, and the role of atmosphere in gravity missions (see IAG Newsletter – August 2016).

Similar activities have been performed for organizing the third Satellite Geodesy and Ionosphere research workshop (SGI2017) during July 11 and 12, 2017 as well as the fourth Satellite Geodesy and Ionosphere research workshop (SGI2018) during June 28 and 29 June, 2018, both at Technical University of Berlin.

WG 4.3.4: Ionosphere and Troposphere Impact on GNSS Positioning

Chair: *Tomasz Hadas (Poland)*
Vice Chair: *Simon Banville (Canada)*

Members

Mainul Hoque (Germany), Jan Kaplon (Poland), Amir Khodabande (Australia), Thalia Nikolaidou (Canada / Greece), Junbo Shi (China), Rafal Sieradzki (Poland), Toshiaki Tsujii (Japan), Pavel Vaclavovic (Czech Republic), Duojie Weng (China), Kinga Wezka (Germany / Poland), Chaoqian Xu (China / Canada)

Activities during the period 2015-2019

Group members realized the goals of WG 4.3.4 in their individual activities as well as in cooperation with other group members. WG studies concerned the impact of several ionosphere-related effects on GNSS positioning and GNSS signal propagation, as well as on Precise Point Positioning (PPP) supported with numerical weather prediction models.

On the cooperation level, members of WG concentrated on Higher-Order Ionospheric (HOI) effects (Banville et al. 2017). HOI, if not properly accounted for, can propagate into geodetic parameter estimates. For this reason, several investigations have led to the development and refinement of formulas for the correction of second- and third-order ionospheric errors, bending effects and total electron content (TEC) variations due to excess path length. Standard procedures for computing HOI terms typically rely on slant TEC computed either from global ionospheric maps (GIMs) or using GNSS observations corrected using differential code biases (DCBs) provided by an external process. Since both of these approaches are relying on external outputs, it was deemed suitable, in the context of the WG, to investigate another approach to mitigate HOI effects. Members of WG 4.3.4 have therefore investigated the feasibility of estimating slant ionospheric delay parameters accounting for both first- and second-order ionospheric effects directly within a PPP solution. The analysis conducted showed that, with a proper handling of the receiver DCB, the PPP method is able to mitigate HOI effects to the same level as existing approaches. The approach is however not entirely free from external inputs since GIMs are required for isolating the receiver DCB, unless the latter is provided to the PPP filter.

Hoque et al. (2017) investigated HOI propagation effects on trans-ionospheric microwave links used in the time and frequency transfer applications. Such a metrology link must provide frequency and time comparison and dissemination with an uncertainty level of 10-18 and beyond. Their investigation shows that for achieving such an accuracy level the HOI propagation effects must be corrected for.

In a separate study Hoque et al. (2016) investigated the magnitude of HOI effects using worldwide ground-based GPS data from both quiet and perturbed ionospheric and geomagnetic activity periods. They found that the range computation between a satellite and a ground receiver during perturbed periods is affected by up to 10 cm due to HOI terms and can significantly degrade the accuracy of PPP especially during times of high TEC values. This indicates that the dual-frequency range equation should have additional terms for correcting HOI terms if centimetre level precision is required.

Hoque and Schlüter (2018) developed an over bounding model for ionospheric residuals that remain after the application of the ionosphere-free linear combination. The model takes into account the second- and third-order ionospheric refraction effects, excess path and increased total electron content (TEC) along the signal path due to ray bending. The model is elevation dependent, easy implementable in the receiver software, and provides a conservative estimate of the worse-case residuals with a risk probability beyond 10^{-7}. The model is accepted by the European Organization for Civil Aviation Equipment (EUROCAE) experts as the dual-frequency multi constellation (DFMC) Minimum Operational Performance Standard (MOPS) for the next generation dual-frequency SBAS.

Precise orbit determination (POD) for Low Earth Orbiting (LEO) satellites mostly relies on dual-frequency first-order ionosphere-free GNSS data. However, higher order ionospheric effects such as the second- and third-order terms and ray path bending effects remain uncorrected in such approaches. Hoque (2018) conducted a simulation study using a ray-tracing tool to trace GPS L1 and L5 signals from a transmitting satellite to a receiver on board LEOs at altitudes of about 400 and 800 km. The results show that during times of high TEC the dual-frequency GPS L1-L5 phase and pseudorange residuals can be up to 20 and 50 cm, respectively for LEOs at 400 km height whereas the residuals become up to 4 and 9 cm, respectively for LEOs at 800 km height.

Sieradzki and Paziewski (2015, 2016) proposed to modify undifferenced phase observables using rate of TEC (ROT) corrections in order to mitigate the dynamic Total Electron Content (TEC) variations (ionospheric disturbances). The application of these corrections in a preliminary step of data processing allows leveling of ionospheric delays for particular arc and consequently treating this parameter as a constant during the entire session. The efficiency of the proposed algorithm was evaluated using rapid static positioning with the ionosphere-weighted model for different latitudes and ionospheric conditions, i.e. mid-latitudes affected by medium scale travelling disturbances and strongly disturbed high latitudes during space weather event on 17.03.2013. The results obtained for the modified algorithm have shown significant improvement of ambiguity success rate (ASR) for European and circumpolar ionosphere. The performed analysis has also confirmed that the application of the new approach leads to the continuous increase in ASR depending on session length. Finally, it is worth to notice that the proposed algorithm does not require any an external modelling of ionospheric conditions and can be easily implemented in multi-GNSS positioning, including both relative and absolute methods.

Banville et al. (2018) analysed the impact of three variables on the accuracy of ionospheric corrections: the input slant ionospheric delays, the mathematical model, and the network configuration. When the input delays are derived from the precise point positioning (PPP) methodology, it was shown that ambiguity resolution (PPP-AR) offers a 20-50% reduction in the RMS error of predicted delays over float ambiguity estimates. Among the models evaluated, the dual-layer and conical models can reduce RMS errors by more than 50% over the single-layer model during moderate ionospheric activity. Finally, for the days analysed, increasing inter-station distances from 75 km to 150 km only deteriorates RMS errors by 10%.

In other ionosphere-related studies, Fujiwara and Tsujii (2016) characterized the effects of equatorial plasma bubbles on received GNSS signals and derived the model of loss-of-lock probability. Wezka et al. (2016) were working on reliability monitoring of GNSS positioning under the influence of strong ionospheric perturbations (scintillations). Finally, Khodabandeh and Teunissen (2016) made use of S-system (singularity-system) theory and developed an undifferenced multi-frequency formulation of the GNSS observation equations. Such formulation enables one to interpret estimable forms of the GNSS parameters, including the first-order slant ionospheric delays. The estimability and precision of multi-frequency GNSS-derived slant Total Electron Content (TEC) was analysed through closed-form expressions of the ionospheric solutions. The widely used phase-to-code levelling technique was generalized to its multi-frequency version. In particular, they showed that only certain specific linear combinations of the GNSS observables, i.e. the time-differenced data, contribute to the TEC solutions.

Troposphere-related research was also conducted by several group members. At the Geodetic Observatory Pecny (GOP), two software applications for tropospheric parameters estimation have been developed: G-Nut/Shu and G-Nut/Tefnut. While the former is based on meteorological information from a numerical weather model, the latter exploits GNSS data. In parallel, GOP have also developed another tool for precise positioning and investigated backward smoothing for precise GNSS applications in post-processing (Václavovic and Douša, 2015) and also in near real-time (Dousa at al., 2018b). Each of these applications can be used for individual purposes, however, their combination is also highly valuable. Estimated tropospheric parameters can be introduced in precise positioning and improve precision and robustness of estimated station coordinates, particularly high-altitude components. This approach can be used offline as well as in real-time processing. To show benefits of introducing external tropospheric parameters in positioning, Václavovic et al. (2017) arranged an experiment with a hot air balloon, where a GNSS receiver was carried up to 2000 meters above the earth surface. They have demonstrated that external tropospheric corrections significantly helped in ZTD-height mutual decorrelation and hence improved the positioning performance. The improvement was most significant in case of poor satellite constellation. It was also demonstrated by Wilgan et al. (2017) that a troposphere model combined from GNSS and NWM data can significantly contribute to real-time PPP, improving the accuracy and precision of receiver height and reducing the initialization time. An alternative approach for combination GNSS-based and NWM-based ZTD for achieving precise and robust troposphere model is presented in Douša et al. (2018a). The optimum correction is achieved when using NWM for the hydrostatic delay modelling and for vertical scaling, while GNSS products are used for correcting the non-hydrostatic delay. Such model can be generated in real-time and thus support precise kinematic positioning.

Research was also conducted towards the improvements in troposphere modelling using GNSS data. An optimal weighting method based on posterior unit weight variances was developed for GPS PPP-based troposphere tomography (Jiming et al. 2016). A modified Saastamoinen model was proposed, in which systematic error were reduced from -3mm to nearly zero, compared with the benchmark values calculated by meteorological data from 91 radiosonde stations distributed worldwide (Zhang et. al, 2016). Moreover, Douša et al. (2015) monitored NWM forecast with near real-time GNSS products. Finally, the impact of real-time satellite clock errors on GPS PPP-based troposphere delay estimation was investigated by Shi et al., 2015. The authors found that among available satellite real-time products, those with better satellite clock precision yield more precise troposphere zenith delay.

The impact of the atmospheric source (NWM) on the tropospheric products was assessed by comparing the regional UNBVMF1-CMC tropospheric products against the VMF1. GNSS and VLBI locations were employed in both delay and position analyses. The two delay products were consistent for the majority of the sites and the positioning analysis showed equivalent results when a long time series was used (Nikolaidou et al. 2017). A further detailed analysis with regard to regional versus global NWM was conducted where atmospheric products were generated on grid and site-wise basis. The latter were able to reduce the height time series bias by up to 49% compared to the former. Also the use of the regional NWM-derived products achieved the fastest convergence in a PPP analysis. (Nikolaidou et al. 2017). A study for the Nigerian GNSS Reference Network accessed the GPS-derived tropospheric delays against the NCEP NWM. Results showed good agreement but also a vulnerability of the NWM to follow rapid seasonal phenomena occurring at certain areas. Time series analysis portrayed the local climatological zones (Mayaki et al. 2017). The tropospheric modelling and its potential advancements were explored in the frame of "big data" analytics by Santos and Nikolaidou (2018).

The launch of the new tropospheric mapping functions from the Technical University of Vienna (TUW) motivated members of the group to conduct two studies between the former state-of-the-art, VMF1, and the latest VMF3. The studies, whose results will be presented at the 27th IUGG General Assembly 2019, concern the delay and position domains respectively for selected GNSS sites. The production of the UNB-VMF1 tropospheric products, namely zenith delays and mapping function coefficients on a grid, has been updated and the availability of the NCEP-NWM products accelerated by 4 days (3days lag instead of 7) (http://unb-vmf1.gge.unb.ca/).

Last but not least, the WG 4.3.4 members Hadas and Kaplon represented the group in Local Organization Committee of the IAG Commission 4 Symposium in Wroclaw. It was a great opportunity to recruit more members, who have already contributed with their studies to the goals of this WG.

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WG 4.3.5: Ionosphere Scintillations

Chair: *Lung-Chih Tsai (Taiwan)*
Vice Chair: *Jens Berdermann (Germany)*

Members

Suvorova Alla (China-Taipei), Chi-Kuang Chao (China-Taipei), Kai-Chien Cheng (China-Taipei), Alexei V. Dmitriev (China-Taipei), Rui Fernandes (Portugal), Yoshihiro Kakinami (Japan), Chinmaya Kumar Nayak (India), Ernest Macalalad (Philippines), Charles L. Rino (USA), Michael Schmidt (Germany), Kuo-Hsin Tseng (China-Taipei), Sudarsanam Tulasiram (India)

Activities and publications during the period 2015-2019

In the following an overview is given on selected activities of WG 4.3.5 members:

1st mini-workshop on Ionosphere Scintillations, Taoyuan, Dec. 4, 2015. The workshop presentations include: Use of GNSS for geophysical applications: from secular to second (Dr. Rui Manuel da Silva Fernandes), Recent surface deformation of the Himalaya and Adjoining Piedmont Zone of the Ganga Plain, Uttarakhand, India (Prof. Chung-Pai Chang, Taiwan), Mid-latitude ionospheric scintillations over Irkutsk (Dr. Alexei V. Dmitriev), Ionospheric irregularities in COSMIC data over Pacific and forbidden electrons (Dr. Alla Suvorova, Russia), Ionospheric observations, N_e specification, modeling, and their applications (Prof. Lung-Chih Tsai).

Dr. Rui Manuel da Silva Fernandes established a CORS (Continuously Operating Reference Station) GNSS system in December of 2015 at Chungli, and to support common researches on scientific and technical applications of GNSS.

2nd mini-workshop on Ionosphere Scintillations, Taoyuan, Feb. 19, 2016. The workshop presentations include: Space weather and its influence on the Ionosphere (Dr. Jens Berdermann), Ionospheric propagation of very low frequency radio waves and advances in solar flare analysis (Dr. Daniela Wenzel, Germany), Equatorial plasma bubbles observed from Equatorial Atmosphere Radar (EAR) over Indonesia (Dr. Sudarsanam Tulasiram), Advanced Ionospheric Probe onboard FormoSat-5 Satellite for ionospheric scintillation study (Prof. Chi-Kuang Chao), Mid-latitude ionospheric scintillations over Irkutsk (Dr. Alexei V. Dmitriev), H2020 project in Taiwan (Dr. Alla Suvorova), Ionospheric observations, N_e specification, modeling, and their applications (Prof. Lung-Chih Tsai).

Daniela Wenzel and Dr. Jens Berdermann established a station of the Global Ionospheric Flare Detection System (GIFDS) in February of 2016 at Chungli, Taiwan to receive very low frequency (VLF) radio signals transmitted from India, Australia, Hawaii, Japan, etc. The fifth station at the National Central University in Taiwan completed the flare detection network GIFDS. GIFDS can analyse VLF signals to identify solar flare events and their temporal progression. In addition GIFDS is able to measure and analyse sudden ionospheric disturbances (SIDs) in the D-layer Ionosphere caused by solar flares. Finally GIFDS can be used to study the impact of solar flare events on the occurrence and strength of ionospheric scintillations; see Fig. 3.5.1.

3rd mini-workshop on Ionosphere Scintillations, Taoyuan, Dec. 2, 2016. The workshop presentations include: A configuration space model for stochastic ionospheric structure (Dr. Charles L. Rino, USA), The International Reference Ionosphere: from climate to real-time weather predictions for Earth's Ionosphere (Dr. Dieter Bilitza, USA), Recurrent ionospheric storms (Dr. Alexei V. Dmitriev), Atmospheric ionization by energetic electrons at the low latitudes (Dr. Alla Suvorova), Suppression of ionospheric scintillation during St. Patrick's Day geomagnetic super storm as observed over the anomaly crest region station Pingtung, Taiwan: A case study (Dr. Chinmaya Nayak, India).

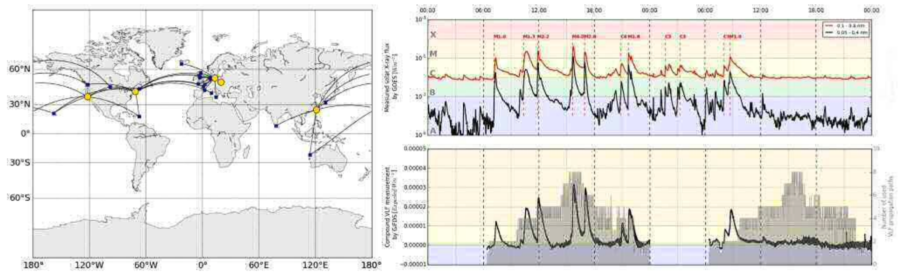

Figure 3.5.1: The GIFDS network and associated radio propagation paths (left panel) and comparison of the compound VLF measurement with the GOES X-ray during solar flare activities (right panel).

Setup and first analysis of a small scale ionospheric disturbances using a high-rate GNSS network in Bahir Dar. Small scale ionospheric disturbances may cause severe radio scintillations of signals transmitted from global navigation satellite systems (GNSS). Consequently, small scale plasma irregularities may heavily degrade the performance of current GNSS such as GPS, GLONASS or Galileo. Ionosphere modeling and monitoring over the African and South American sector is of great interest due to spread of the so called equatorial anomaly region over it. This region experiences equatorial plasma bubbles, blobs, irregularities which may cause scintillation especially during evening and nighttime hours. DLR installed and operates in Bahir Dar together with the partner institutions TUB and IEEA a small scale high rate GNSS receiver network (50 Hz) in order to estimate the drift velocity and the size of the so called "Plasma Bubbles"; see Fig. 3.5.2.

The DFG joint 3-year research project titled as **'**Development and application of GNSS remote sensing techniques for Earth Observation' (PIs: Lung-Chih Tsai (Taiwan), Harald Schuh (Germany) is focusing on GNSS remote sensing in the atmosphere, ionosphere, ocean altimetry and sea state as well as on new opportunities for the future FS7/COSMIC2 mission. Both participants, GPSARC-NCU Taiwan and IGG-TUB Germany (in cooperation with GFZ) have long-term experiences in GNSS radio occultation and reflectometry and also published numerous scientific papers. We could summarize all proposed objectives here: (1) using GPS/GNSS RO atmosphere data and developing advanced algorithms for the lower troposphere and climatological investigations, (2) retrieving and monitoring sporadic E (Es) layer, scintillations and related effects including vertical couplings, and (3) developing real-time FPGA based and/or software GPS/GNSS reflectometer for applications on ocean altimetry and sea state observations.

The mini-workshop on "oblique ionospheric sounding/ observations using the Vertical Incidence Pulsed Ionospheric Radar (VIPIR) systems in Japan, Korea, and Taiwan" participated persons: Dr. Young-Sil Kwak (KSSS, Korea), Dr. Han Jinwook (KSWC, Korea), Dr. I. S. Park (WIBTEL, Korea), CEO K. M. Song (WIBTEL, Korea), Dr. W. H. Yeh (NSPO, Taiwan), Dr. Alexei V. Dmitriev (NCU, Taiwan), Dr. S. Alla Vasiljevna (NCU, Taiwan), Dr. Lung-Chih Tsai (NCU, Taiwan), Taoyuan, Oct. 30, 2018.

5th mini-workshop on Ionosphere Scintillations, Taoyuan, April 15 & 16, 2019. The workshop presentations include: "Development of GNU Radio Beacon Receiver 2 for TBEx & F7/C2 satellites" (Prof. Mamoru Yamamoto, RISH, Kyoto University), "Ionospheric Es layer scintillation characteristics studied with Hilbert-Huang Transform" (Prof. Shin-Yi Su, CSRSR, National Central Univ), "How can we trace the mid- and low-latitude aurora?" (Dr. Alexei V. Dmitriev, ISS, NCU), "The observations of low latitude ionospheric scintillation events" (Dr. Tung-Yuan Hsiao, National Tsing-Hua Univ), "Space weather studies at Ionospheric Sounding Lab. (ISL), CSRSR/GPSARC, NCU" (Prof. Lung-Chih Tsai, GPSARC/CSRSR, NCU), "On understanding equatorial spread F" (invited seminar) (Prof. Roland Tsunoda, SRI, USA), "Near-equatorial ionization by energetic electrons a protons injected to the ionosphere from the inner radiation belt" (Dr. Alla Suvorova, GPSARC, NCU), "Variability of ionospheric irregularities over Taiwan" (Dr. Lalit Mohan Joshi, CSRSR, NCU)

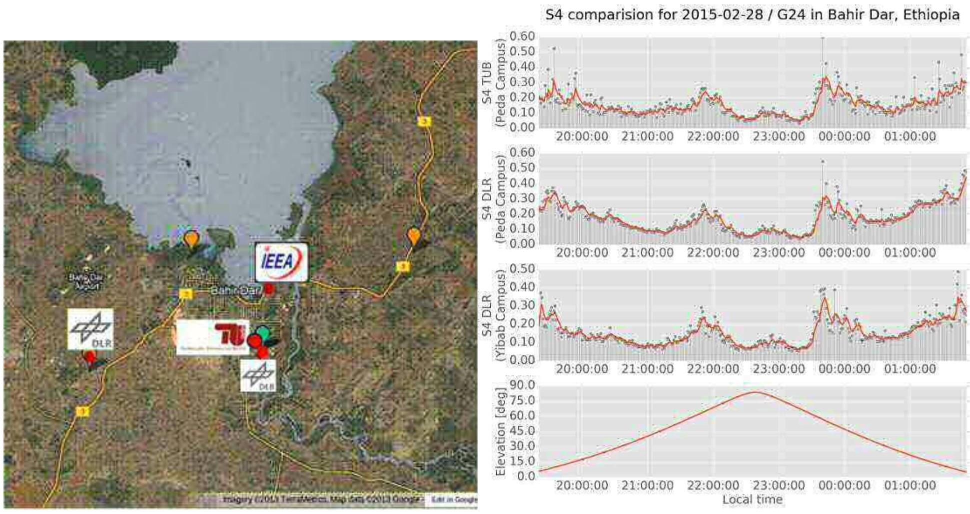

Figure 3.5.2: Small scale high-rate GNSS network of DLR,TUB and IEEA in Bahir Dar (left panel). The right panel shows the signature of S4 indices calculated for satellite G24 using different scintillation receivers and processors in comparison to the averaged elevation (below) [Kriegel at al 2017].

1st VIPIR Group/User Meeting on April 17 (Wednesday) 2019 at Howard Civil Service International House (Room #205), Taipei, Taiwan. Participants: Alla Suvorova (GPSARC, NCU, Taiwan), Alexei V. Dmitriev (ISS, NCU, Taiwan), Alexander Karpachev (IZMIRAN, Russia), Bob Livingston (SCION, USA), Brett Isham (Inter American Univ of Puerto Rico Bayamon Campus, USA), Jong-Yeon Yun (Korea Space Weather Center, Korea), Lung-Chih Tsai (GPSARC/CSRSR, NCU, Taiwan), Roland Tsunoda (SRI, USA), Shin-Yi Su (CSRSR, NCU, Taiwan), Terry Bullett (NOAA, USA), Trang Thu Nguyen (VAST, Vietnam), Takuya Tsugawa (NICT, Japan). Young-Sil Kwak (Korea Astronomy and Space Science Institute, Korea), Program includes “Welcome words and introductions” (Prof. Lung-Chih Tsai, NCU), “VIPIR Technology for Future Science” (Dr. Brett Isham, Inter American Univ of Puerto Rico Bayamon Campus, USA), “Open source ionogram scaler programs”, (Dr. Terry Bullett, NOAA, USA), “Joint observations using VIPIRs” (Dr. Bob Livingston, SCION, USA; Dr. Takuya Tsugawa, NICT, Japan), “Next VIPIR User/Group Meeting in Korea” (Mr. Jong-Yeon Yun, Korea Space Weather Center, Korea).

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WG 4.3.6: Troposphere Tomography

Chair: *Witold Rohm (Poland)*

Members

Hugues Brenot (Belgium), Michael Bender (Germany), Michal Kacmarik,(Czech Republic), Toby Manning (Australia), Alain Gaiger (Switzerland), Zhizhao (George) Liu (Hong Kong China), Zohre Adavi (Iran), Laurent Morel (France), Gregor Moeller (Austria), Krzysztof Kroszczynski (Poland), Cédric Champollion (France), Yan Xin (Austria), Andre Sa (Portugal), Eric Pottiaux (Belgium), Estera Trzcina (Poland), Natalia Hanna (Austria)

Activities and publications during the period 2015-2019

Working group is currently looking into three major topics:

Quality assurance factors in GNSS tomography processing, [QUALITY]

One of the most important factor that limits the accuracy of GNSS tomography is related to neglected bending effects in the construction of tomography design matrix. In the study by Moeller and Landskron (2019) authors demonstrated that all signals below 15 degrees elevation angle are affected by bending effects, introducing 1-2ppm systematic bias in the retrieval. Introducing raytracing in the bottom part of the troposphere and iterative retrieval method can greatly reduce the impact of bending effects and tomography solution for country size model, can still be provided within 2 minutes.

Another study showing impact of using different signal parameterisation algorithms on tomography retrieval was also performed by Adavi et al., (2019). Following results were obtained:

- Considering topography of study area in tomography model can increase the number of rays which are crossed through model elements.
- Using ray tracing method increase solution accuracy.
- Applying low elevation angles observations enhance the differences between the raytracing method with straight line methods.

Use of tomography retrievals in severe weather investigation, [SEVERE]

The study of application of GNSS observation is base of two distinct cases:

1. Australian severe weather that involved testing of multiple tomography model settings and multiple models (TOMO2, BIRA, TUW, VUT, SWART) validating using data from radiosondes, Numerical Weather Model (analysis step) and Radio Occultation (Fig. 3.6.1)

The study involved 21 steps in total; testing use of apriori data (step1 to step4 – major work in previous ToR), data stacking (step7 to step9), pseudo-slant solution (step10 to step13), data uncertainty on the solution (step14 to step17), as well as verifying the impact of more realistic uncertainty on the solutions (step18 to step21).

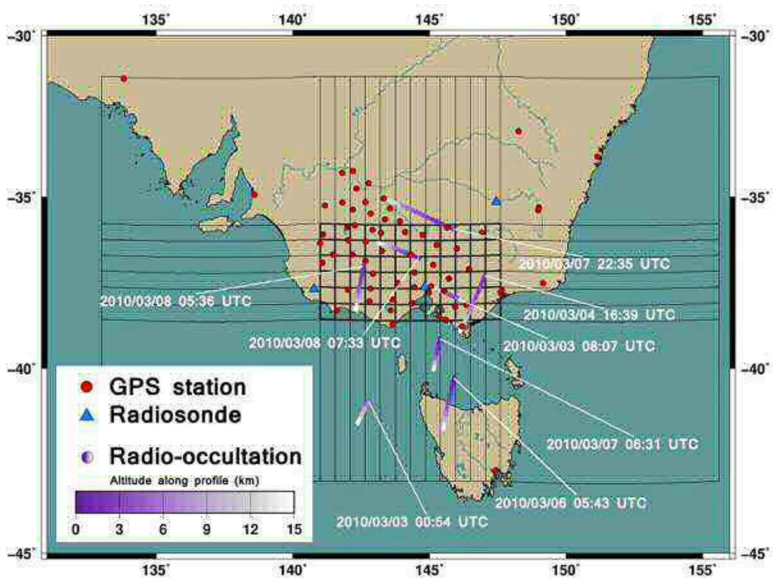

Fig. 3.6.1: Location of CORS GPS stations, RS sites, RO profiles and the tomographic grid (in black).

The major outcomes are as follows:

- The GNSS tomography results are comparable to the NWM ACCESS-R, retrieved from the analysis step and containing assimilated observations from: ATVOS, radiosondes, buoys, ship, etc.. Moreover tomography solution is similar to the model in the location of radiosonde, which has largest weights in the assimilation system. This means that the model might have accuracy of analysis step of NWM, across the whole domain.
- In the case of stacked data, especially for 5 observation epochs every 30 minutes solved in one combined set of normal equations, tomography solution is better than ACCESS-R field in the bottom part of the troposphere below 2000m (Fig. 3.6.2).
- Pseudo-observations introduced as an additional input to the observation matrix does not improve solution,
- Adding more uncertainty to a priori data only cause the solution to stick less to the a priori, which cause to improve slightly solution around 2000m. Combination of data stacking and loosing constraints is optimal solution that stick to the a priori in the ground part and improves solution around 2000m.
- RO profile 2010_063_1639 located over Alpine region has strong inversion reproduced tomography models but not visible in the ACCESS-R model, this might mean that ACCESS-R model have not resolved complex orography weather.

2. Poland, widespread precipitation. Another aspect of tomography monitoring for severe weather is linked with widespread precipitation. The applied tomography model (TOMO2) allows to get full picture of troposphere at all locations covered by GNSS network. In this study we investigate: 1) the meteorological correctness of the tomography retrieval, 2) whether the 15 new temporal and spatial resolution of the troposphere water vapour content will provide new information regarding these well studied events. Two events were investigated one in May 2014 and one in August/September 2014, the tomography retrievals compared with radiosonde profiles and numerical weather prediction (NWP) model. Currently, the retrieved data are analysed and prepared for presentation at EMS Annual Meeting: European Conference for Applied Meteorology and Climatology 2017. The results are also available, on the website: http://www.igig.up.wroc.pl/igg/

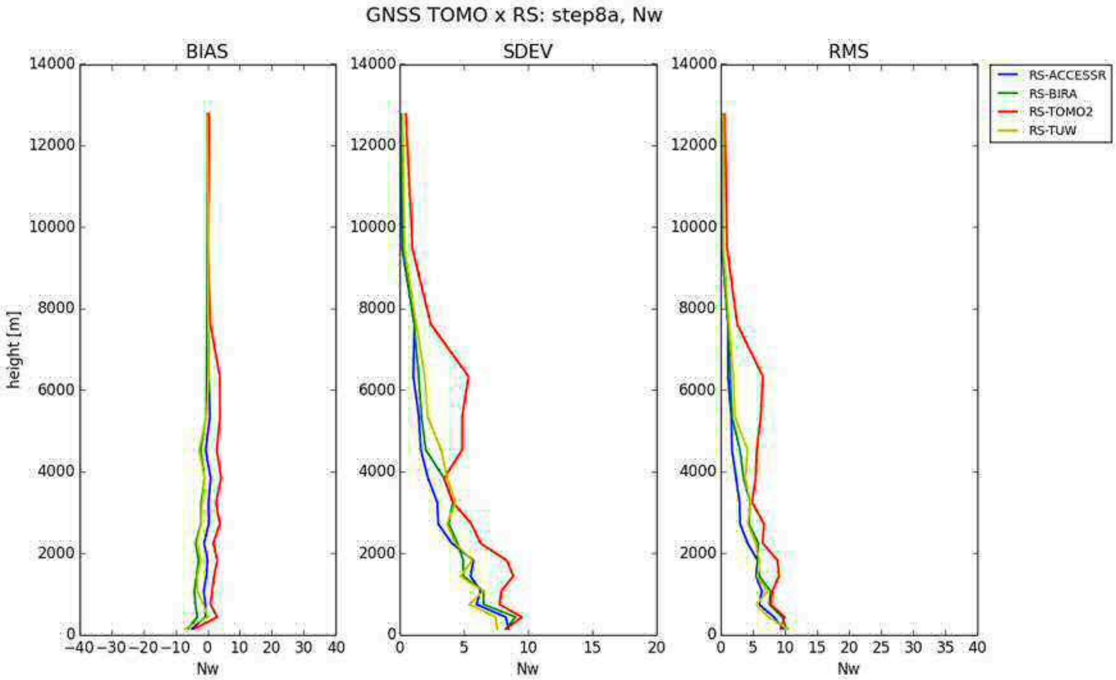

Fig. 3.6.2. Statistics for wet refractivity computed as a mean, standard deviation and RMS of residuals between radiosonde and ACCESS-R, BIRA, TOMO2 and TUW.

Use of tomography retrieval in weather system assimilation. [ASSIMILATION]

Two initial studies in 2015 were launched to investigate use of tomography retrievals in the numerical weather models: 1) Over part of Austria to study use of tomography retrieved relative humidity in generation of weather forecasts (Moeller et al., 2016) for intense rain, 2) Over Poland in standard weather conditions (Kryza et al., 2016). Both shows impact of GNSS tomography retrievals on weather parameters such as rain intensity, rain location, humidity and temperature.

Further study by Trzcina and Rohm, (2019), run for two weather cases in Poland (summer storms and autumn rainfalls). The following model settings were tested: 1) assimilation of tomography based (wet refractivity) and model based (dry refractivity) total refractivity using gpsref operator in WRFDA, 2) assimilation of radiosonde profiles as refractivity profiles. Simulations were verified using ground-based and radiosonde observations i.e.: integrated water vapour, relative humidity, temperature, wind speed. Following results were obtained:

- Increased accuracy in the top tropospheric layers in both scatter and bias,
- Improved mid troposphere in the summer case,
- The lead time 6-18h humidity forecasts were visibly improved for humidity in the autumn case but had no or negative impact in the summer cases,
- Most of the observations were not assimilated as it did not pass the quality test in the obsproc routine.

In the further study TUW and WUELS team (Hanna et al., 2019) investigated a case in East Germany and the western part of Czech Republic (Fig. 3), considered time period is between 29 May - 14 June 2013, the study is based on slant delays from benchmark campaign of the COST Action. Results of two tomography models, namely TOMO2 and Atom, were assimilated in WRF model with gpsref operator (radio occultation operator). Following results comparing simulations to the reference ground-based data were found:

- Improvement in the relative humidity forecasts in both bias and standard deviation,
- Improvement in the temperature field.

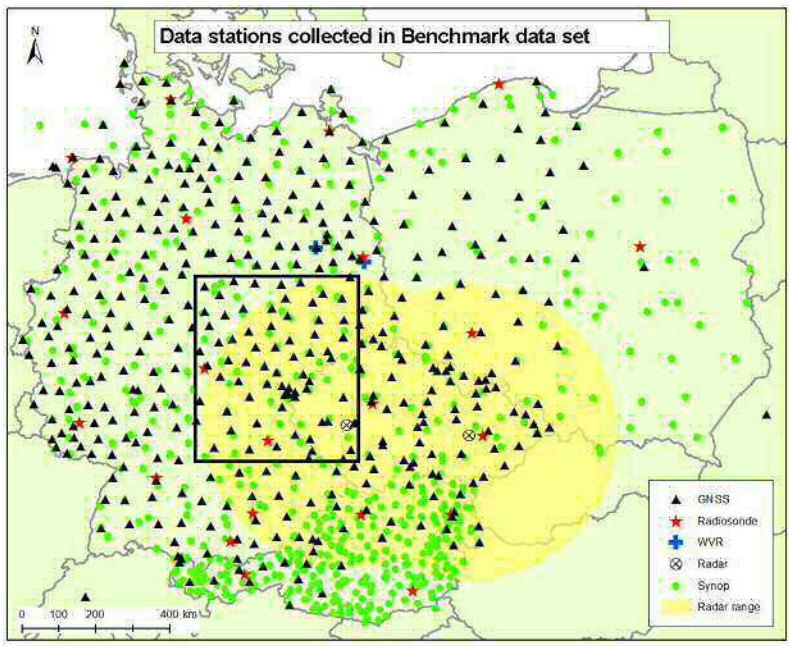

Figure 3.6.3. Location of tomography domain for investigated case of strong precipitation over Central Europe.

Towards end of June 2019 another publication describing development, validation and application of the tomoref operator, will be submitted to Weather Research and Forecasting.

Publications

Adavi, Z., Rohm, W. and Weber R.: Analysing different parameterisation methods in GNSS Tomography using the COST benchmark dataset, Geophysical Research Abstract Vol. 21, EGU2019-18797-1, 2019 EGU General Assembly 2019

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WG 4.3.7: Real-time Troposphere Monitoring

Chair: *Jan Dousa (Poland)*
Vice Chair: *Eric Pottiaux (Belgium)*

Members

Kefei Zhang, (Australia), Xiaoming Wang (Australia), Fabian Hinterberger (Austria), Thalia Nikolaidou (Canada), Junping Chen (China), Min Li (China), Pavel Václavovic (Czech Republic), Henrik Vedel (Denmark), Galina Dick (Germany), Xingxing Li (Germany), Rosa Pacione (Italy), Yoshinory Shoji (Japan), Felix Norman Teferle (Luxembourg), Siebren de Haan (Netherlands), Tomasz Hadaś (Poland), Jonathan Jones (United Kingdom), John Braun (USA)

Activities and publications during the period 2015-2019

Providing new real-time or ultra-fast tropospheric products, such as Zenith Total Delays (ZTD), horizontal tropospheric GRaDients (GRD), Slant Total Delays (STD), Integrated Water Vapour (IWV) maps or other derived products estimated using data from GNSS permanent networks, is a prerequisite for numerical and non-numerical weather nowcasting and severe weather event monitoring (Guerova et al, 2016). The Precise Point Positioning (PPP) processing strategy plays a key role in the production of real-time tropospheric products because of its high processing efficiency, and sensitivity to the absolute value of the tropospheric delay. It enables to exploit optimally data from all available GNSS multi-constellations, and supports the production of all interesting GNSS parameters such as ZTDs, GRDs or STDs. Most importantly, the PPP is supported with the global orbit and clock products provided by the Real-Time Service (RTS, Caissy et al., 2012) of the International GNSS Service, IGS (Dow et al., 2009).

The main objectives of the IAG WG 4.3.7 'Real-Time troposphere monitoring' are:

Objective 1. : Stimulate the development of software that enable routine production of real-time/ultra-fast tropospheric products.

Objective 2. : Develop optimal strategies suitable for numerical or non-numerical weather nowcasting applications, and severe weather event monitoring.

Objective 3. : Demonstrate reliable high-temporal resolution real-time/ultra-fast production, assess applied method, software and precise real-time orbit and clock products.

Objective 4. : Evaluate real-time/ultra-fast tropospheric parameters and their potential for applications in meteorology.

Objective 5. : Setting up a link to the users, review product format and requirements.

The COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC, http: //gnss4swec.knmi.nl) played an initiative and significant role in the coordination of the development and the evaluation of GNSS real-time (RT) tropospheric products. The main achievements focused on the development of the RT multi-GNSS PPP software, the design and operation of the GNSS4SWEC Real-Time Demonstration campaign by the Working Group 1 „Advanced GNSS processing Techniques" (Douša and Dick, 2017), and various the product evaluations and validations.

Developing real-time/ultra-fast application software

Several working group members continued developing their software to produce reliable real-time/ultra-fast tropospheric products. These include the G-Nut/Tefnut software (Douša and Václavovic et al. 2013) developed by Geodetic Observatory Pecny (GOP), the EPOS-RT Software (Lit et al., 2014) from GFZ, GNSS-WARP from Wroclaw University of Environmental and Life Science (WUELS, Hadaś, 2015), BKG Ntrip Client from BKG (Weber et al, 2016). Besides developments of real-time ZTDs productions only, GOP developed and assessed methods of real-time STDs retrievals (Kačmařík et al. 2017) and carefully analysed resulting tropospheric gradients (Kačmařík et al. 2018). The benefit of multi-GNSS for meteorological applications was investigated by several other groups including impact of all available systems (GPS+GLO+GAL+BDS) in post-processing as well as simulated real-time solutions (Hadaś, 2015, Li at al., 2015a, 2015b, 2015c, Lu et al., 2015, 2016a, 2016b, Václavovic et al. 2013, Douša et al. 2018).

The Real-Time Demonstration campaign

From April 2015 eight agencies contributed routinely to the GNSS4SWEC Real-Time Demonstration Campaign (Dousa and Dick, 2017). They provided real-time/ultra-fast solutions using six different software and using various flavours of processing options (Table 3.7.1). Seven contributors provided solutions from truly real-time processing engine. Additional contributors are still preparing their submissions to the Real-Time Demonstration Campaign.

Table 3.7.1: Contributions to GNSS4SWEC Real-Time Demonstration campaign

AC	Running agency	Software	Start	Update	Solutions
GOP	Geodetic Observatory Pecný, RIGTC	G-Nut/Tefnut	9.4. 2015	real-time	GPS, GLO, gradients
TUW	Technical University Vienna	TUW software	15.4. 2015	real-time	GPS
ROB	Royal Observatory of Belgium	G-Nut/Tefnut	23.4. 2015	real-time	GPS, GLO, gradients
ASI	Agenzia Spaziale Italiana/Centro di Geodesia Spaziale , Matera	Gipsy-Oasis	5.5. 2015	hourly	GPS, gradients
ULX	University of Luxembourg	BNC	15.6. 2015	real-time	GPS
TUO	Technical University of Ostrava	RTKLib	5.11.2015	real-time	GPS
BKG	Bundesamt für Kartographie und Geodäsie	BNC	1.3.2016	real-time	GPS, GLO
GFZ	Deutsches GeoForschungsZentrum	EPOS-RT	16.2.1017	real-time	GPS, GLO

In a spirit of workload sharing, several members focused on different objectives of the campaign. As an example, ROB has collaborated with GOP to contribute to the Real-Time Demonstration campaign using their G-Nut/Tefnut software (Václavovic et al. 2013) but with a particular focus on 1) a larger set of GNSS stations with various equipment (for assessment purposes), and 2) on the high spatial and temporal estimation of the parameters (aiming at a nowcasting exploitation in the Benelux region). To this aim, in addition to the standard network of (~30) stations proposed to participate to the Real-time Demonstration Campaign, ROB real-time solutions includes in total 185 GNSS stations (Figure 3.7.), of which 76 belongs to the Belgian dense network.

Another example is ASI/CGS which contributed to the GNSS4SWEC Real-Time Demonstration Campaign by focusing on testing the IGS Real-Time orbit and clock corrections in more conventional Near-Real-Time PPP using the Gipsy-Oasis software. Pacione and Shoene (2013) describes the processing scheme (Figure). GOP also contributed by estimating ZTDs from numerical weather forecasts in Europe using the G-Nut/Shu software (Douša and Eliaš, 2014) to enable comparisons of real-time GNSS and Numerical Weather forecasted

ZTDs, which also suggests an exploitation of external tropospheric corrections from the forecasts for real-time GNSS kinematic positioning. It also showed an overall accuracy of 10-12 mm, i.e. by a factor of 2 worse than GNSS real-time ZTDs and its degrading by about 1-2 mm in ZTD per 6 hours (Douša et al., 2015).

Another example is ASI/CGS which contributed to the GNSS4SWEC Real-Time Demonstration Campaign by focusing on testing the IGS Real-Time orbit and clock corrections in more conventional Near-Real-Time PPP using the Gipsy-Oasis software. Pacione and Shoene (2013) describes the processing scheme (Fig. 3.7.2). GOP also contributed by estimating ZTDs from numerical weather forecasts in Europe using the G-Nut/Shu software (Douša and Eliaš, 2014) to enable comparisons of real-time GNSS and Numerical Weather forecasted ZTDs, which also suggests an exploitation of external tropospheric corrections from the forecasts for real-time GNSS kinematic positioning. It also showed an overall accuracy of 10-12 mm, i.e. by a factor of 2 worse than GNSS real-time ZTDs and its degrading by about 1-2 mm in ZTD per 6 hours (Douša et al., 2015).

Real-time monitoring

GOP developed a dedicated web service for an easy monitoring and comparison of individual contributions to the Real-time Demonstration campaign (Fig. 3.7.4). It is publicly accessible at http://www.pecny.cz/COST/RT-TROPO and enables visualising station time-series (ZTD and GRD components) from real-time solutions over past two months together with operational near real-time regional and global solutions from GOP contributing routinely to the EIG EUMETNET GNSS Water Vapour Programme, E-GVAP (http://egvap.dmi.dk).

A long-term evaluation over more than a year demonstrated a feasibility of a stable provision of ZTD with the precision of 5-10 mm for real-time ZTDs when estimated at a 5-minute sampling interval and a maximum latency of ~1 minute. Initially, significant station-dependent biases were observed with an overall mean values within 0-5 mm in ZTD and some extreme values up to 10 mm, which were continuously reducing along with software developments and precise products improvements. As an example, Fig. 3.7.2 shows a one-year monthly statistics for the GOP solution.

In parallel to this centralized web service, several members developed their own monitoring and automatic validation procedures, focusing on their contributions and specific needs. WUELS developed an automatic assessment of real-time ZTDs by comparison with their near real-time solution and developed an online tool to present the results graphically. Similarly, ROB carry out automatic validations of its real-time products w.r.t. to its near real-time solution for E-GVAP and w.r.t. to a post-processing PPP solution using the Bernese GNSS software 5.2. These comparisons reported similar precision/accuracy as mentioned by GOP is achieved (Pottiaux et al. 2015). ROB also developed a web interface that allows the monitoring of its real-time solutions and to represent the results of its validation procedures.

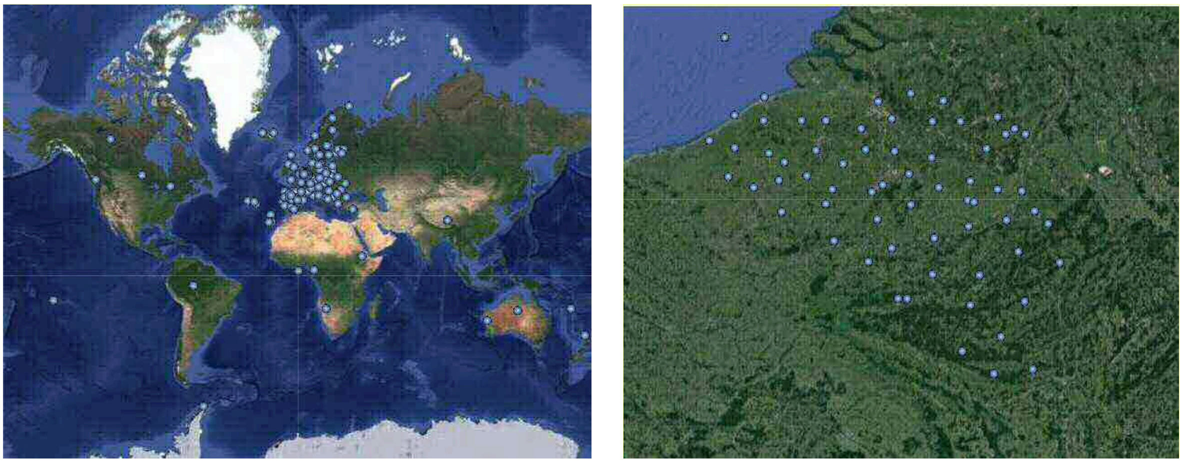

Figure 3.7.1: Left: network of 185 GNSS stations used in the operational real-time processing at ROB. Right: Zoom over Belgium showing the Belgian dense network.

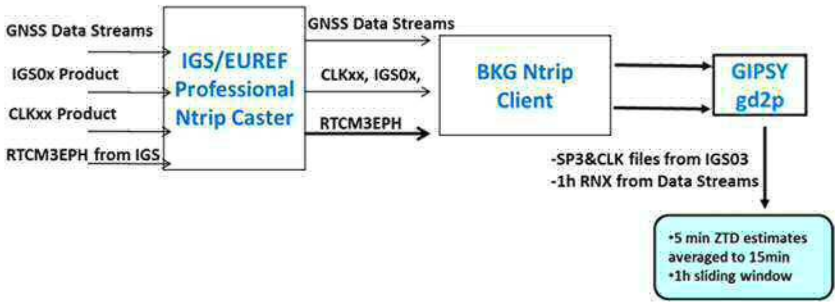

Figure 3.7.2: ASI/CGS Processing Scheme.

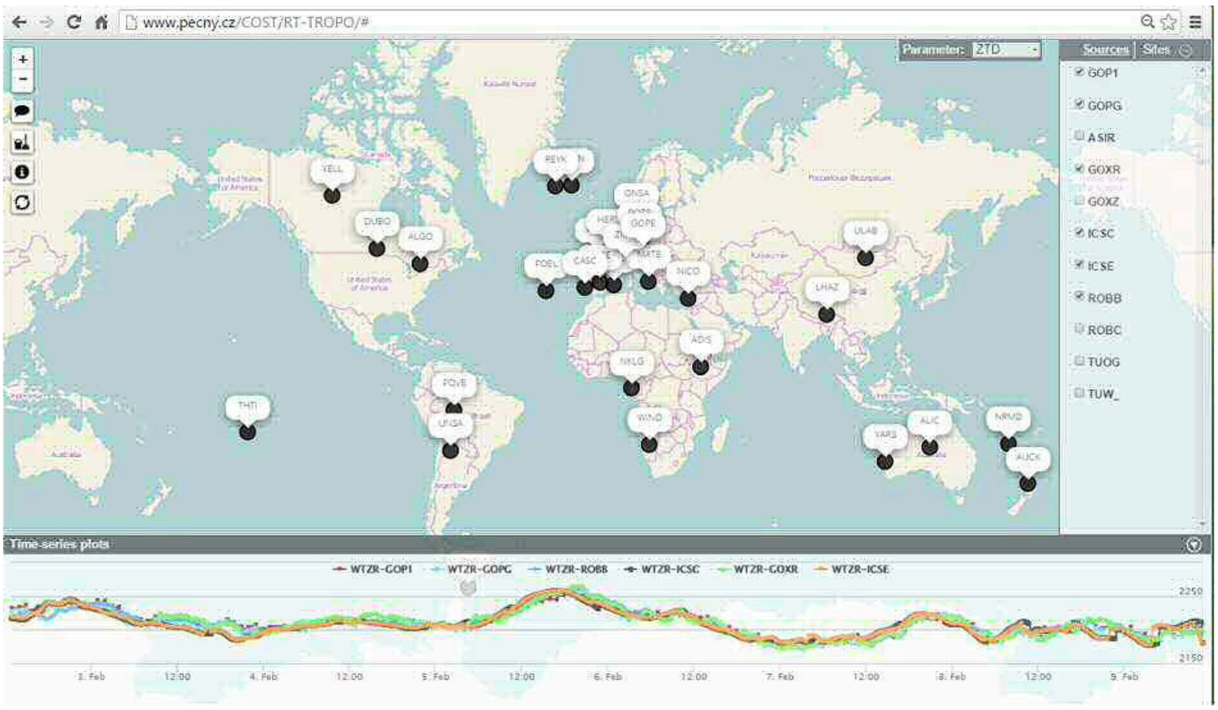

Figure 3.7.3: Web service for the monitoring of the GNSS4SWEC Real-Time Demonstration campaign.

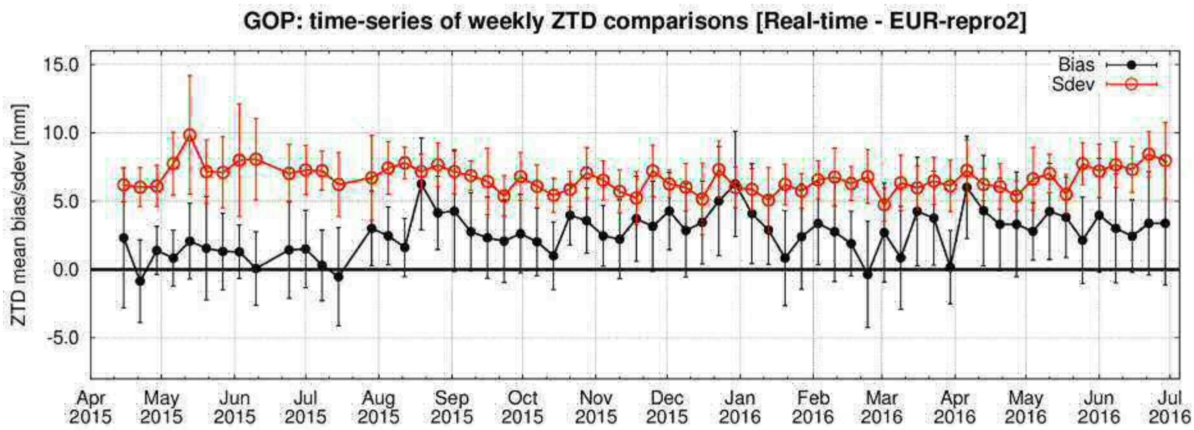

Figure 3.7.4: Long-term assessment of GOP real-time product: monthly mean biases and standard deviations over 38 European and global stations of the Real-Time Demonstration campaign.

Product optimisation and validation

Existing operational real-time ZTD productions at GOP and University of Luxembourg have been evaluated in European and global scopes (Douša and Václavovic, 2014; Ahmed et al., 2016), and comparing to the standard near real-time regional and global products officially contributing to E-GVAP (Douša and Václavovic, 2016). In addition to the Real-Time Demonstration campaign, monitoring and validation, several members carried out offline studies to optimize their strategy/software. Indeed, fine-tuning processing methodologies (i.e. comparing various processing schemes over the same dataset and period) and assessing their results could barely be done in a true real-time operation setup. Offline studies based on simulating real-time processing overcome this problem. To this aim, GOP and ROB used the dense network of the GNSS4SWEC WG1 Benchmark campaign (Douša et al., 2016), together with archived real-time IGS global orbit and clock products, for optimizing their real-time strategy using simulated real-time mode.

Using the offline studies, GOP has developed a hybrid scenario providing a new all-in-one or flexible solutions optimally mixing features of real-time (RT), and near real-time (NRT) processing modes (Douša et al. 2018), the latter using Kalman filter supported with a backward smoother (Václavovic and Douša, 2016) and both using RT and NRT data and products. GOP also assessed three different IGS global precise orbit and clock products, and showed that it resulted in small impacts on differences in real-time ZTD estimates, but indicated an overall systematic error of 2 mm for ZTD compared to (Douša et al., 2017). Similarly, ROB has used its real-time simulated setup and the benchmark to produce 320 ZTD/gradient dataset flavours (based on different constraints, constellation, orbit and clock products...), that was inter-compared and studied to define an optimized processing strategy. The evaluation of the real-time gradients has been performed by Kačmařík et al. (2018). WUELS worked on a strategy optimization (Hadaś et al., 2017) and proper GNSS weighting, due to the quality of real-time products for various systems, satellite blocks and types (Kaźmierski et al., 2017). GFZ validated real-time products including precise orbit/clock corrections, tropospheric parameters (Li et al., 2015b).

Other related activities

In addition to the main objectives of this working group mentioned in the introduction, several members have worked on the link between empirical tropospheric models, Numerical Weather Models (NWM) and GNSS real-time processing software. In that context, the GNSS workgroup at the Shanghai Astronomical Observatory has developed the SHAtrop empirical tropospheric model. The model improves the accuracy of real-time tropospheric modelling by ~30% over China continent. The SHAtrop model provides real-time ZTDs and enables the capabilities of decimetre-level real-time PPP (Chen et al. 2015, 2017). GFZ also investigated the use of real-time NMM data to augment the real-time GNSS precise positioning (Lu et al., 2016c, 2016d).

GOP demonstrated high-rate ZTD estimates and the use of NWM augmentation tropospheric corrections in GNSS high-rate observations carried out on board of a vertically flying hot-air balloon platform (Václavovic et al. 2017). Similarly, UNB used high-resolution NWM to augment their PPP processing (not yet in real-time) and investigated cases where the NWM information helps to stabilize solution and bring it to a sooner convergence.

As a first step towards developing true real-time tropospheric estimates and, thanks to the operation of Australian national positioning infrastructure (NPI) and GPSnet in the Victorian region, NRT ZTD information can be obtained with a very high spatial and temporal resolution for Victoria, Australia. Since 2015 a new Near Real-Time NRT ZTD monitoring platform has been established at SPACE Research Centre, RMIT. The platform can automatically retrieve GPS data from both NPI and the Victorian GPSnet and then determine NRT hourly ZTDs across about 154 stations. The ZTDs obtained are then converted to PWV by using surface meteorological observations (i.e. pressure and temperature). All the obtained NRT ZTDs are stored at the SPACE server with a delay of about half an hour, which provides valuable data source for the forecasting and study of severe weather events. At the moment, only the researchers at RMIT and the Australian Bureau of Meteorology can access the ZTD data, but we plan to make it accessible to the scientific community in the near future.

Link to the users, review product format and requirements

Initial link with the user community (meteorologists, forecasters, nowcasters) has been established via the Working Group 2 "Use of GNSS tropospheric products for high resolution NWM and sever weather forecasting" of the COST Action ES1206 (GNSS4SWEC) and via E-GVAP (objective 5). The use of real-time/ultra-fast tropospheric products for nowcasting and severe weather monitoring was advertised, and the user requirements and product format exchange was discussed (see also below). The impact of assimilation of GNSS high-resolution tropospheric horizontal delay gradients was estimated in a variational data assimilation in NWM (Zus et al., 2019). Improving GNSS ZWD interpolation by utilizing tropospheric gradients with a dense station network in central Europe in the warm season was demonstrated by Zus et al. (2019). In Belgium, ROB established a first link with the forecasters of the Royal Meteorological Institute (RMI) to advertise this activity and its potential use in their day-to-day forecast operation. In January 2019, GOP has started an operational real-time processing of all available EUREF real-time streams (150) for a continuous contribution to the E-GVAP.

Working group meeting and outreach

The first IAG WG 4.3.7 working group meeting took place in Wroclaw (September 5-7, 2016), along with the IAG Commission 4 Positioning and Applications Symposium. Six members participated, discussing individual developments and future goals. Actually, these discussions were started already a week before during the COST Action ES1206 Working Group meeting in Potsdam (September 1-2, 2016) by several group members. Related presentations and important discussions between provider and user communities took place during several E-GVAP annual meetings and IGS Workshop in Wuhan (2018), which included also completing the standardization of SINEX_TRO v2.0 format. The GNSS4SWEC Real-Time Demonstration campaign, related developments and product assessment were presented at the IAG C4 Symposium and the COST ES1206 Final Workshop in ESTEC, Noordwijk.

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WG 4.3.8: GNSS tropospheric products for Climate

Chair: *Rosa Pacione (Italy)*
Vice Chair: *Eric Pottiaux (Belgium)*

Members

Full Members: A. Araszkiewicz (Poland), F. Alshawaf (Germany), O. Bock (France), J. Dousa (Czech Republic), G. Dick (Germany), G. Halloran (United Kingdom), R. Heinkelmann (Germany), G. Liu Zhizhao (Hong Kong), T. Ning (Sweden), M. Santos (Canada), Y. Shoji (Japan), K. Stepniak (Poland), R. Van Malderen (Belgium), S. Vey (Germany), F. N. Teferle (Luxembourg), J. Wang (United States)

Corresponding Members: A. Klos (Poland), S. Zengin Kazanci (Turkey)

Activities and publications during the period 2015-2019

The Joint Working Group was established in 2015 with the approval of the terms of reference and objectives The main objectives targeted by the working group are: to assess existing reprocessed GNSS tropospheric products, foster the development of forthcoming reprocessing activities, test different homogenization methodologies to setup a common long-term homogenized dataset to be re-used for climate trends and variability studies, review and update GNSS-based product requirements and exchange formats for climate, and promote their use for climate research, including a possible data assimilation of GNSS troposphere products in climate reanalysis. The main targeted results and deliverables are datasets, reports and scientific papers, which have been elaborated in collaboration among the participants.

The activities of this working group continued within the main lines sketched by the WG3 during the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC: http://gnss4swec.knmi.nl/).

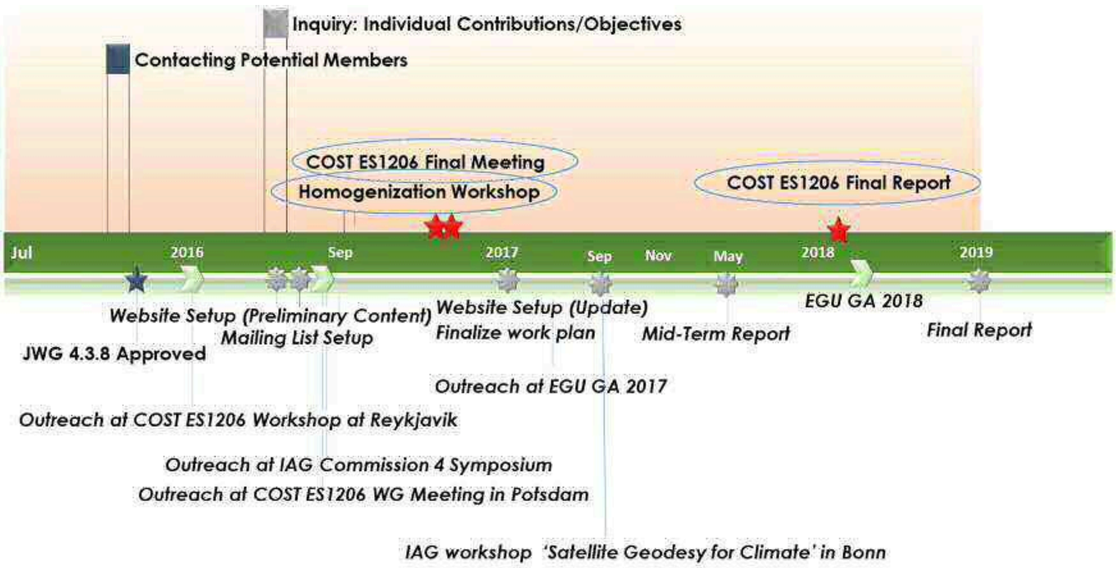

Figure 3.8.1: Timeline and Achievements.

The main objectives of this working group are: to assess existing reprocessed GNSS tropospheric products, foster the development of forthcoming reprocessing activities, test different homogenization methodologies to setup a common long-term homogenized data set to be re-used for climate trends and variability studies, review and update GNSS-based product requirements and exchange formats for climate, and promote their use for climate research, including a possible data assimilation of GNSS troposphere products in climate reanalysis.

The main targeted results and deliverables are data sets, reports and scientific papers, which will be elaborated in collaboration between the participants. During the period 2015-2017, the activities has followed the timeline reported in Fig. 3.8.1.

A dedicated website was set-up (http://iag-gnssclimate.oma.be/index.php, Figure_7) in order to disseminate the main outcomes for each of the five scientific objectives, and a dedicated mailing list (http://mailman-as.oma.be/mailman/listinfo/iag.gnssclimate**)** was established for the communication among the members. After an inquiry sent out to the members about their individual contribution(s), a work plan has been prepared and distributed. The work plan is also publicly available on the website at http://iag-gnssclimate.oma.be/Outreach/Documents.php.

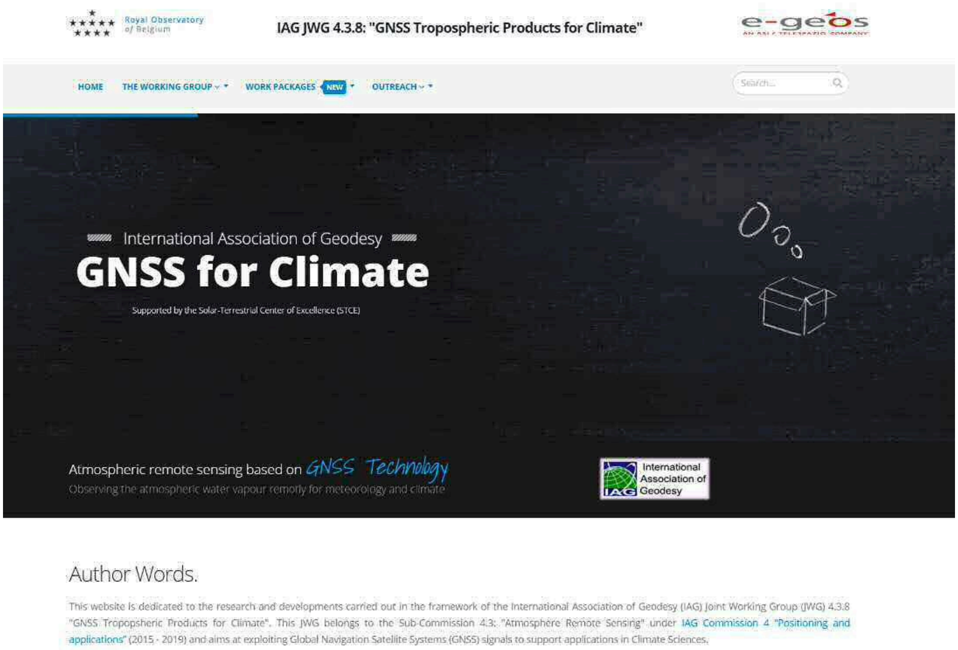

Figure 3.8.2: Screenshot of the main page of the website

Below are listed the main activities carried out during the 4-year period for each of the five scientific objectives.

Objective 1 REPRO:

Assess existing reprocessed troposphere solutions and provide recommendations for the forthcoming reprocessing activities.

International Reprocessing Activities:

- EUREF Tropospheric 2nd Reprocessing Campaign (Pacione, 2016, Pacione et al. 2017) *http://www.epncb.oma.be/_productsservices/troposphere/*

  A reference tropospheric dataset over Europe has been generated in the framework of the second EPN (EUREF Permanent Network) Reprocessing campaign, hereafter EPN-Repro2. A huge effort has been made by five EPN AC to homogenously reprocess the EPN network for the period 1996-2014 (from GPS week 0834 to 1824) for providing solutions that are the basis for deriving new coordinates, velocities, and troposphere parameters for the entire EPN. The individual contributions are then combined in order to provide the official EPN reprocessed products. The EPN-Repro2 tropospheric dataset is open to the user community. Solutions (eu0wwww7.tro.Z, where wwww is the GPS week) in SINEX-TRO format along with a summary file (eu0wwww7.tsu.Z) with some statistics about it, can be downloaded at the EPN-Repro2 product directory at the BKG data center. For each EPN stations time series files are available here. The dataset has been evaluated against radiosonde data and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) data.

- TIGA Reprocessing Campaign *http://adsc.gfz-potsdam.de/tiga/index_TIGA.html*

  The consortium of the British Isles continuous GNSS Facility (BIGF) and the University of Luxembourg TIGA Analysis Centre (BLT), as one of the ACs contributing to the IGS Tide Gauge Benchmark Monitoring (TIGA) Working Group, completed a new solution using up to 750 GPS stations with global distribution and observation time spans of 6 to 21 years. The selected station network included all IGb08 core stations and more or less the complete archive of TIGA, which encompasses a large number of GPS stations at or near the global network of tide gauges. The GPS data was re-processed using the Centre for Orbit Determination in Europe (CODE) final precise orbits and Earth orientation parameters. The IGS08 satellites and receiver antenna phase center models were employed and an elevation cut-off angle of 3° was adopted. In the reprocessing, the Vienna Mapping Function 1 (VMF1) was used. It allows the mapping function to describe the atmosphere with the finest detail, leading to the highest precision in the derived tropospheric parameters. We also modelled the azimuthal asymmetry in the troposphere using gradient (tilt) corrections in North-South direction (GN) and in East-West direction (GE), following Chen and Herring [1997]. In BSW52 the ZHD is parameterized as a piece-wise function variation of the delay using a piecewise linear interpolation between temporal nodes. Observations of atmospheric pressure at the GPS station offer high precision for the ZHD estimates and minimize station height errors. However, many of the TIGA and IGS stations do not possess integrated meteorological sensors. Thus, ZHD in units of meters was a priori obtained reliably from surface pressure data from the gridded output of the ECMWF NWP model, and is provided by VMF1 using the modified Saastamoinen model, which assumes that the atmosphere is in hydrostatic equilibrium. The ZTD parameters were estimated in an interval of 1 hour with a loose constraint of 5 meters. In addition, horizontal gradients in the North-South and East-West directions are estimated in a 24 hour interval with the same 5 meters loose relative constraint.

- GRUAN Reprocessing Campaign *http://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/gruan/*

  The Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) of the World Meteorological Organization (WMO) is an international observing network, designed to meet climate requirements. Upper air observations within the GRUAN network will provide long-term high-quality climate records. The data will be used to constrain and validate data from space based remote sensors, and for scientific studies of atmospheric processes.

National Reprocessing Activities

- CORDEX.be Reprocessing Campaign (Belgium) *http://cordex.meteo.be/*

  The CORDEX.be project brought together the Belgian climate and impact modelling research groups into one network as the first step towards the realization of climate services. It is based on the international CORDEX ("COordinated Regional Climate Downscaling Experiment") project but the ".be" indicates that it goes beyond for Belgium. Within CORDEX.be, a specific task is dedicated to the validation of the high-resolution (3 to 5 km spatial resolution) climate simulations using GNSS-derived products. Therefore, a careful reprocessing of the historical observations at about 320 world-wide GNSS stations has been carried out for the period 2000-2010 (period of assessment for the models). First results show that the 4 climate models participating in this project correlate well with the GNSS-derived products.

- Historical Reprocessing of the German Network (SAPOS).
- Reprocessing of the Japanese nationwide GNSS network (established mid-90's) to derive GNSS-based PWV (Precipitable Water vapour) using IGS's 2nd reprocessed ephemerides (IG2).
- IPGP-IGN (former IGN/LAREG) prepared a new enhanced global IWV dataset (436 stations over the 1994-2018 period) built up from CODE REPRO_2015 solution for the period 1994-2014 and CODE operational solution for the period 2015-2018 (Bock, 2019). Consistency between the two data streams has been checked on the common year 2014. The ZTD data are based on long-arc (3-days) solutions produced by AIUB (University of Berne) with a time sampling of 2 hours. The ZTD data have been screened based on a range-check and outlier check, and converted to IWV using ERA-Interim pressure level data (one every 6 hours) with bi-linear horizontal interpolation from four surrounding grid points. Daily and monthly IWV values are available from AERIS data portal (https://en.aeris-data.fr/)..

Objective 2 HOMO

Set-up a common GNSS climate dataset on which different homogenisation methodologies can be tested. The homogenised common long-term dataset can then be re-used for climate trends and variability studies within the community.

In the last years, several groups studied the homogeneity of the re-processed GNSS ZTD time series. They clearly showed evidence that these time series, even if carefully reprocessed, still suffer from inhomogeneity which e.g. may impact the calculation of the long-term water vapour trend (and its associated error), hence preventing a correct and precise interpretation in terms of climate change and time variabilities. Consequently during the COST Action ES1206 (GNSS4SWEC), a sub-WG was formed with the aim to inter-compare different statistical methods that detects change points in time series, identify their capability, advantages and drawbacks in identifying these change points, with the final goal to come up with a homogenised dataset for further climate trends and variability studies within the community. These activities have been a follow-up of the GNSS4SWEC sub-WG3 on data homogenisation. In that context a specific attention will be given to the available meta-data necessary for the homogenization, process and their exchange format (see also objective 4 on product requirements and exchange formats). The ultimate objective if this activity is to use the homogenized long-term datasets for further studies, e.g. determination of the long-term trends of the water vapour, and/or investigation the temporal and spatial variability of the water vapour

To assess the performance of the different statistical methods synthetic datasets with increasing complexity level and mimicking the characteristic of the actual dataset (i.e. the dataset that we wanted to homogenise) have been created. It was then asked to run each statistical method on each synthetic dataset and on daily and monthly aggregated time series, when possible. The performance was then assessed in terms of statistical and probabilistic scores and skills, but also in terms of CRMSEs and trend bias. In total 13 break detection methods (from 8 operators) have been evaluated. The statistical methods includes 1) t-test with cutting algorithms, 2) t-test with cutting algorithms, 3) t-test with cutting algorithm, and 4) t-test with cutting algorithms. Recently, a new R-package dedicated to the homogenization of daily differenced GNSS IWV series (candidate minus reference series) was developed at IPGP-IGN (former IGN/LAREG). The segmentation algorithm is based on the classical model of a Gaussian random process with the unknown means and multiple breakpoints, modified to account for specific characteristics of the GNSS – ERAI differences: a monthly varying variance (Bock et al., 2018) and a seasonal bias represented by a Fourier series of order 4 (Quarello et al., in preparation). A penalized maximum likelihood approach is used with several different penalty criteria implemented. The R-package provides diagnostics such as the sum of squares, estimated parameters, their formal errors, etc., to select the best solution. A fully automatic mode is also implemented. The R-package "GNSSseg" is available on the Comprehensive R Archive Network (https://cran.r-project.org/).

A review of the homogenization activity has been presented at EGU General Assembly 2019 (Pottiaux et al., 2019). The assessment of the performance of the different contributing homogenization algorithms on the break identification for three different sets of benchmark time series (with different complexity on the used noise model, the presence of gaps and trends) will be submitted to JGR – Atmospheres in 2019.

Objective 3 ASSIM:

Advocate the data assimilation of GNSS troposphere products in Climate Re-Analysis.

Activities carried out during the period 2015-2019:

- At University at Albany: use GNSS PW (Precipitable Water) data to develop PW diurnal matrices and validate weather and climate models, and plan to deploy a GNSS receiver in a fix or mobile mode for New York State Mesonet validation and calibration.
- At the Met Office: As part of the European FP7 UERRA (Uncertainties in Ensembles of Regional Re-analysis, http://www.uerra.eu/) project, EPN-Repro2 reprocessed Zenith Total Delay observations were assimilated into a European regional climate model, which produced a climate reanalysis for 1979 to 2014. Zenith Total Delay observations were bias corrected using an online bias correction to account for any evolution of systematic bias. The regional reanalysis data is available through the UERRA website.
- At Hong Kong Polytechnic University: collaboration with the China Meteorological Administration (CMA) scientists to evaluate PW accuracy of CMA's weather satellites' various PW products, using GNSS-derived and other PW data (such as WVR) as a reference.
- At GFZ: In recent publications (Alshawaf et al. 2016 and Alshawaf et al. 2018) the temporal trends estimated from GNSS time series are compared with those estimated from European Center for Medium-Range Weather Forecasts Reanalysis (ERA-Interim) data and meteorological measurements to evaluate climate evolution in Germany by monitoring different atmospheric variables such as temperature and PWV (Precipitable Water vapour). PWV time series were obtained by three methods: 1) estimated from ground-based GNSS observations using the method of Precise Point Positioning (PPP), 2) inferred from ERA-Interim reanalysis data, and 3) determined based on daily in situ measurements of temperature and relative humidity. The other relevant atmospheric parameters are available from surface measurements of meteorological stations or derived from ERA-Interim. The trends are estimated using two methods; the first applies least squares to seasonally adjusted time series and the second using the Theil-Sen estimator. The trends estimated at 113 GNSS sites, with 10 and 19-year temporal coverage varies between −1.5 and 2 mm/decade with standard deviations below 0.25 mm/decade. These values depend on the length and the variations of the time series. Therefore, we estimated the PWV trends using ERA-Interim and surface measurements spanning from 1991 to 2016 (26 years) at synoptic 227 stations over Germany. The former shows positive PWV trends below 0.5 mm/decade while the latter shows positive trends below 0.9 mm/decade with standard deviations below 0.03 mm/decade. The estimated PWV trends correlate with the temperature trends.

We have determined linear trends of IWV from synchronized time series of VLBI and GNSS atmospheric parameters as well as from ECMWF ERA-Interim at co-located sites. The three solutions were all determined at GFZ. The GNSS solution was part of the second TIGA reprocessing solution that included 840 stations in total (Deng et al., 2016) and the numerical weather model was exploited applying the Direct Numerical Simulation (DNS) software (Zus et al. 2012; 2014; 2015). The VLBI solution was determined by the VLBI group at GFZ with the software VieVS@GFZ (Nilsson et al. 2015). The linear IWV trends show a range of values below 1 kg/m^2 / yr magnitude with positive and negative signs. The linear trends significantly vary depending on the start and end date of the time series what is probably caused by the large seasonal signals that show inter-annual variations. Some linear trends are quite small or even insignificant. The agreement between the techniques is rather low and sometimes the trends show different signs. As an explanation for the disagreement, we suppose several data analysis aspects that affect the determination of atmospheric parameters.

VLBI for Climate: As part of the assessment we investigated the sensitivity of linear trends determined by VLBI w.r.t. various analysis options. One possibility for the trend differences might be the usage of different delay and gradient mapping functions. We tested three mapping functions: GPT2w (Böhm et al. 2015), Potsdam Mapping Function (PMF), and VMF1 (Böhm et al. 2006), but did not find significant different IWV trends. The largest effect on the trends was found to be the usage of atmospheric pressure in the analysis of space geodetic techniques. The atmospheric pressure enters the a priori hydrostatic zenith delay models in VLBI and GNSS analyses. A trend in the a priori hydrostatic zenith delays in the sequel propagates into the trend of the non-hydrostatic zenith delays that is directly proportional to the IWV trend. In contrast to other space geodetic techniques, VLBI data have been recorded together with atmospheric pressure records from nearby meteorological sensors. As any longer time series of meteorological data, these recordings need to be homogenized. This has been done in the past and was recently repeated (Balidakis et al. 2016). The usage of different atmospheric pressure data for the analysis of space geodetic techniques results in significantly different IWV trends (Balidakis et al. 2017).

- IPGP-IGN and LATMOS analysed IWV from GPS observations and two modern atmospheric reanalyses (ERA-Interim and MERRA-2) for the period 1995–2010. Means, variability and trend signs were in general good agreement. Regions and GPS stations with poor agreement were investigated further. Representativeness issues, uncertainties in reanalyses, and inhomogeneities in GPS were evidenced. Reanalyses were compared for an extended period, and a focus on North Africa and Australia highlighted the impact of dynamics on water vapour trends (Parracho et al., 2018). Consistency and representativeness differences between GPS IWV data and ERA-Interim reanalysis were further investigated. It was shown that both average and extreme representativeness differences exhibit a strong location dependence (due to station specific geographic, topographic, and climatic features). A methodology for reducing the representativeness errors and detecting the extreme, outlying, cases was proposed (Bock and Parracho, 2019).
- Berckmans et al. (2018) used the EPN-Repro2 IWV dataset to evaluate the regional climate model ALARO running at 20 km horizontal resolution and coupled to the land surface model SURFEX, driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data.
- SMHI (Swedish Meteorological and Hydrological Institute) is contracted to provide the Regional Reanalysis for Europe by the EU Copernicus Climate Change Service (C3S_322 Lot 1). A high-resolution (5 km grid) reanalysis from the early 1980's up to today will be delivered. It uses state-of-the-art data assimilation and a wide range of observations including many remote sensing instruments. GNSS Zenith Total Delay observations are

planned to be used in the HARMONIE-ALADIN modelling system. There is several years operational experience of using near real-time data at SMHI and its partner institutes. There is a variational bias correction used and a white list of stations to be considered reliable. The EPN-Repro2 data (Pacione et al. 2017) from 1997-2014 have been retrieved, resorted and re-formatted for assimilation. A 4-week test assimilation has shown that it works and the data give a reasonable and small positive impact. In addition, the operational EPN product will be accessed after 2014.

- Van Malderen et al. (2018) compare and investigate different aspects of the Integrated Water Vapour (IWV) variability for the period 1995/96-2010 at 118 globally distributed Global Positioning System (GPS) sites, using additionally UV/VIS satellite retrievals by GOME, SCIAMACHY and GOME-2 (denoted as GOMESCIA below), and ERA-Interim reanalysis output at these site locations: the geographical distribution of the frequency distributions of the IWV time series, the seasonal cycle and linear trend differences among the three different datasets. Finally, we reconstruct the monthly mean IWV time series by means of a stepwise multiple linear regression from the mean annual cycle, the linear trend, and a selection of regionally dependent candidate explanatory variables.

Objective 4 FORMAT:

Review and update GNSS-based product requirements and exchange format for climate. An effort on SINEX-TRO standardization is on-going in collaboration with the GNSS4SWEC WG3, E-GVAP, IGS, EUREF, and GRUAN. The collection, exchange format, and usage of meta-data information (particularly important for the processing and for the homogenisation) might be revisited in this context.

Interaction with other research programmes

Collaboration/cooperation is on-going with researchers from national, European and international organisations through participation of experts to the working group activities:

1. IGS (The International GNSS Service, *http://www.igs.org*), including the IGS Troposphere and the TIGA (The GPS Tide Gauge Benchmark Monitoring, *http://adsc.gfz-potsdam.de/tiga/index_TIGA.html*) working groups.
2. EUREF (The Reference Frame Sub-Commission for Europe, *http://www.euref.eu*).
3. GRUAN (The GRUAN GNSS-PW Task Team, *http://www.dwd.de/EN/research/international_programme/gruan/tt_gnss-pw.html*).
4. E-GVAP (The EUMETNET EIG GNSS water VApour Program, *http://egvap.dmi.dk*).
5. European FP7 project UERRA (Uncertainties in Ensembles of Regional Re-analysis, *http://www.uerra.eu/*).
6. GEWEX water vapor assessment (G-VAP, *http://gewex-vap.org*).
7. IAG JWG 1.3: Tropospheric ties.

Outreach Presentations

The activities of the working group have been presented at the following conferences:

- IAG JWG 4.3.8: GNSS tropospheric products for Climate, R. Pacione, E. Pottiaux and JWG members, COST ES1206 Workshop, 8-10 March 2016, Reykjavik, Island.

- IAG JWG 4.3.8: GNSS tropospheric products for Climate, E. Pottiaux, R. Pacione and JWG members, IAG Commission 4 Symposium Wroclaw, Poland, 4-7 September 2016 http://www.igig.up.wroc.pl/IAG2016/.
- IAG JWG 4.3.8: GNSS tropospheric products for Climate: Objectives and Future Plans, R. Pacione, E. Pottiaux, and JWG members, EGU GA, Vienna 23-28 April 2017, http://meetingorganizer.copernicus.org/EGU2017/EGU2017-8332.pdf.

An IAG workshop on 'Satellite Geodesy for Climate' was organized in September 19-21, 2017, in Bonn, Germany. This was a joint workshop between the IAG SC 2.6: 'Gravity and Mass Transport in the Earth System', the IAG JWG 2.6.1: 'Geodetic Observations for Climate Model Evaluation', and the IAG JWG 4.3.8: 'GNSS Tropospheric Products for Climate'.

These two JWGs are the pillars for the foundation of the IAG Inter-Commission Committee on 'Geodesy for Climate Research' (ICCC). It will be proposed, and most likely accepted, during the next IUGG conference in Montreal in July 2019, and will continue the roadmap initiated at the successful workshop 'Satellite Geodesy for Climate Studies', which, for the first time, brought together geodesists representing all different observation techniques and climate scientists in a dedicated framework.

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WG 4.3.9: GNSS-R

Chair: *Felipe Nievinski (Brazil)*
Vice Chair: *Thomas Hobiger (Sweden)*

Members

Karen Boniface (France), Estel Cardellach (Spain), Rüdiger Haas (Sweden), Kosuke Heki (Japan), Yukihito Kitazawa (Japan), Kristine Larson (USA), Wei Liu (Germany), Manuel Martín-Neira (Europe), Miguel Ribot (Switzerland), Nicolas Roussel (France), Maximilian Semmling (Germany), Joakim Strandberg (Sweden), Sajad Tabibi (Luxembourg), Sibylle Vey (Germany), Kegen Yu (China), Wei Wan (China), Jens Wickert (Germany), Simon Williams (UK)

Activities and publications during the period 2015-2017

A kick-off meeting was organized during the European Geophysical Union General Assembly on 20 April 2016. It was attended by Thomas Hobiger, Estel Cardellach, Maximilian Semmling, Yukihito Kitazawa, and Nicolas Roussel on site and Felipe Nievinski remotely. Felipe prepared and sent slides to the whole IAG WG prior to the meeting. Simon Williams provided comments via email. During the meeting, the ten objectives of the WG were reviewed and revised. Minutes of the meeting were prepared and circulated among WG members on 25 May 2016; a copy is provided in Annex II.

We established liaisons with neighboring organizations, such as the Permanent Service for Mean Sea Level (PSMSL) and the IEEE Geosciences and Remote Sensing Society (GRSS). It should be noted that IEEEE GRSS has its own GNSS-R working group, though it has a broader scope than WG 4.3.9.

The WG scope has been clarified so as to contemplate two types of geodetic GNSS-R. It now includes both the retrieval of GNSS-R environmental parameters by means of geodetic instrumentation and the utilization of generic GNSS-R information to aid in geodetic positioning. Ground-based soil moisture retrievals derived from IGS tracking station data would be an example of the former type of geodetic GNSS-R. Airborne GNSS-R soil moisture retrievals, later used to correct for seasonal loading at co-located ITRF sites, would be an example of the latter type. It was proposed that GNSS-R tide gauges for sea level monitoring be the IAG WG flagship data product, as it is perceived as the most mature target for geodetic GNSS-R.

In June 2016 an abstract titled "Current status and future activities of the IAG/GGOS joint working group 4.3.9 on GNSS reflectometry" was submitted to the IAG Commission 4 Symposium. The poster was later presented, on 4-7 September 2016, by Jens Wickert in Wroclaw, Poland. An inter-comparison campaign on GNSS-R for sea level monitoring was announced on 16 August 2016. It was planned as an opportunity to validate retrieval solutions from independent research groups under comparable conditions. Results will also serve to showcase the level of maturity attained with this technique as a potential GGOS data product. Measurements collected at a sea-facing location having a conventional tide gauge nearby were made available to the WG members. We have started with station GTGU at the Onsala Space Observatory for the one-year period from 1st July 2015 to 31 June 2016. The 1-Hz GNSS data (8 GB size) was generously provided by the team at Chalmers University (Rüdiger Haas, Thomas Hobiger, and Joakim Strandberg).

Five groups submitted retrieval solutions for the inter-comparison campaign: Chalmers University, Sweden; University of Luxembourg, Luxembourg and Federal University RGS, Brazil; GFZ Potsdam, Germany; University of Toulouse, France; and the National Oceanography Centre, UK. Initial comparison between GNSS-R and the conventional tide gauge indicate very high correlation (0.99), centimeter-level error (2-3 cm), and few-percent bias regression slope bias (1-4% overestimation) in sea level height for some solutions. Figure 1 and 2 illustrate the conditions.

In January 2017 the campaign goals and preliminary results were summarized and submitted as an abstract for the session "Geodetic remote sensing", part of the Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior. The event is to be held in Kobe, Japan, from July 30 to August 4, 2017 and the session is convened by Michael Schmidt and co-convened by WG members Jens Wickert and Felipe Nievinski. The WG was well represented at the GNSS+R 2017 – Specialist Meeting on Reflectometry using GNSS and other Signals of Opportunity (23-25 May 2017, in Ann Arbor, U.S.), with 15 presentations as listed in Annex I. For the next edition of the event, GNSS+R 2019 (20-22 May 2019, in Benevento, Italy), again several abstracts have been submitted by WG members and selected for presentation, as listed in Annex III.

In the year 2018 the WG suffered a hiatus period, although members remained active in their individual efforts related to GNSS-R. Annex IV lists all publications related to GNSS-R by WG members during the 2015-2019 term.

In early 2019 activities resumed, with the finalization of a 15-page manuscript reporting results from the first inter-comparison campaign, to be submitted to the Journal of Geodesy. A summary was submitted and accepted for presentation at the 27th IUGG General Assembly (08-18 July 2019, Montreal, Canada).

The rest of the term was spent on pending objectives. We have started an inventory of GNSS stations demonstrated in the literature for reflectometry purposes, focusing on sea-level sensing; Table 3.9.1 indicates the stations that have been used in multiple studies, while Annex VI lists these instances in more detail. Finally, tentative GNSS-R site guidelines for multi-purpose GNSS stations were drafted but have not reached final form (Annex VII).

In summary, the WG objectives were met as follows:

1. Identify GNSS-R products which have a strong relation to IAG services and goals: *relevant GNSS-R products were identified during kick-off meeting.*
2. Foster and establish interactions with neighboring societies (such as the IEEE Geoscience and Remote Sensing Society, GRSS) and cooperate with technological, engineering, and operational entities related to GNSS (e.g., the International GNSS Service, IGS), identifying common goals and detecting potential synergies: *implemented in the first year.*
3. Provide an online inventory of GNSS-R products relevant to geodesy and point to corresponding data archives: *not developed.*
4. Evaluate the possibility to obtain formal errors for GNSS-R products in order to enable better combination with other data-sets: a*n initial uncertainty evaluation was performed and reported as part of the first inter-comparison campaign.*
5. Provide guidelines and define formats for GNSS-R products being used for geodetic purposes: *not developed.*
6. Organize working meetings with GNSS-R experts, while also inviting stakeholders from the geodetic community to participate in such events: *WG members took part in the organizing committee for the IEEE GNSS+R meetings.*
7. Extend IGS Site Guidelines so as to maximize the shared usefulness of new GNSS site installations for reflectometry applications: *a tentative version was provided.*
8. Supplement the GNSS-R Campaign Spreadsheet (initiated by the IEEE GRSS) so as to list existing GNSS tracking stations that can be leveraged for reflectometry purposes: *an initial version was provided.*
9. Evaluate the feasibility of a pilot project on GNSS-R for coastal sea level monitoring, demonstrating its current level of maturity towards an operational service; possibly in cooperation with the IGS Tide Gauge WG (IGS-TIGA): a *first inter-comparison campaign was successfully accomplished.*

10. Plan future inter-comparison campaigns for the cross-validation of theoretical model simulations and measurement parameter retrievals: *future campaigns were outlined at the end of the manuscript.*

Table 3.9.2: Number of articles reporting on each GNSS station.

Station	Occurrences
SC02	5
GTGU	5
BRST	4
SPBY	3
BUR2	3
PBAY	2

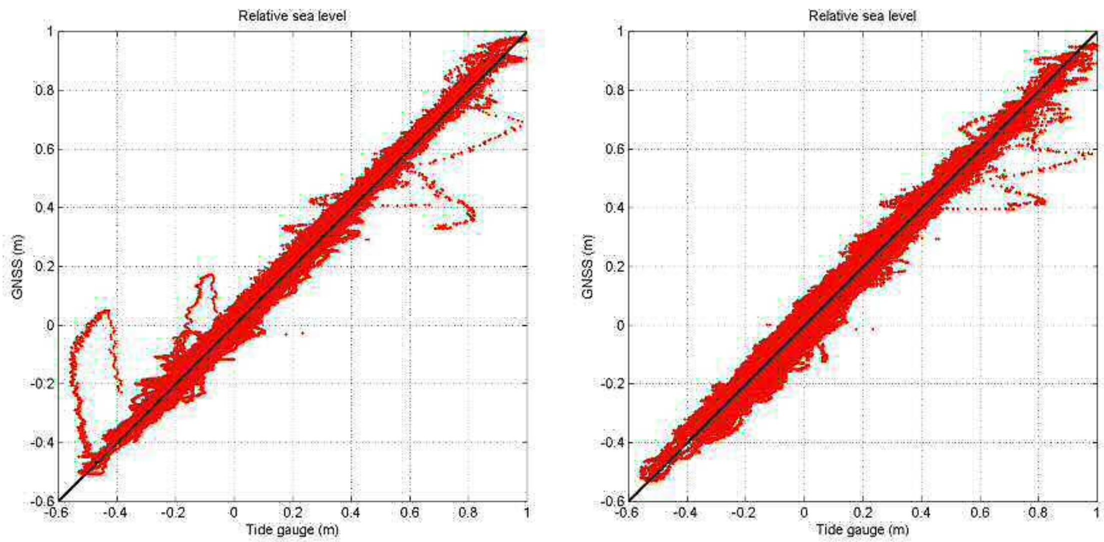

Figure 3.9.1: Two representative solutions of the GNSS-R sea level inter-comparison campaign.

Figure 3.9.2: Photograph of the first inter-comparison site at Onsala Space Observatory, Sweden.

Annex I: Presentations by WG members at the GNSS+R 2017 Workshop

- "IAG/GGOS inter-comparison campaign on SNR-based GNSS reflectometry for sea level monitoring" by Felipe Nievinski, Thomas Hobiger, Karen Boniface, Rüdiger Haas, Wei Liu, Nicolas Roussel, Joakim Strandberg, Sajad Tabibi, Sibylle Vey, Jens Wickert, and Simon Williams;

- "Tropospheric delays in ground-based GNSS multipath reflectometry – Towards a unified angular/linear refraction model using ray-tracing simulations" by Felipe Nievinski and Simon Williams;
- "GNSS multipath reflectometry for coastal sea level monitoring: Extended dynamic model based on the sea vertical acceleration" by Sajad Tabibi and Felipe Nievinski;
- "Troposphere self-calibration in ground-based GNSS-R" by Thomas Hobiger, Joakim Strandberg, and Rüdiger Haas;
- "Retrieving sea surface heights by inverse modeling of GNSS SNR data" by Joakim Strandberg, Thomas Hobiger, and Rüdiger Haas;
- "GNSS as a sea ice sensor – detecting coastal freeze states with ground-based GNSS-R" by Joakim Strandberg, Thomas Hobiger, and Rüdiger Haas;
- "Synoptic iGNSS-R altimetry from aircraft using SPIR" by Estel Cardelach et al.;
- "The Bi-Band Software PARIS Interferometric Receiver" by Estel Cardelach et al.;
- "Wavpy: an open-source tool for the GNSS+R community" by Estel Cardelach et al.;
- "The GRAIS project: one year of GNSS reflectometry in Antarctica" by Estel Cardelach et al.;
- "A Fram Strait Experiment: Sensing Sea Ice Conditions using Shipborne GNSS Reflectometry" by Maximilian Semmling, Jens Wickert, et al.;
- "A new era in space-borne GNSS Reflectometry: Potentials in near real time storm scale predictions" by Jens Wickert et al.
- "GNSS Reflectometry onboard the International Space Station with GEROS-ISS: Review of activities and current status" by Jens Wickert, Manuel Martin-Neira, Estel Cardelach, et al.;
- "Reduced GEROS-ISS Mission" by Manuel Martin-Neira, Jens Wickert, Estel Cardelach, et al.;
- "Snow Depth Estimation Based on Multipath Phase Combination of BDS Triple-Frequency Signals" by Kegen Yu et al.;
- "PBO H2O 2012-2017: Environmental Products from GPS Reflections" by Kristine Larson et al.

Annex II: Minutes of the kick-off meeting

The kick-off meeting started at 3 pm local time and lasted for 90 minutes. It was attended by Thomas Hobiger, Estel Cardellach, Maximilian Semmling, and Nicolas Roussel on site and Felipe Nievinski remotely. FN sent slides to the whole IAG WG prior to the meeting. Simon Williams (UK) provided comments via email. FN started reviewing the ten objectives as given in the terms of reference.

Objective #1, *"Identify GNSS-R products which have a strong relationship to IAG services and goals,"* lead to two forms of geodetic GNSS-R products: internal ones, with the IAG as a consumer (i.e., GNSS-R providing ancillary products for geodetic purposes); and external products, with the IAG as a producer (e.g., environmental by-products of geodetic instruments enabled by GNSS-R). The following possibilities of geodetic GNSS-R products were raised: sea level, snow depth, soil moisture, vegetation, and sea state. FN suggested that sea level could serve internally for ocean tidal loading and externally for coastal altimetry; SW found the internal contribution non-significant as it could only improve current tidal models at locations where no tide gauges exist. FN remarked that ground-based snow depth and soil moisture could serve internally as input for hydrological loading corrections in GNSS positioning and externally for weather/climate monitoring. MS mentioned that air- and space-borne platforms should be considered in addition to ground-based networks, especially for sea altimetry. FN remarked that retrievals of vegetation (biomass, greenness, etc.) and sea state (wind waves) were less well developed, and proposed GNSS-R tide gauges as the IAG WG flagship product, as it is perceived as the most mature target for geodetic GNSS-R.

Objective #2 was titled *"Foster and establish interactions with neighboring societies (e.g., IEEE GRSS) and cooperate with entities related to GNSS (e.g., the IGS), identifying common goals and detecting potential synergies."* FN added on the geodetic side the IGS Tide Gauge Benchmark Monitoring WG (IGS TIGA) and the Global Geodetic Observing System (GGOS); and on the oceanographic side the Global Sea Level Observing System (GLOSS), the Permanent Service for Mean Sea Level (PSMSL), and the Système d'Observation du Niveau des Eaux Littorales (SONEL). FN indicated the IAG WG could benefit from having liaisons with these organizations. EC had offered to bridge efforts with the IEEE WG, which she co-chairs. SW volunteered to serve as liaison with the PSMSL and IGS-TIGA, of which he is already a member. FN identified as shared goals with the IEEE WG two of its resources that had been recently publicized within the IAG WG: the GNSS-R discussion list, hosted by NASA/JPL, and which has a wider scope compared to the IAG WG mailing list; and the campaign spreadsheet, initiated by EC and recently augmented by MS, which could be further extended so as to include geodetic networks – EC advised to create a separate sheet in the IEEE WG spreadsheet for that. As for the IGS, common goals could include: mass loading corrections, improved site guidelines, and tide gauge leveling. With regard to oceanographic organizations, shared interests would be, again, tide gauge leveling and also shared GNSS data.

At this point EC was kindly invited to present an overview of GNSS-R opportunities, based on the technical report "State of the Art Description Document," prepared as a deliverable of the ongoing E-GEM project (available at <www.e-gem.eu>). EC first discussed the applicability of various GNSS-R retrieval algorithms in three platform altitudes (ground, air, and space) for a number of products: altimetry (sea level), scatterometry (sea wind and waves), sea surface salinity, soil moisture, vegetation/biomass, and the cryosphere (snow, sea-ice, and glaciers). Then she summarized how the GNSS-R spatial resolution varied with receiver altitude as well as transmitter elevation angle; and illustrated the global coverage for multiple GNSS constellations. Finally, EC described the latest and upcoming spaceborne GNSS-R missions, including UK-TDS1, 3Cat-2, CYGNSS, and GEROS-ISS. TH and MS asked about the data availability of the first ongoing mission; EC responded that vast quantities of delay-Doppler maps as well as a few raw data sets are freely available.

Discussion resumed on the objectives, with #3 reading "*Provide an online inventory of GNSS-R products relevant to geodesy and point to corresponding data archives*." FN pointed out the current scientific debate on reproducibility and open science in general, emphasizing that open data – including output retrievals, input measurements, and in situ validation – could help protect against unwarranted claims in the literature and serve as a solid foundation for further development in retrieval algorithms. FN indicated that geodetic GNSS-R products can be a result of a near operational service, one-off efforts, or can be periodically updated and extended for longer time series. It was proposed that the IAG WG could host a webpage linking to geodetic GNSS-R products, such as the PBO-H2O portal (University of Colorado Boulder) and eventually similar efforts by other research groups worldwide.

Objective 8 was considered next, as it was closely related to #3: "*Supplement the GNSS-R Campaign Spreadsheet (initiated by the IEEE GRSS) so as to list existing GNSS tracking stations that can be leveraged for reflectometry purposes.*" FN rephrased it as "build a list of publicly-known GNSS stations demonstrated for GNSS-R purposes in the literature." It could include both temporary campaigns and continuously-operating reference stations. While the previous objective #3 focused on products or output retrievals, the current objective #8 considered input measurements (#8). At least metadata should be provided in case any dataset is too large. Volunteers would be needed so as to draft such a listing; NR suggested that PhD students could be appropriate candidates.

Straddling the two previous objectives, #3 and #8, FN volunteered to curate a topical geodetic GNSS-R data repository, for researchers interested in publicizing their article's data (input, output, and validation) in machine-readable format. He envisioned leveraging existing software-as-a-service infrastructure – such as figshare, Dryad, and Dataverse – to facilitate citations and track usage (via, e.g., DataCite Digital Object Identifiers). Potential contributing authors would get credit for their data collection efforts and be allowed to impose preferred usage policies at their discretion.

Objective #5 is connected to both #3 and #8: "*Provide guidelines and define [data and metadata] formats for GNSS-R products being used for geodetic purposes [as well as geodetic measurements being used for GNSS-R purposes]*" [portions in brackets are absent in the official terms of reference]. FN argued that the format of output products may be left up to their respective data producers to specify, but the IAG WG could issue recommendations for input measurement formats. Possibilities include RINEX version 3 (which supports modernized and multi-GNSS SNR better than version 2), the software-defined radio format sponsored by the Institute of Navigation (<sdr.ion.org>), and an undetermined open format for delay-Doppler maps (DDM) as well as correlation-vs-delay waveforms. Finally, formats could be established for data elements at intermediate processing levels in a typical GNSS-R data workflow, linking instrument-oriented measurements on the one end to geophysical products on the other end. (For example, reflector heights are an intermediate quantity between signal-to-noise ratio and snow depth.) A more pressing need currently is the definition of a metadata format to support objectives #3 and #8, encompassing aspects such as temporal coverage (extent: start/end epochs; resolution: sampling rate, duty cycle, etc.), spatial coverage (extent: latitude/longitude limits; resolution: Fresnel or glistening zones), equipment (antenna: model, orientation, height; receiver: model, firmware, settings), retrieval (observable, algorithm), validation (coverage in time and space; error statistics), etc. Again, a call for volunteers was issued.

Objective #6 is "*Organize working meetings with GNSS-R experts, while also inviting stakeholders from the geodetic community to participate in such events,*" to which FN added: "present posters to update various communities (GNSS at large, non-geodetic GNSS-R, oceanographic, etc.) about our progress. The IAG WG is part of the IAG Commission 4, which will hold a symposium next September in Poland, and has abstracts due June 15; this would be a first opportunity to publicize our objectives and future plans. Another upcoming opportunity in is the AGU Fall Meeting in December, which has abstracts due around August 5. TH reminded about IGARSS 20116, July in Beijing, although abstracts were due last January. Besides these recurring annual events, other pertinent events are the GNSS+R Workshop in 2017, the IGS Workshop in 2018, and the IUGG Assembly in 2019. It was agreed that any attending member could represent the IAG WG in a poster presentation.

Objective #7 reads "*Extend IGS Site Guidelines [SG] so as to maximize the shared usefulness of new GNSS site installations for reflectometry applications.*" FN recalled that the SG were last update in July 2015 by the IGS Central Bureau and that it contains several elements pertinent to GNSS-R, such as section 6, "TIGA Stations" and section 2, "General Station Guidelines" (with subsection 2.1, Strict general guidelines, and 2.2, Recommended general guidelines). A number of proposals were made. TH mentioned the usefulness of having a sky visibility mask, i.e., a profile of elevation angle-vs-azimuth corresponding to the highest obstructions (or the lowest uninterrupted clearance) around a GNSS station. FN listed as additional proposal that station operators consider maximizing the potential of new sites for reflectometry purposes (e.g., by guaranteeing clearance/visibility at negative elevation angles to natural surfaces such as soil and sea and avoiding the built environment). TH asked if recommendations could be made about the proximity to surfaces, in terms of ideal horizontal distance and vertical height as well as their minimum and maximum limiting values. FN recalled the interplay between the height of the antenna above the surface on the one hand and both height and distance of obstructions such as trees. Further proposals were: operators to give preference to antennas with publicly available gain patterns; to provide additional photos (including panoramic); to indicate the existence of *in situ* measurements (tide gauges, soil moisture probes, snow depth sensors) and where their detailed metadata can be found. As with other objectives, the IAG WG needs volunteers to draft these proposals and study the existing site guidelines (e.g., section items 2.1.12, 2.1.37, 2.2.22, 2.2.8, 6.*, etc.).

The last remaining objectives were grouped together: #4, "*Evaluate the possibility to obtain formal errors for GNSS-R products in order to enable better combination with other data-sets;*" #9, "*Evaluate the feasibility of a pilot project on GNSS-R for coastal sea level monitoring, demonstrating its current level of maturity towards an operational service;*" and #10, "*Plan future inter-comparison campaigns for the cross-validation of theoretical model simulations and measurement parameter retrievals.*" Preliminary planning between the chair and vice-chair led to the idea of a sea level monitoring demonstration campaign with 3 sites for 3 months. If successful, it could serve as a model for future demonstrations for other environmental targets, such as snow depth, soil moisture, etc. Although many studies have been published about this topic, it would be the first time that a coordinated effort is made to compare and cross-validate solutions from different groups for a given common dataset. Making an analogy with the IGS, many groups worldwide perform GNSS satellite orbit determination, and their ephemerides solutions are routinely combined in a weighted average under the umbrella of the IGS analysis center. It was envisioned that an international GNSS-R sea-level service could be setup in a few years, and that the IAG WG should relay such a level of maturity to the geodetic and the oceanographic communities. TH offered Onsala, Sweden, as one of the three sites; there is *in situ* validation (conventional tide gauge) nearby. Any GNSS equipment, observable, and algorithm would be allowed; there would be an opportunity for setting up experimental receivers/antennas if any research group so desired. NR mentioned the Cordouan site in France. There was a call for other sites. Preliminary results are to be presented in a poster and final results would be submitted for publication in a journal.

Finally, a summary of current needs is:

- compile list of GNSS stations demonstrated for GNSS-R purposes in the literature;
- compile metadata documenting input measurements, output retrievals, and *in situ* data used in each study listed above
- define an initial metadata format;
- create webpage linking to GNSS-R products (routine or near operational rather than temporary or one-off efforts);
- create prototype of open science data curation platform for GNSS-R;
- draft proposed changes for IGS Site Guidelines;
- obtain sea-facing GNSS sites (with tide gauge nearby) for the demonstration.

Annex III: WG member presentations at the GNSS+R 2019 Meeting

- PRETTY: Cubesat for precise altimetry using navigation satellites (Jens Wickert et al.)
- Spaceborne carrier phase altimetry using gnss reflected signals at grazing angles of observation over open sea water (Estel Cardellach et al.)
- An overview of tropospheric delays in ground-based GNSS reflectometry (Thalia Nikolaidou et al.)
- Motivation for dense coastal ground-based GNSS-R networks (Joakim Strandberg et al.)
- Forward and inverse modeling of SNR-based GNSS reflectometry for soil moisture retrieval in Luxembourg (Sajad Tabibi et al.)
- Open-source hardware options for SNR-based GPS/GNSS reflectometry: Proof-of-concept and initial validation (Manuella Fagundes et al.)

- Towards a vertical sensor array for sub-hourly sea level retrieval in SNR-based GNSS reflectometry (Mauricio Yamawaki et al.)
- Impact of sea surface temperature on GNSS-R observations over mesoscale ocean eddies; preliminary results from CYGNSS (Mostafa Hoseini et al.)
- Recent advances and prospects in spaceborne GNSS-R: Can machine learning help in data modeling and analysis? (Milad Asgarimehr et al.)
- Estimation of Soil Moisture and Sea Ice Concentration A GNSS Reflectometry Concept (Maximilian Semmling et al.)
- GNSS-based remote sensing: Innovative observation of key hydrological parameters in the Central Andes (Nikolaos Antonoglou)
- GNSS derived soil moisture from the global IGS permanent network (Tzvetan Simeonov et al.)
- Kepler observing Earth - A reflectometry concept for ocean altimetry (Kyriakos Balidakis)
- GNSS Reflectometry for sea ice detection using differential delay waveform from UK TechDemoSat-1 data (Yongchao Zhu et al.)
- Investigating the altimetric sensitivity of grazing elevation data - A case study at Kongsfjorden, Svalbard (Saman Khajeh et al.)
- Cycle ambiguity resolution in GNSS-R carrier phase altimetry (Manuel Martin-Neira et al.)

Annex IV: WG member publications
(Note: we have included only journal publications, excluding conference proceedings.)

Aparicio, J. M., Cardellach, E., & Rodríguez, H. (2018). Information content in reflected signals during GPS Radio Occultation observations. *Atmospheric Measurement Techniques*, *11*(4), 1883–1900. https://doi.org/10.5194/amt-11-1883-2018

Asgarimehr, M., Zavorotny, V., Wickert, J., & Reich, S. (2018). Can GNSS Reflectometry Detect Precipitation Over Oceans? *Geophysical Research Letters*, *45*(22), 12,585-12,592. https://doi.org/10.1029/2018GL079708

Asgarimehr, M., Wickert, J., & Reich, S. (2018). TDS-1 GNSS Reflectometry: Development and Validation of Forward Scattering Winds. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(11), 4534–4541. https://doi.org/10.1109/ JSTARS.2018.2873241

Ban, W., Yu, K., & Zhang, X. (2018). GEO-Satellite-Based Reflectometry for Soil Moisture Estimation: Signal Modeling and Algorithm Development. *IEEE Transactions on Geoscience and Remote Sensing*, *56*(3), 1829–1838. https://doi.org/10.1109/TGRS.2017.2768555

Bogena, H. R., Huisman, J. A., Güntner, A., Hübner, C., Kusche, J., Jonard, F., et al. (2015). Emerging methods for noninvasive sensing of soil moisture dynamics from field to catchment scale: a review: Emerging methods for noninvasive sensing of soil moisture dynamics. *Wiley Interdisciplinary Reviews: Water*, *2*(6), 635–647. https://doi.org/10.1002/wat2.1097

Boniface, K., Braun, J. J., McCreight, J. L., & Nievinski, F. G. (2015). Comparison of Snow Data Assimilation System with GPS reflectometry snow depth in the Western United States. *Hydrological Processes*, *29*(10), 2425–2437. https://doi.org/10.1002/hyp.10346

Cardellach, E., Vey, S., & Wickert, J. (2016). Foreword to the Special Issue on GNSS Reflectometry. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *9*(10), 4519–4524. https://doi.org/10.1109/JSTARS.2016.2607618

Cardellach, Estel, Wickert, J., Baggen, R., Benito, J., Camps, A., Catarino, N., et al. (2018). GNSS Transpolar Earth Reflectometry exploriNg System (G-TERN): Mission Concept. *IEEE Access*, *6*, 13980–14018. https://doi.org/10.1109/access.2018.2814072

Cartwright, J., Clarizia, M. P., Cipollini, P., Banks, C., & Srokosz, M. (2018). Independent DEM of Antarctica using GNSS-R data from TechDemoSat-1. *Geophysical Research Letters*. https://doi.org/10.1029/2018GL077429

Chew, C., Small, E. E., & Larson, K. M. (2016). An algorithm for soil moisture estimation using GPS-interferometric reflectometry for bare and vegetated soil. *GPS Solutions*, *20*(3), 525–537. https://doi.org/10.1007/s10291-015-0462-4

Chew, C. C., Small, E. E., Larson, K. M., & Zavorotny, V. U. (2015). Vegetation Sensing Using GPS-Interferometric Reflectometry: Theoretical Effects of Canopy Parameters on Signal-to-Noise Ratio Data. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(5), 2755–2764. https://doi.org/10.1109/TGRS.2014.2364513

Darrozes, J., Roussel, N., & Zribi, M. (2016). The Reflected Global Navigation Satellite System (GNSS-R): from Theory to Practice. In *Microwave Remote Sensing of Land Surface* (pp. 303–355). Elsevier. https://doi.org/10.1016/B978-1-78548-159-8.50007-4

Fabra, F., Cardellach, E., Ribó, S., Li, W., Rius, A., Arco-Fernández, J., et al. (2019). Is Accurate Synoptic Altimetry Achievable by Means of Interferometric GNSS-R? *Remote Sensing*, *11*(5), 505. https://doi.org/10.3390/rs11050505

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JWG 1.3: Troposphere ties

Chair: *Robert Heinkelmann (Germany)*
Vice Chair: *Jan Douša (Czech Republic)*

Members

Kyriakos Balidakis (Greece), Elmar Brockmann (Switzerland), Sebastian Halsig (Germany), Younghee Kwak (South Korea), Daniel Landskron (Austria), Gregor Möller (USA), Angelyn W. Moore (USA), Tobias Nilsson (Sweden), Rosa Pacione (Italy), Tzvetan Simeonov (Bulgaria), Krzysztof Sośnica (Poland), Peter Steigenberger (Germany), Kamil Teke (Turkey), Daniela Thaller (Germany), Xiaoya Wang (China), Pascal Willis (France), Florian Zus (Austria)

Activities and publications during the period 2015-2019

The Joint Working Group was established in 2015 with the approval of the terms of reference and objectives. The JWG chair gave the first presentation about the objectives at the IAG Commission 4 Meeting at the Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland, on 5th of September 2016, see http://www.igig.up.wroc.pl/ IAG2016/?page=2. The first regular JWG Meeting was held on the 26th of April 2017 aside the EGU General Assembly at Vienna University of Technology, Vienna, Austria. Following that, two more meetings were held in conjunction with EGU General Assemblies 2018 and 2019. We thank the Vienna University of Technology, namely Johannes Böhm, Gregor Möller and Daniel Landskron, for kindly providing meeting rooms and hosting our JWG meetings during EGU.

Tropospheric ties are the way to compare or combine tropospheric slant delays or tropospheric parameters obtained from various stations and / or space geodetic techniques. The state of the art is working with tropospheric parameters, however, in principle the tie between slant delays should be more direct. Typically, the tropospheric parameters considered for tropospheric ties are obtained synchronously at co-location sites. One of the largest systematic component of the tropospheric tie is the tropospheric parameter difference caused by different physical heights of stations. For this time-variable vertical scaling either hypsometric propagation of meteorological quantities and corresponding zenith delays (Teke et al. 2011) or ray tracing differences (Heinkelmann et al. 2016) can be used. Besides this major systematic effect, the different sampling of atmosphere through the individual observation geometry and the earlier effects through refraction in the ionosphere were identified as potential systematics for ground based space geodetic techniques. Both remain to be investigated in more detail.

During the 2015 – 2019 term, the working group primarily progressed on the derivation and comparison of refraction of optical and radio signals through the neutral atmosphere. This is a crucial requirement, when optical techniques, such as SLR, are to be included in a combination of tropospheric parameters together with space geodetic techniques at radio wavelength (GNSS, DORIS, and VLBI). Most of the Working Group Members were concerned with tropospheric parameter determination and / or theoretical atmospheric modelling or ray tracing and hence, the assessment of the effects of tropospheric parameter combination on the reference frame or station coordinates determination did not progress at the same level. It remains to be studied in full detail. Hopefully, this objective can be reached in the upcoming term with a slightly revised group of members.

Of course a number of additional techniques are available and provide or require atmospheric refraction corrections, such as SAR and InSAR, Altimetry, water vapor radiometers etc. If the working group can involve scientists from these and other disciplines, comparison with those techniques apart from the four ITRF techniques (GNSS, SLR, DORIS and VLBI), might provide very interesting insights as well.

During past years, Geodetic Observatory Pecny (GOP) has developed a powerful database, GOP-TropDB (Gyori and Dousa, 2017), for the intra-/inter-technique comparisons for tropospheric parameters stemming from data analyses of space geodetic techniques. The database was completed with a web-gui service for interactive exploration of site/pair metadata and comparison statistics. It is under construction within the IGS Tropospheric WG (Hackman et al, 2016). The current database is ready to accommodate tropospheric path delays in zenith and horizontal gradients estimated using data of GNSS, VLBI and DORIS, Numerical Weather Model (NWM) re-analysis and radiosondes at least. For inter-technique comparisons of nearby stations, tropospheric parameters usually refer to different locations and thus require vertical, time-dependent correction between site reference altitudes. We developed and assessed several models for calculating tropospheric ties/corrections and vertical scaling with support of different parametrization, vertical approximations and different meteorological data. With the help of the IGS Tropospheric WG a letter of endorsement was created and sent to IVS in order to increase the awareness of the tropospheric products and to improve the IVS tropospheric parameter combination. We thank S. Bayram, Chair of the IGS TWG, for her invaluable help in that regard.

The tropospheric ties are optimally separated into two components - zenith dry and wet delays - and we thus focused on developing new model particularly for the wet scaling (Dousa and Elias, 2014). Different strategies for both wet and dry scaling were evaluated in the scenario using numerical weather data fields only, i.e. by approximating NWM differences in vertical profile by using new models for parameter scaling. Additionally, the impact of tropospheric ties was assessed in a comparison of GNSS and radiosonde tropospheric parameters and it will be finally evaluated by applying tropospheric ties specifically for GNSS and VLBI intra/inter-technique site collocations.

The online service has been developed for calculating tropospheric parameters from NWM reanalysis which can be directly used for several scenarios of calculating tropospheric ties. The web is currently available at http://www.pecny.cz/Joomla25/index.php/gop-tropdb/tropomodel-service and it is under preparation to become a part of the IGS Tropospheric WG webpages (http://www.igs.org).

swisstopo is since years active in generating information which allow to extract tie information. With the enhancement from GPS to GPS/GLO in 2008, 9 from 30 site antennas and receivers were not switched to the new technology: parallel to the continued GPS-only station double stations were build. Furthermore, local tie measurement linked these double stations on a precision of a millimeter (baselines of some 10 meters).

In May 2015, all permanent stations (with the exception of the old GPS-only stations) were enhanced to GPS/GLO/GAL/BDS and a data flow based on RINEX3 was established in summer 2015. Since summer 2016 the complete processing chain is switched to Multi-GNSS using a special development version of the Bernese Software and using CODES MGEX orbit products. The tie information is extremely helpful, because the antennas were "only" calibrated on GPS/GLO.

Routinely, so-called inter system transformation parameters are calculated on a daily basis, showing the differences of coordinates and troposphere parameters between GPS and the satellite systems GLO/GAL/BDS. Troposphere biases are extremely sensitive to analysis models (especially the antenna PCVs for receiver and satellite antennas). These parameters are made available online.

Example ZIM2: http://pnac.swisstopo.admin.ch/pages/en/qsumzim2.html#TRA_LONG

Local refraction effects in space geodetic techniques are normally investigated by small scale GNSS networks. However, with the new pair of radio telescopes at the Geodetic Observatory

Wettzell in Germany, the Institute of Geodesy and Geoinformation, University of Bonn, is now able to carry out similar investigations with geodetic VLBI observations, which are affected by the same refraction phenomena. The main objective is to analyze systematic effects between the tropospheric parameters in space and time. In a further step, this scenario is augmented by a local GNSS network set up on the Wettzell area in order to investigate the systematics between different measurement techniques.

The Vienna University of Technology contribution to JWG 1.3 aimed at improving the understanding of systematic effects in tropospheric delay modelling between various satellite techniques. First action is related to the modelling of hydrostatic effects. Comparisons between in-situ measurements of pressure (TAWES) and global HRES weather model data (as provided by ECMWF) reveal in general high accuracy in pressure within 0.5 +/- 1 hPa. Slightly worse agreement was found between in-situ data (TAWES) and regional weather model data (ALARO) with 60% larger standard deviation, see Fig. 1.3.1.

Independent from the pressure sources high consistency can only be guaranteed if comparable data processing methods are applied. In particular vertical interpolation methods and distance dependent pressure variations were further investigated and compared at co-located sites. Figure 2 and 3 show the pressure extrapolation error as function of station distance and height difference, respectively.

From the analysed pressure values a regression line was computed which describes the increase in standard deviation for Central Europe as follows:

$$\text{stddev}(p)\ [\text{hPa}] = 0.60\ [\text{hPa}] + 0.0068\ \ \text{dist}\ [\text{km}]$$

By means of this equation, the expected pressure extrapolation error can be assessed. In order to keep the extrapolation error smaller than +/-2 hPa in 95% of the cases, the extrapolation distance should be smaller than 60 km.

Further activity was related to the modelling of wet delays. GNSS tomography techniques allow for the estimation of accurate wet refractivity fields in the lower atmosphere, see Moeller (2017). By vertical integration or ray-tracing through these fields, accurate tropospheric wet delays can be derived and introduced into the parameter estimation process of various space geodetic techniques - either treated as a priori information or as replacement of the tropospheric parameters. Within the term of this working group (2015-2019) the tomography software ATom has been developed (see https://github.com/GregorMoeller/ATom), the test network and preprocessing of the GNSS observations has been carried out. Until 2019, unfortunately the study could not be finished but thanks to the good cooperation established within the working group, the analysis will be continued within the new term or outside the JWG.

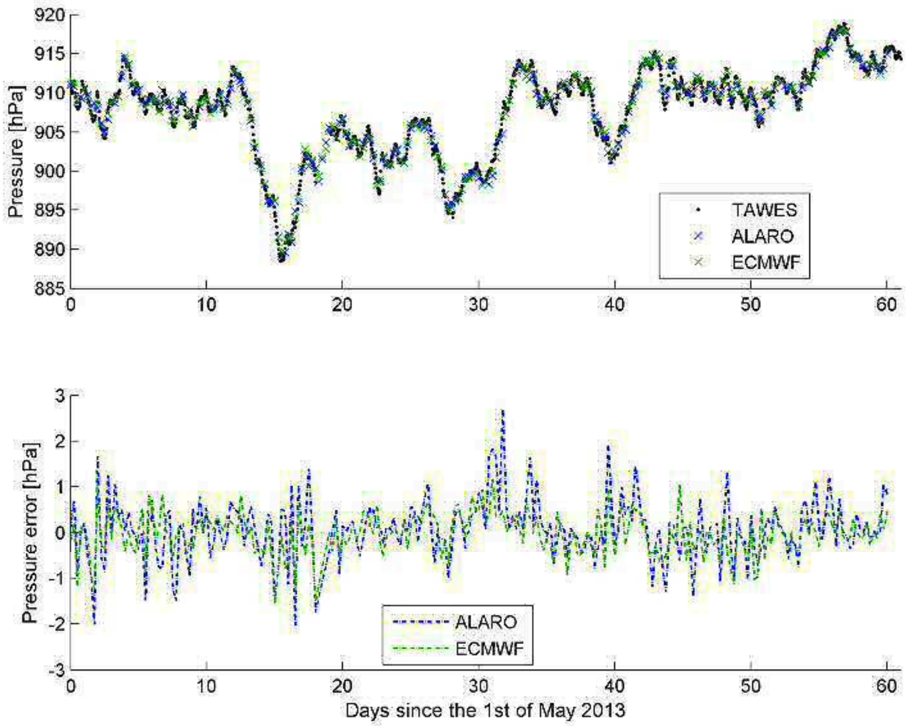

Figure 1.3.1 Top: Pressure values at GNSS site Dalaas in Western Austria, extrapolated from various pressure sources. Bottom: Differences in pressure between in-situ (TAWES) and NWM (ECMWF and ALARO) data.

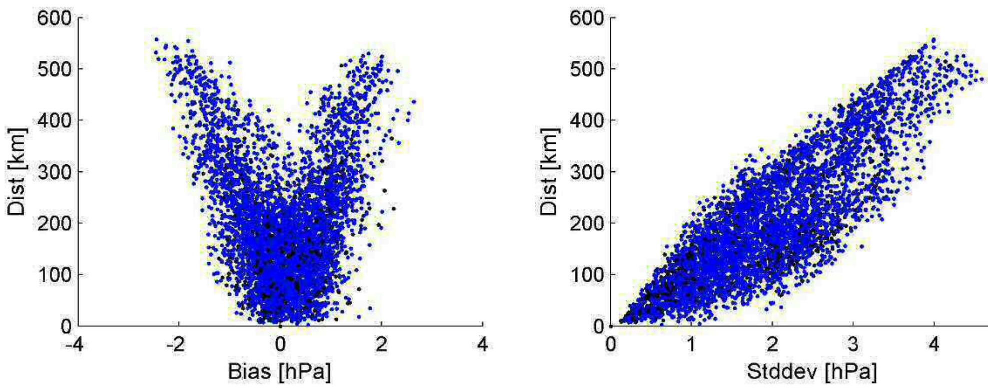

Figure 1.3.2: Pressure extrapolation error as function of station distance in the Central Europe area. A dot drawn in black indicates that both stations are located on the same height level +/- 100m

Ideally, a common parameter at the co-located sites can be regarded as a single parameter. However, if one technique has non-negligible errors, the errors can easily propagate to the other techniques and contaminate the solutions. Therefore, as an interim strategy, we estimate parameters separately and apply additional inter-technique constraints between common parameters, i.e., troposphere gradients, ZWD and clock parameters.

$$EGR_{GNSS} - EGR_{VLBI} = 0 \pm \sigma_{EGR}$$

where EGR_{GNSS} and EGR_{VLBI} are total horizontal east troposphere gradients of GNSS and VLBI, respectively. σ_{EGR} is a constraint uncertainty.

$$NGR_{GNSS} - NGR_{VLBI} = 0 \pm \sigma_{NGR}$$

where NGR_{GNSS} and NGR_{VLBI} are total horizontal north troposphere gradients of GNSS and VLBI, respectively. σ_{NGR} is a constraint uncertainty.

$$ZWD_{GNSS} - ZWD_{VLBI} = \Delta ZWD \pm \sigma_{ZWD}$$

where ZWD_{GNSS} and ZWD_{VLBI} are ZWDs of GNSS and VLBI, respectively. ΔZWD is the modeled ZWD difference between two co-located instrument reference points according to the height difference. σ_{ZWD} is a constraint uncertainty.

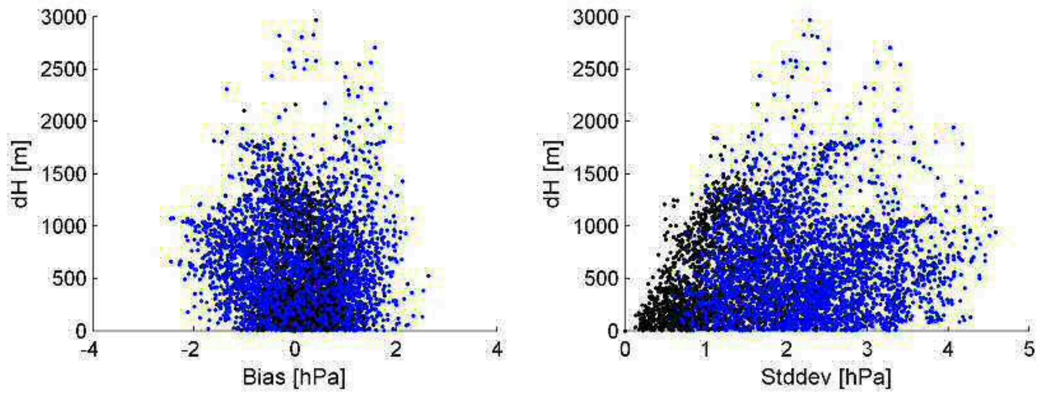

Figure 1.3.3: Pressure extrapolation error as function of height difference. The black dots highlight station pairs closer than 100 km

In this study, we integrated VLBI data (CONT11 and CONT14) and single differenced GNSS data into a single file and implemented common parameter constraints for ZWDs and troposphere gradients in VieVS for the combination of two space geodetic techniques. We introduced common parameter constraints to ZWDs and troposphere gradients for all the sites.

To find optimal constraint values, we evaluated the combination results applying various constraints on common parameters. The troposphere gradients hardly contribute to improve or degrade the combination results in any cases. The 1 cm-constraint of ZWD improves both techniques within our data set. Eventually, with optimal constraints for common parameters, the combination solutions are improved in terms of station position repeatability compared to single technique solutions by 6–10 % in horizontal components and by 13–16 % in vertical components (Fig. 1.3.4). Better sky coverage of GNSS observations due to multiple radio sources at one epoch is expected to improve the VLBI solution. However, we should confine the fact that GNSS benefits from the combination with VLBI to our data set in this study because we have a cm-level accuracy of the GNSS observation model implemented in VieVS.

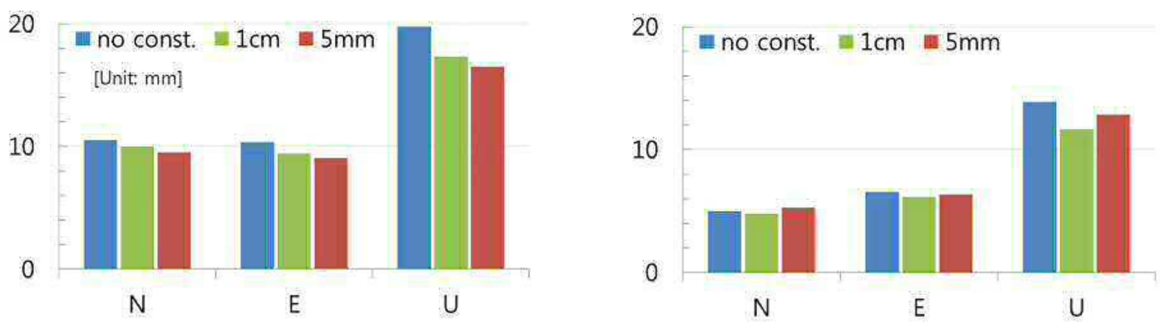

Figure 1.3.4 Impact of ZWD constraint on combination solutions (left: GNSS, right: VLBI).

The analysis strategy of common parameter constraints can be easily adopted for enhancing not only for inter-technique tie but also intra-technique tie at the co-located sites with twin and/or sibling telescopes. In the future VLBI Global Observing System (VGOS) network, there will be a lot of twin and/or sibling telescopes (a legacy antenna + a brand new small VGOS antenna) and several observing scenarios with them. For instance, a VGOS antenna observes a VGOS session with very well determined ZWD while the co-located legacy antenna runs a celestial reference frame (CRF) session and struggles to properly estimate the troposphere. Common parameter constraints will support such type of observations and enhance the VLBI results.

In 2018, TU Wien launched their new VMF webserver for the provision of troposphere delay models, accessible at vmf.geo.tuwien.ac.at. There, all discrete and empirical troposphere delay products are published, such as the Vienna Mapping Functions 1 & 3, the horizontal gradients model GRAD or empirical models such as Global Pressure and Temperature 3. The coefficients for the models are available for different numerical weather models of the ECMWF from 1980 on and are updated on a daily basis. In addition, the ray-tracing software RADIATE is freely available via GitHub (https://github.com/) and can thus be used by everyone in order to perform ray tracing through arbitrary NWMs. In future, the VMF server will be complemented by troposphere delay models for SLR. Hopefully, all these troposphere products constitute a helpful tool for the JWG, in particular for the upcoming term.

ASI/CGS is going to contribute to objective 1 through VLBI and GNSS inter-technique comparison of atmospheric parameters at the eight European co-located sites. These sites are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA). We plan to compute long-term time series of the differences between the EPN-Repro2 (Pacione et al. 2017) for the period 1996-2014 completed with the EPN operational products afterwards and the EVGA combined solutions. With the help of the EUREF Tropospheric Analysis Center at ASI a letter of endorsement was created and sent to IVS in order to increase the awareness of the tropospheric products and to improve the IVS tropospheric parameter combination. We thank the ASI/CGS group for their invaluable help in that matter.

The issue of troposphere delay modeling for SLR is addressed in the project OPUS NCN "Innovative Methods of the Troposphere Delay Modeling for Satellite Laser Ranging Observations" led by Krzysztof Sośnica from the Wroclaw University of Environmental and Life Sciences (WUELS), Poland. In the frame of the OPUS project, a doctoral thesis is being prepared by Mateusz Drożdżewski, under the title "Troposphere delay modeling for Satellite Laser Ranging observations". The susceptibility of laser observations to tropospheric asymmetry has been first verified by Drożdżewski & Sośnica (2018), in which the horizontal gradients were calculated on the basis of long-term measurements to LAGEOS satellites. It turned out that SLR observations allow determining horizontal gradients that are similar in direction and amplitude to gradients determined on the basis of hydrostatic delay from numerical weather models, while GNSS gradients are similar to the sum of hydrostatic and wet delays for most SLR-GNSS co-locations (see Fig. 1.3.5).

One of the factor limiting the consistency between the SLR and GNSS solutions is the difference in the tropospheric delay modeling. The vulnerability of SLR measurements to tropospheric delay is different from the sensitivity of microwave observations (GNSS, VLBI, DORIS) to the tropospheric delay. The hydrostatic delay is similar in magnitude, as it is associated with the distribution of atmospheric pressure in both optical and microwave wavelengths. In contrast, the wet delay associated with the distribution of water vapor content in the atmosphere is about by a factor of 70 smaller in laser observations in relation to microwaves.

Models of the tropospheric delay dedicated to laser observations do not currently take into account horizontal gradients, which means that they assume that the atmospheric zenith (i.e. the direction of the minimal tropospheric delay) coincides with the geometric zenith (normal to the ellipsoid at a given point). In SLR measurements, both the zenith delay and the parameters of the mapping function are calculated on the basis of meteorological observations conducted simultaneously with laser measurements.

In order to improve modeling of the tropospheric delay in laser observations and to improve the consistency between SLR and GNSS, we proposed extending the currently used model by including horizontal gradients that account for the asymmetry of the tropospheric state above laser stations. Hence, the tropospheric delay in the SLR technique can be modeled in a similar way to that in the GNSS technique.

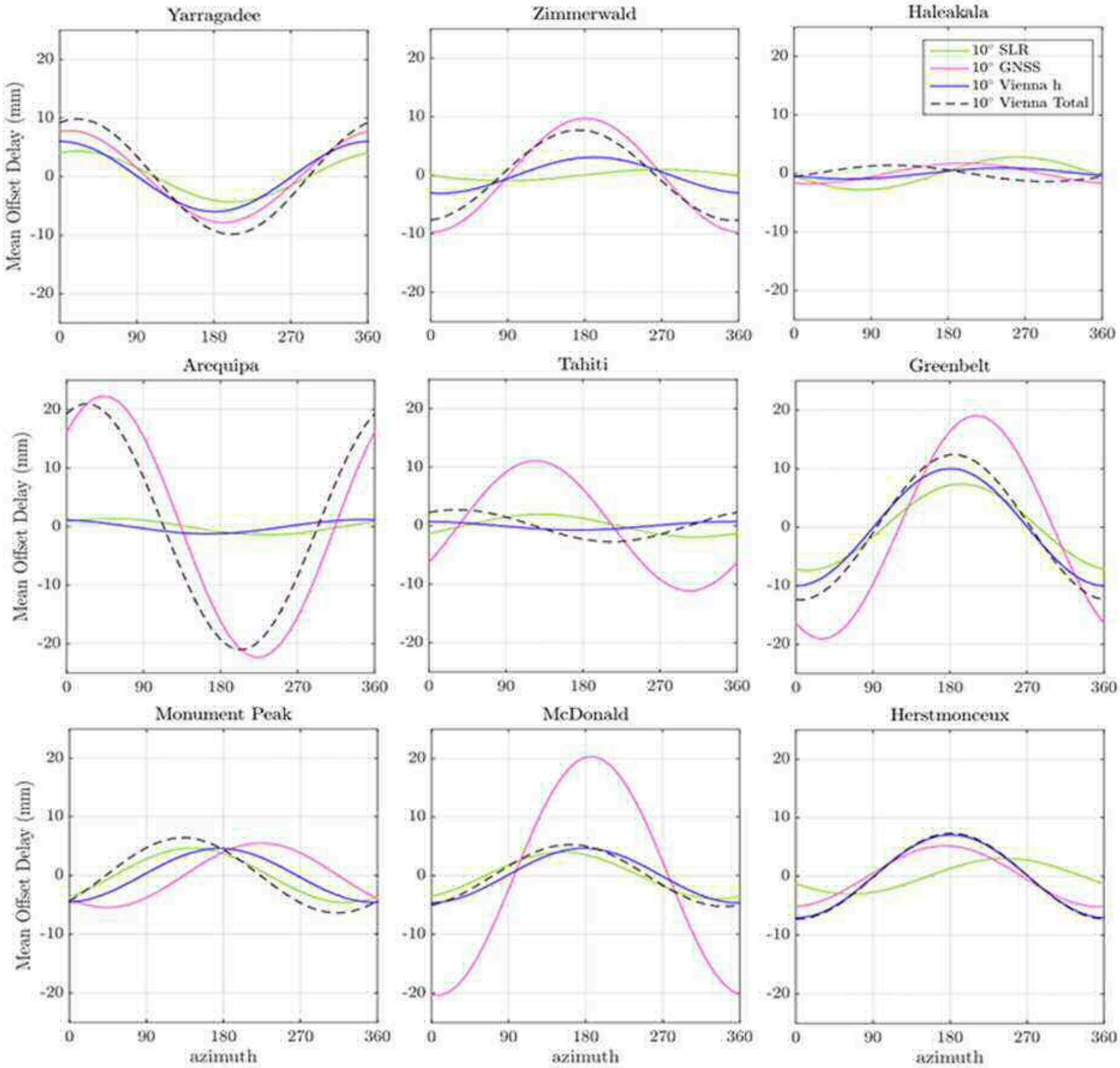

Fig. 1.3.5. Horizontal gradients of the tropospheric delay determined from SLR and GNSS observations and from hydrostatic and total tropospheric delays determined using numerical weather models projected onto 10 degrees of the elevation angle.

Works in this field are developed in a cooperation between WUELS (K. Sosnica, M. Drozdzewski), GFZ Potsdam (F. Zus, K. Balidakis), and TU Vienna (J. Boisits, J. Böhm, D. Landskron). In GFZ Potsdam, a computationally efficient method for determining tropospheric delay parameters based on numerical weather models has been developed. The method allowed determining gradients and an improved mapping function for all laser stations for over a 20-year period. Then, delays and mapping functions were used in SLR solutions employing laser observation for LAGEOS-1/2 geodetic satellites and for the Sentinel-3A remote sensing satellite. The influence of first and second order horizontal gradients on global geodetic parameters was investigated. The research allowed us to conclude that the current approach to modeling laser observations causes systematic errors reaching up to 3 mm in the geocenter position and 20 μas in the pole position due to the neglecting of horizontal gradients. The results were summarized in the articles and conference proceedings: Drożdżewski et al. (submitted), Drożdżewski et al. (2019a), Drożdżewski et al. (2019b), Boisits et al. (2018), Sośnica et al. (2018a), and Sośnica et al. (2018b).

The further activities will include the comparison between Vienna Mapping Function for optical frequencies (VMFo http://vmf.geo.tuwien.ac.at/trop_products/SLR_prelim/) and the Potsdam Mapping Function for SLR (PMF ftp://ftp.gfz-potsdam.de/pub/home/kg/ zusflo/TRO/SLR/), as well as the analysis of the impact of the separation between the hydrostatic and wet mapping functions and horizontal gradients and the consistency improvement between SLR solutions and other space geodetic techniques.

The German Space Operations Center (GSOC) of the German Aerospace Center (DLR) performs precise orbit and clock determination for satellites of the global and regional navigation systems GPS, GLONASS, Galileo, BeiDou, and QZSS on a routine basis. A global network of about 150 stations is processed with the NAPEOS software to solve for station coordinates, troposphere and Earth rotation parameters, receiver and satellite clocks as well as satellite orbit parameters. DLR/GSOC provides normal equations obtained from the multi-GNSS analysis in SINEX format including station coordinates, troposphere, and Earth rotation parameters for analysis and combination studies of the joint working group.

In last years Xiaoya Wang, Fan Shao and Qunhe Zhao at Shanghai Astronomical Observatory, Chinese Academy of Sciences, studied the possibility of common tropospheric parameters as another 'local ties' of TRF. The work mainly includes the following:

1) We compared the tropospheric parameters obtained by different techniques at co-located sites and found the VLBI tropospheric zenith delay is approximately consistent with that of GNSS. But there exists a big constant term and a long period (about 1 year) term in the tropospheric zenith delay difference between SLR and GNSS.
2) We compared the mapping function used in SLR (FCULa mapping function) and GNSS (GMF) at all co-located sites, we found the difference is very small.
3) Compared with the strategy used in GNSS, our SLR orbit determination didn't consider estimating the ZTD parameters. So, we change our software to estimate the ZTD parameters in SLR. The results show that there are big differences between the dry zenith delay models of SLR and GNSS. We analyzed the difference and found that it is almost approximately a scaling factor between the two kinds of dry zenith delays. The factor is equal 1.061392746364195.
4) Then we compare the wet delays obtain by SLR and GNSS. And there was still a big offset exiting in SLR and GNSS zenith wet delay because the radio wavelength technique is more sensitive to water vapor in troposphere than optical wavelength technique. The SLR zenith wet delay is very small.
5) We also consider the effect of the horizontal gradients of atmosphere on tropospheric delay in SLR, which is described by Hulley (2007). We adopt the parameterization used in GNSS to our SLR data processing and estimate the horizontal gradient parameters G_N and G_E. It shows too much parameters are estimated for SLR data processing. It is maybe a good method for SLR to import the horizontal gradients of atmosphere estimated by other ways. In future it will be tested.

6) Projects:

- Construction techniques for the millimeter global Epoch Terrestrial Reference Frame (ETRF), the National Key Research and Development Program of China (2016YFB0501405), 2016.07-2021.06
- Specifications for laser ranging data and related geodetic references, the Ministry of Science and Technology of China (2015FY310200), 2015.07-2018.06

The German Federal Agency for Cartography and Geodesy (BKG) performs analysis of global VLBI and SLR data on a routine basis by operating an IVS and ILRS Analysis Center, respectively. Troposphere products (zenith delays and horizontal gradients) based on the global VLBI analysis are regularly estimated and provided as products within the IVS.

Additionally, combination studies are carried out in the framework of research projects. Based on earlier work on establishing tropospheric ties documented in Thaller (2008) and Krügel et al. (2007), funding could be acquired in 2018 for a dedicated research project on combining VLBI and GNSS normal equations including troposphere parameters. The project work will start in 2019 so that reporting on the scientific achievements will be during the next term of this working group or any follow-up working group on a similar topic.

At GFZ Potsdam we installed a service which provides Numerical Weather Model (NWM) based tropospheric parameters valid for radio frequencies. The station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~800 GNSS stations. Recently we updated our ray-trace algorithm (Zus et. al 2014) in order to derive tropospheric parameters valid for optical frequencies. Therefore, station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~100 SLR stations as well. The tropospheric parameters are derived from short range forecasts and are available with no latency. The underlying NWM is the NCEP Global Forecast System (0.5 deg resolution, 31 pressure levels). The epochs 0, 6, 12 and 18UTC are based on 6h forecasts whereas the epochs 3, 9, 15, 21 UTC are based on 9h forecasts. The data and a short description (how to use) are available at ftp://ftp.gfz-potsdam.de/pub/home/kg/zusflo/TRO/. Currently we do not fully exploit the information from NWMs. For example, we use model level (or pressure level) fields but we do not take into account the near surface fields. Within this working group we will update our algorithms to extract the near surface pressure, temperature and humidity. We will derive the corresponding lapse rates which can then be used as tropospheric ties.

Employing ray-tracing (Zus et al., 2012; 2014) in state-of-the-art NWMs we studied intra- and inter-system atmospheric ties. The techniques we considered are those currently contributing to the realization of ITRS, that is GNSS, VLBI, SLR, and DORIS. In essence, there are three reasons why atmospheric parameters, that is zenith delays and gradient vector components, differ across e.g., two co-located stations:

a. frequency differences (microwave, optical),
b. position differences (mainly in height component),
c. observing system differences (technique, geometry, and hardware).

Brief summary of the results

a. Zenith hydrostatic delays at optical frequencies (532nm) are 6% larger than those at microwave frequencies;
b. Zenith non-hydrostatic delays at optical frequencies (532nm) are 66 times smaller than those at microwave frequencies;

c. Gradient components for SLR are spatially and temporally smoother than those estimated from GNSS/VLBI/DORIS;
d. Inter-frequency atmospheric ties vary with time;
e. Given a direction and the weather conditions aloft a station, it is always mf_SLR < mf_VLBI < mf_GNSS < mf_DORIS. This ranking is due to a combination of frequency- and orbital-altitude-induced reasons;
f. Non-hydrostatic mapping factors and gradients should be adjusted for height differences; and
g. Additional discrepancies in the slant delays between microwave-based space geodetic techniques observing at different frequencies are induced by the fact that the ray-path is slightly different due to ionospheric refraction.

A more detailed report of our investigations can be found in Balidakis (2019).

At GFZ we further simulated GNSS, VLBI, SLR, and DORIS observations, analyzed the related observations, and performed the inter-technique combination employing local (LT) and atmospheric (AT) ties (residual zenith delays and gradient components) at the normal equation (NEQ) level. Some of our findings follow (Balidakis et al., 2018b; 2019):

a. ATs are not sufficient to replace LTs;
b. ATs improve tropospheric estimates, especially under poor observation geometry (e.g., SLR and VLBI);
c. ATs slightly mitigate the "damage" induced by failing to identify and remove biased LTs; and
d. ATs are very useful to detect systematic errors in LTs.

In addition to our work directly related to NWMs, we have successfully applied some of the atmospheric refraction models we developed in the analysis of real VLBI (Balidakis et al., 2018a) and SLR (e.g., Koenig et al., 2018; Drożdżewski et al., 2019) data.

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Sub-commission 4.4: Multi-Constellation GNSS

Chair: *Pawel Wielgosz (Poland)*
Vice Chair: *Yang Gao (Canada)*
Secretary: *George Liu (China)*

Overview

Multi-GNSS Constellation is rapidly growing extending the number of satellites and available signals/frequencies. In addition to two already operational GPS and GLONASS systems, the new Galileo and BDS systems offer initial services. Both GPS and GLONASS are currently undergoing a significant modernization, which adds more capacity, more signals, better accuracy and interoperability. These new developments in GNSS provided 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. Recognizing the central role of GNSS in providing high accuracy positioning information, the SC4.4 foster research that address standards, theory and applications of Multi-GNSS Constellation.

SC 4.4 is composed of two Study Groups and two Working Groups. Besides, several of SC 4.4 members participate in other IAG Joint Study Groups related to GNSS methods, i.e., IAG-ICCT JSG 0.10 “High-rate GNSS” and IAG ICCT JSG 0.17: “Multi-GNSS theory and algorithms”.

The main meetings of the SC 4.4. took place during European Geoscience Union General Assemblies (EGU GA) that are held every year in April in Vienna, Austria. The SC 4.4. organizes dedicated session at EGU, recently session G.1.3 “High-precision GNSS: methods, open problems and Geoscience applications”:
https://meetingorganizer.copernicus.org/EGU2019/session/30380.

Study Groups of Sub-commission 4.4:

SG 4.4.1: Integrity Monitoring for Precise Positioning

Chair: Ahmed El-Mowafy (Australia)
Vice Chair: Aboelmagd Noureldin (Canada)

Members
- Ilaria Martini (Germany)
- Samer Khanafseh (USA)
- Jinling Wang (Australia)
- Nobuaki Kubo (Japan)
- Allison Kelley (Australia)
- Per Enge (USA)
- Naser El-Sheimy (Canada)
- Slawomir Cellmer (Poland)
- Pedro Francisco Navarro Madrid (Spain)

Overall activities during the period of 2015-2019

The study group addresses integrity monitoring (IM) for precise positioning, where several sensors can be used including GNSS, Inertial Measurement Units (IMU), Lidar, cameras and odometers. The focus was mainly on Precise GNSS positioning techniques include Precis Point Positioning (PPP), Real-Time Kinematic (RTK) or Network RTK. For a real-time user, integrity and performance-based monitoring is important for protection from faults. These faults are likely to occur and those which may present a threat or degrade quality of precise positioning, the nature of each threat, and its source, possible magnitude, duration and likelihood are considered. For GNSS, these faults may be present in: i) all GNSS constellations navigation data; ii) their measurements; iii) augmentation systems (e.g. precise orbits and clock corrections or atmospheric corrections); and iv) user work environment (in open sky, urban environment, etc). Different algorithms were presented for integrity monitoring in precise positioning with new models, addressing particular issues in the precise positioning mode both in the open sky and in the urban environment. Case studies of vehicle positioning in intelligent transport systems have been selected as a future application of great interest.

During the period 2015-2019, the study group had face to face meetings during:
- The 31st International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2018), Sep 20-24, 2018, Miami, Florida
- ION Pacific PNT-2017 Honolulu, Hawaii, 1 – 4 May 2017.
- The 29th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2016) September 12 - 16, 2016, Portland, Oregon.

In addition, the group had a few online video conference meetings. During these meetings the group discussed challenges of IM for Precise positioning in land applications, possible algorithms and collaboration between the group members. The group members have collaborated in several research articles, as listed in the following list of publications related to our activity in the interest of this study group. In addition, we are currently together working in several follow on research papers.

Over the past 4 years, the group members have contributed in several journal and conference publications that address integrity monitoring. The following sections summarizes some of the research being carried out, including the research question, approach and key findings.

In the second period of our SG term (2017-2019) our research work includes the following work:

While IM was considered until recently only in aviation, it is currently a key performance parameter in land applications, such as Intelligent Transport Systems (ITS). In one study the IM concepts, models and methods developed so far are compared. In particular, Fault Detection and Exclusion (FDE) and bounding of positioning errors methods borrowed from aviation (i.e. ARAIM) are discussed in detail, in view of their possible adoption for land applications. Their strengths and limitations, and the modifications needed for application in the different context are highlighted. A practical demonstration of IM in ITS is presented.

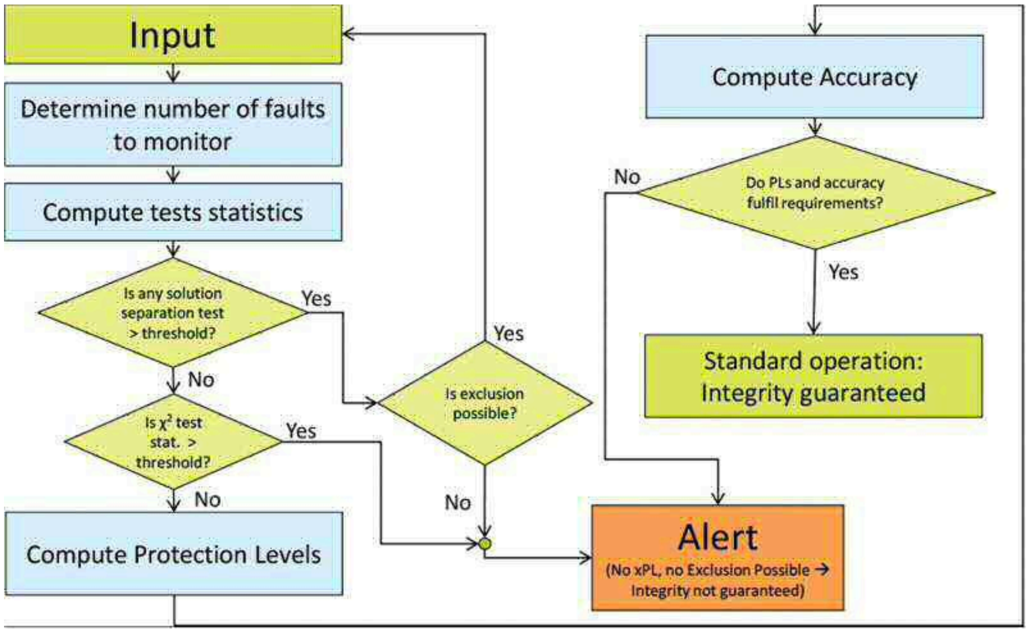


Fig. 1 ARAIM baseline architecture

In order to develop efficient models and methods that can provide high levels of integrity, it is necessary to study the vulnerabilities of the GNSS-based positioning systems intended for applications such as ITS, in particular those which require positioning accuracy at the sub-metre level. This was carried out in one study, where these vulnerabilities are attributed to several sources and include biases and errors in the GNSS measurements, and in the corrections applied to the measurements for augmented performance, as well as those induced by the operating environment. The vulnerabilities also comprise possible anomalies that may affect each component of the system, including disturbances or disruption in the communications between the service provider and users, data latency, to name a few. A detailed overview of possible vulnerabilities is presented for two widely-used GNSS positioning techniques for precise positioning applications: the Satellite-Based Augmentation System (SBAS) and low-cost RTK. Some examples are given, including the source of these errors, e.g. satellite or receiver hardware, environment, external communications, the error magnitude, temporal and spatial behaviour, their deterministic and stochastic characteristics, and their impact on estimated positions. Furthermore, some of the corresponding mathematical models that can be used to describe these vulnerabilities in the integrity monitoring algorithms are presented.

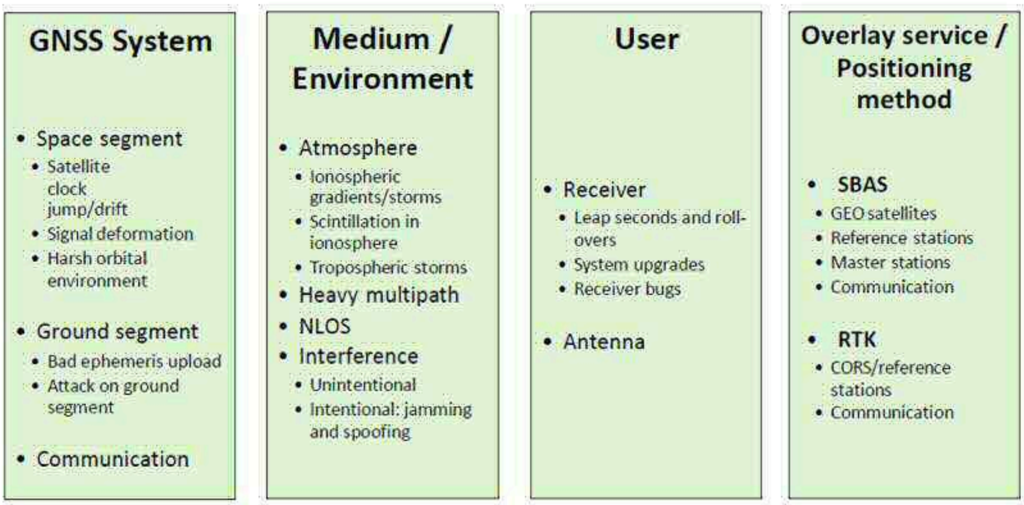


Fig. 2 GNSS vulnerabilities

In another contribution we address the problem of assuming that positioning errors are normally distributed in modelling of the FDE and protection level. While this assumption might hold in open sky, in urban environments, this traditional assumption may no longer be valid. The study investigates characterization of positioning errors using GNSS when the Australian satellite-based augmentation system (SBAS) test-bed is used, which comprised different positioning modes, including single point Positioning (SPP) employing the L1 GPS legacy SBAS, the second-generation dual-frequency multi-constellation (DFMC) SBAS service, and finally precise point positioning (PPP) using GPS and Galileo observations. Statistical analyses are carried out to study the position error distributions over different possible operational environments including open sky, low-density urban environment, and high-density urban environment. Significant autocorrelation values are also found over all areas. This, however, is more evident for PPP solution. Furthermore, based on the various distribution analyses applied such as the goodness of fit test, it is found that along Normal distribution, a few popular distribution functions including Logistic, Weibull, and Gamma can also be a good candidate to fit the position error data. These can be utilised in building more representative FDE models according to the work environment.

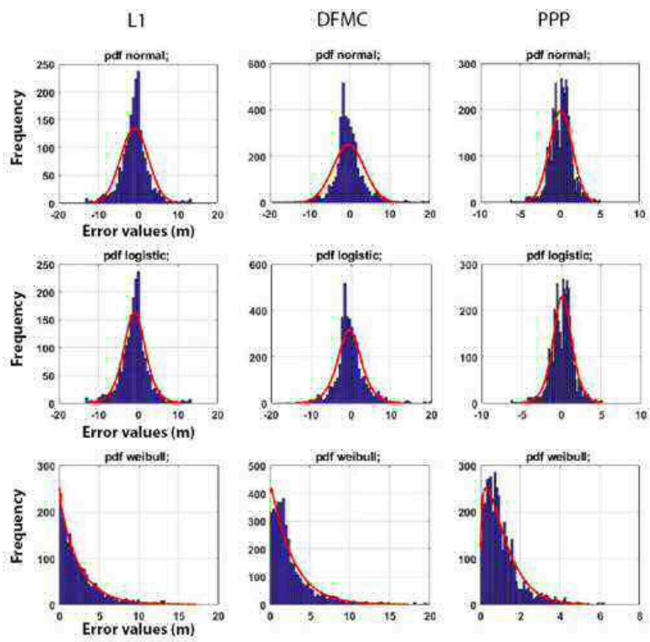


Fig. 3 Models for describing distribution of positioning errors

In another study, we studied integrity monitoring at the level of the network that provide corrections to the user. High- care must therefore be exercised to continuously check the quality of the corrections and to detect the possible presence of mis-modeled biases in the network data. In network-RTK or its state-space implementation, PPP-RTK, quality control of the solutions is executed in two separate phases: the network-component and the user-component. Once confidence in the network-derived solutions is declared, a subset of the solutions as corrections are sent to a single-receiver user, thereby allowing the user to separately check the integrity of his network-aided model. In such a two-step integrity monitoring procedure, an intermediate step is missing, the integrity monitoring of the corrections themselves. Therefore, in this contribution a quality control procedure for GNSS parameter solutions at the correction level is developed, and to measure the impact a missed detection bias has on the (ambiguity resolved) user position. New detection test statistics are derived with which the single receiver user can check the overall validity of the corrections even before applying them to his data. A small-scale network of receivers is utilized to provide numerical insights into the detectability of mis-modeled biases using the proposed detectors and to analyze the impact of such biases on the user positioning performance.

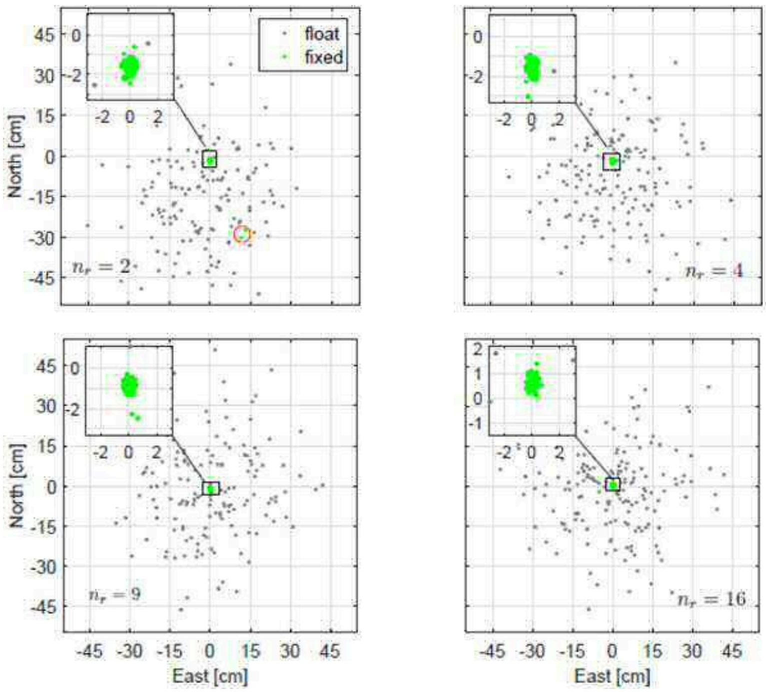
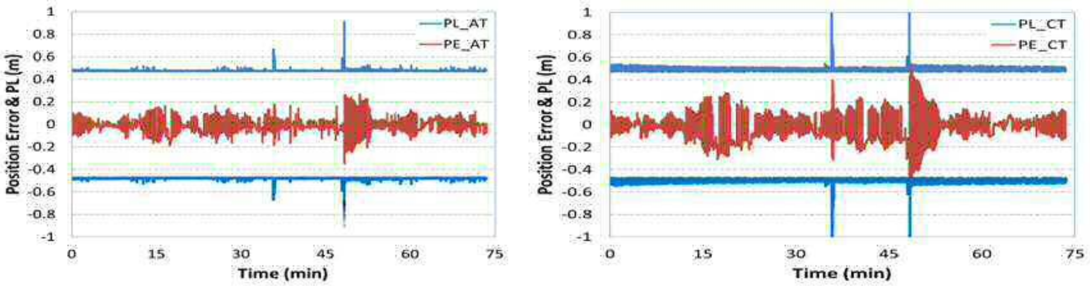


Fig. 4 User single-epoch horizontal positioning scatter-plots when a missed detection L1 phase-slip corresponding to the MDBs

In another study, the focus was on accurate detection of GPS jammers in the frequency domain where fast Fourier transform (FFT) is predominantly used. An innovative high-resolution frequency estimation method to accurately detect single and multiple in-band continuous-wave jamming signals transmitted at very close-by frequencies is proposed. The proposed method utilizes orthogonal search that provides robust nonlinear spectral estimation to detect dominant jammer frequencies. The Spirent GSS 6700 GPS simulator was utilized in this study to generate several cases for the GPS L1 signal. The output of the GSS 6700 was acquired using the Novatel FireHose GPS frontend receiver that digitizes and down-converts the signal into in-phase (I) and quadrature (Q) samples. The results demonstrated its capabilities of simultaneously detecting more than one GPS jammer existing at close-by frequencies. It is also shown that jammer frequency estimates obtained for a single jammer are more accurate than those obtained by FFT. Furthermore, FOS yields more accurate results than FFT at considerably smaller window sizes.

In a novel contribution, new models for fault detection in the position domain are presented that are tailored for Intelligent Transport systems. The fault detection tests are parameterized for the track frame of the vehicle, and in a combined single test form. Another new form is presented where the detection testing is parameterized in the direction of the maximum possible error. The tests are formed where position errors are assumed to have a zero-mean Gaussian distribution, which is a working hypothesis in the open environment. The case of positioning in the urban environment is also addressed using two approaches. The first is by using a Logistic distribution that is found to empirically better fit a very large sample of position errors compared to the normal distribution in this environment. The second approach is to use of an overbounding Gaussian distribution. The protection levels (PL) in the track frame are presented, and the advantage of expressing PL along the maximum direction is shown. The presented methods are experimentally demonstrated in practice through a kinematic test.



Position errors and PL for AT and CT

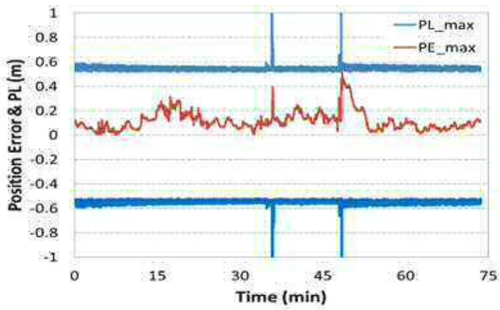


Fig. 5 Position errors and PL for max error

In another article, the derivation, analysis and evaluation of a new sequential integrity monitoring for Kalman filter (KF) applications is described. The monitor uses innovation sequence obtained from a single Kalman filter for fault detection. Unlike multiple hypothesis solution separation monitors, it does not require running sub-filters to detect and exclude the fault. The main contributions of this paper is an analytical recursive expression of the worst case failure mode slopes, which is direct means of computing protection levels in real-time. The performance of the monitor is evaluated and verified against single satellite faults through a tightly-coupled INS/GNSS integrated navigation systems in aircraft approach and en route operations. However, the methodology developed in this paper is not limited to INS/GNSS systems but applicable to any other multi-sensor systems using KF estimators.

In another work, GNSS multipath error models for automotive applications is presented by leveraging methods used in aviation applications. These error models are intended for navigation integrity and continuity risk evaluation. Error models for code and carrier phase GNSS measurements under both static and dynamic multipath environments are presented. The dynamic dataset was collected in realistic driving conditions for a vehicle traveling in an urban canyon and on a highway with overpasses and road signs. The static test was conducted in a more controlled environment, first, to precisely evaluate measurement errors under open sky, and then, to quantify the effect on multipath error of a semi-truck next to a car equipped with a commercial GNSS antenna. the errors were characterized by the mean and standard deviation of a bounding Gaussian distribution and by the autocorrelation time constant of the measurement errors.

The challenge of robust indoor positioning using integrated UWB and Wi-Fi measurements is discussed in another study. Comparisons of ranges from the UWB sensors and the Wi-Fi built into the smartphone to true ranges obtained from a robotic total station is presented.

In one study, we studied continuous and trustworthy positioning for advanced driver assistance systems (ADAS). GNSS RTK, Doppler-based positioning, and low-cost inertial measurement unit (IMU) with car odometer data are combined in this study. To ensure reliable positioning, the system target integrity monitoring above 99%. Achieving this level, when combining different types of measurements that have different characteristics and different types of errors, is a challenge. A novel integrity monitoring approach is presented. A threat model of the measurements of the system components is discussed, which includes both the nominal performance and possible fault modes. A new protection level is presented to bound the maximum directional position error. The proposed approach was evaluated through a kinematic test in an urban area in Japan with a focus on horizontal positioning. Test results show that by integrating RTK, Doppler with IMU/odometer, 100% positioning availability was achieved. The integrity monitoring availability was assessed and found to meet the target value where the position errors were bounded by the protection level, which was also less than an alert level, indicating the effectiveness of the proposed approach. Figure 1 illustrates the horizontal protection level (HPL) bounding the Horizontal Positioning Error HPE for the integrated positioning systems.

In the second period of our SG term (2015-2017) our research work includes the following work:

Another study discusses the use of triple frequency data in Advanced Receiver Autonomous Integrity Monitoring (ARAIM). Currently, most ARAIM methods are designed to use dual-frequency ionosphere-free observations. These methods assume that receiver bias is absorbed in the common receiver clock offset and bound satellite biases by nominal values. However, most multi-constellation Global Navigation Satellite Systems (GNSS) can offer triple frequency data, which can improve observation redundancy, solution precision and detection of faults. In this contribution, we explore the use of this type of observations from GPS, Galileo and BeiDou in ARAIM. Nevertheless, the use of triple frequency data introduces receiver differential biases that have to be taken into consideration. To demonstrate the significance of these additional biases we first present a method to quantify them at stations of known coordinates and using available products from the International GNSS service (IGS). To deal with the additional receiver biases, we use a between-satellite single difference (BSSD) observation model that eliminates their effect. A pilot test was performed to evaluate ARAIM availability when using the triple-frequency observations. Real data were collected for one month at stations of known coordinates located in regions of different satellite coverage characteristics. The position error was always found to be bounded by the protection level proven initial validity of the proposed integrity model. Figure 2 shows some of the triple-frequency results demonstrating the vertical Protection level (VPL), vertical alert limit (VAL) and vertical position error (VPE) for airborne applications.

In another study, the current availability of ARAIM is experimentally investigated using real navigation data and GPS measurements collected at 60 stations across Australia. Sensitivity analysis of ARAIM availability due to changes in the elevation mask angle and the error model parameters *URA*, *URE*, and nominal biases for integrity and accuracy used for computation of the protection level is presented. It is shown that incorporation of other GNSS constellation with GPS in ARAIM is needed to achieve 99.9% Australia wide. The inclusion of BeiDou with GPS at two tests sites in Western and Eastern Australia demonstrated the promising potential of achieving this goal.

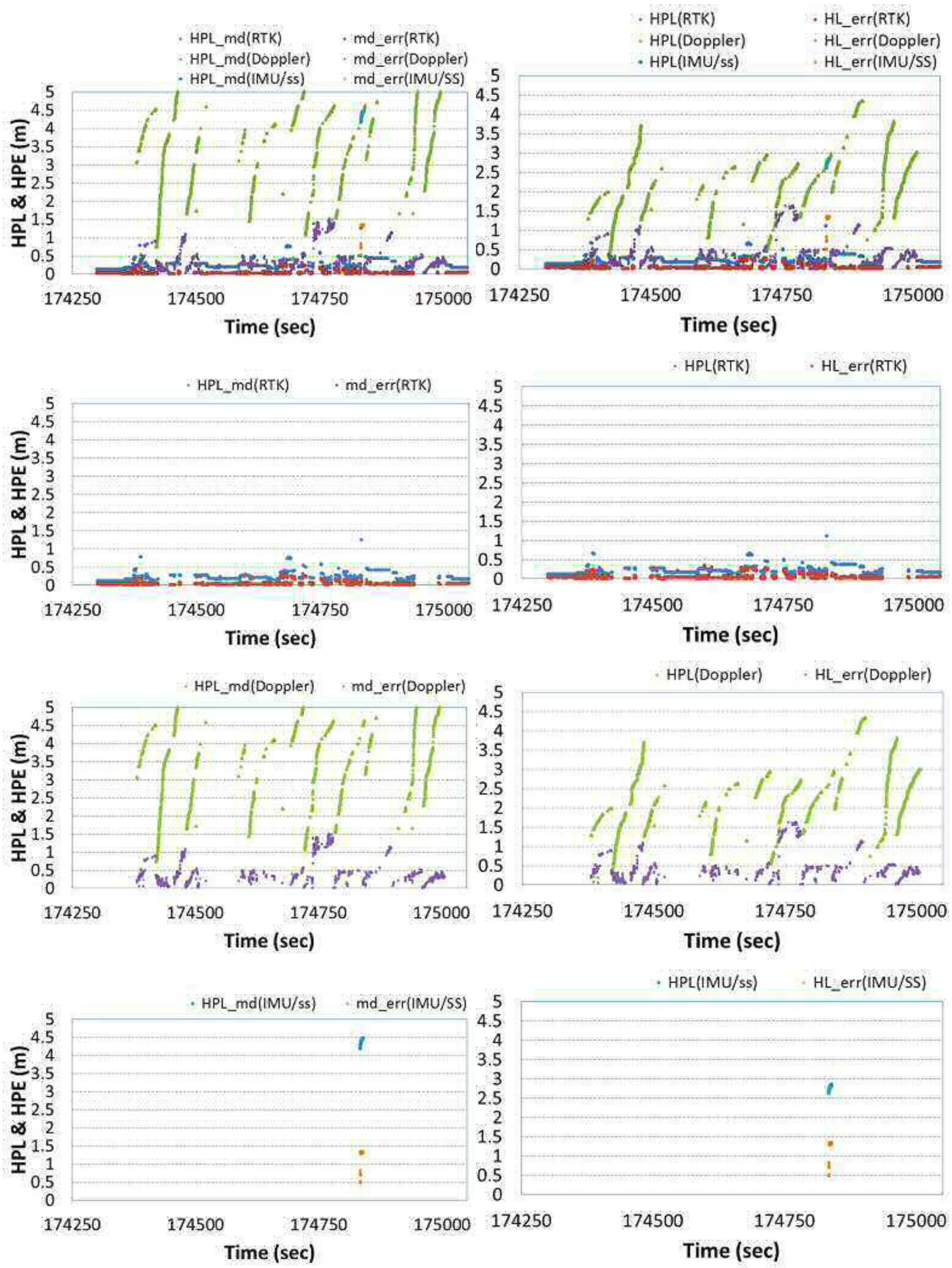


Fig. 6 *HPL* and *HPE* linear 2D error for the integrated positioning systems - combined (top panel), RTK (2nd panel), Doppler Positioning (3rd panel), and IMU/SS positioning (bottom panel), = 1×10^{-4}.

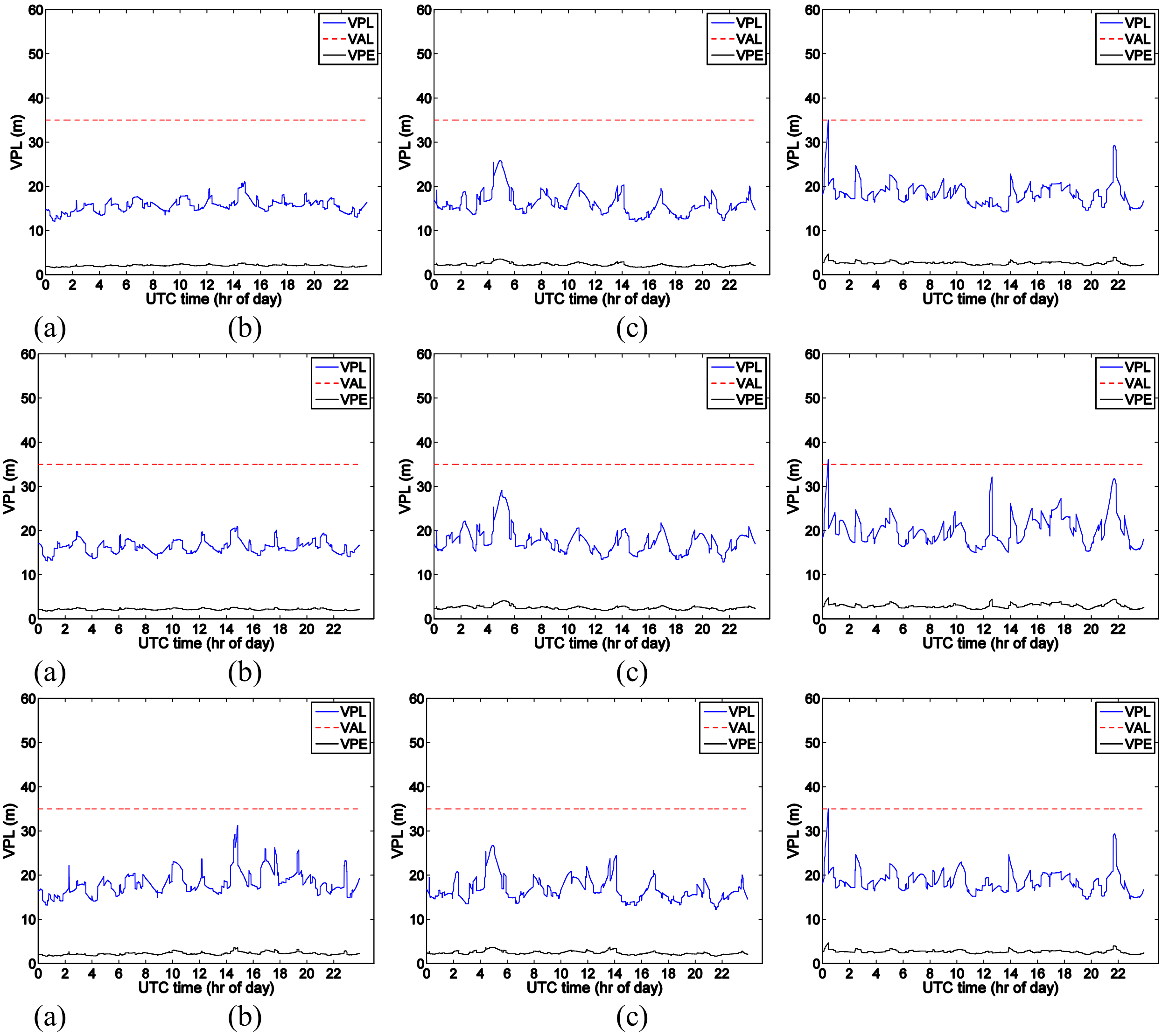


Fig. 7 Time series of *VPL* (1m *URA*) and *VPE* with *VAL* using triple-frequency observations; GPS +Galileo +BeiDou (top panel); GPS and BeiDou (middle panel) and GPS with Galileo (bottom panel) on 19th June 2016 at IGS stations CUT0 (a), ZIM3 (b), and CPVG (C).

In another pilot study, availability of the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) when integrating various combinations of satellite constellations including; Galileo, GLONASS and BeiDou with GPS is investigated. The Multiple Hypothesis Solution Separation method was applied using one month of real data. The data was collected at stations of known positions, located in regions that have different coverage levels by the tested constellations. While most previous studies used simulated data, the importance of using real data is twofold. It allows for the use of actual User Range Accuracy (URA) received within the satellite navigation message, which is a fundamental component for computation of the integrity protection level; and the computation of vertical position errors to validate the integrity approach. Results show that the vertical position error was always bounded by the protection level during the test period and the ARAIM availability can reach 100% of the time when using all constellations even though some constellations are yet incomplete.

The Precise Point Positioning (PPP) is a popular positioning technique that is dependent on the use of precise orbits and clock corrections. One serious problem for real-time PPP applications such as natural hazard early warning systems and hydrographic surveying is when a sudden communication break takes place resulting in a discontinuity in receiving these orbit and clock corrections for a period that may extend from a few minutes to hours. A method is presented to maintain real-time PPP with 3D accuracy less than a decimeter when such a break takes place. We focus on the open-access International GNSS Service (IGS) Real-time Service (RTS) products and propose predicting the precise orbit and clock corrections as time series. For a short corrections outage of a few minutes we predict the IGS-RTS orbits using a fourth order polynomial, and for longer outages up to 3 hrs, the most recent IGS ultra-rapid orbits are used. The IGS-RTS clock corrections are predicted using a second order polynomial and sinusoidal terms. The models parameters are estimated sequentially using a sliding time window such that they are available when needed. The prediction model of the clock correction is built based on the analysis of their properties, including their temporal behavior and stability. Evaluation of the proposed method in static and kinematic testing shows that positioning precision of less than 10 cm can be maintained for up to two hours after the break. When PPP re-initialization is needed during the break, the solution convergence time increases; however, positioning precision remains less than a decimeter after convergence. Figure 3 shows the PPP results of kinematic tests in sea and on land using the proposed method.

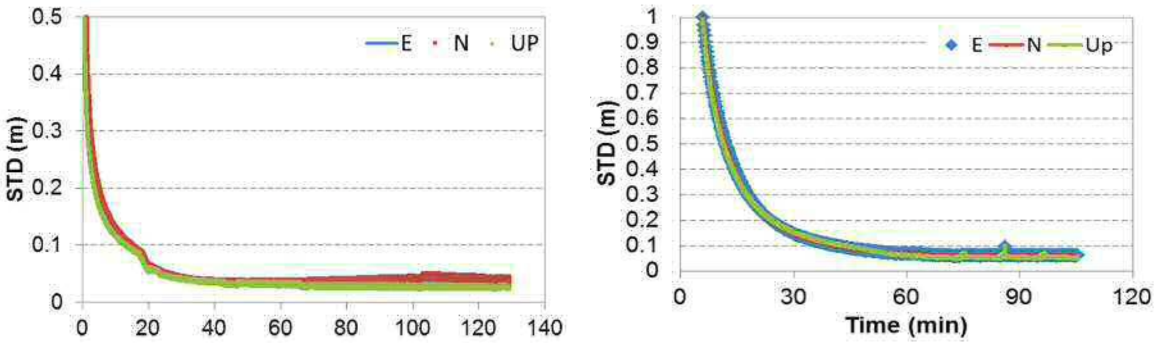


Fig. 8 PPP results of the kinematic tests; shipborne (left) and vehicle (right).

Another study addressed the fact that detecting and repairing cycle slips and clock jumps is a crucial data pre-processing step needed in fault detection and exclusion (FDE) procedure when performing Precise Point Positioning (PPP). If left unrepaired, cycle slips and clock jumps can adversely affect PPP convergence time, accuracy and precision. Algorithms are proposed for detection and repair of cycle slips and clock jumps using multi-constellation and multi-frequency (MCMF) GNSS data. It is shown that availability of a third frequency enables reliable validation of detected cycle slips. This is because triple frequency analysis can identify the frequency on which the cycle slip occurred as part of the detection process. A clock jump detection and repair procedure is also proposed for a receiver with both carrier phase and code measurements showing jumps. The proposed method uses the average code and phase linear combination and applies to static data. A spline function is used to approximate the data for a pre-defined time window prior to each measuring epoch and a test is performed for detecting presence of a clock jump by comparing the interpolated value to measured value. The algorithm can effectively determine clock jumps for single frequency data from a single constellation as well as MCMF GNSS data. However, MCMF GNSS data adds redundancy, hence improves the reliability of the clock jump detection algorithm. It is recommended to detect and repair clock jumps when using PPP to allow improved modelling of the receiver clock offset in the dynamic model.

A method to compute the minimum HPL using the test statistic of normal distribution, which exploits advances in computational power to meet the requirement of Time to Alert (TTA), was proposed in one article to improve service availability. To obtain the minimum solution, two approximations used in traditional algorithms need exact solutions: the distribution of the horizontal position error and the determination of the worst case to ensure that the resulted HPL is able to accommodate all possible bias. This was validated where the optimal solution was achieved with a pre-defined accuracy and sufficient computational efficiency. Furthermore, the new HPL is used to determine if current approximated methods are conservative, where one of the methods does not meet the integrity requirement with given test statistic, error model and integrity risk definition.

The performance of online fault detection and isolation (FDI) algorithm under multiple fault scenarios was evaluated e.g., for two, three and four faults in the GNSS and GNSS/INS measurements under different conditions of visible satellites and satellite geometry. Besides, the reliability (expressed in terms of the minimal detectable bias - MDB) and separatebility (correlation coefficients between faults detection statistics) measures are also investigated to measure the capability of the FDI method. A performance analysis of the FDI method is conducted under the geometric constraints to show the importance of the FDI in terms of fault detectability and separability for robust positioning and navigation for real time applications.

For efficient IM, the focus in one study was on the quality assessment of precise orbit and clock products for the emerging Galileo, BeiDou, and QZSS systems. Products provided by Multi-GNSS Experiment (MGEX) over 2 years were used for evaluation. First, the products were assessed by orbit and clock comparisons among individual analysis centers (ACs), which give us an objective impression of their consistency. In addition, the precise orbits were verified by satellite laser ranging (SLR) residuals, which can be regarded as indicators of orbit accuracy. Moreover, precise point positioning (PPP) tests were conducted to further verify the quality of MGEX precise orbits and clocks. Orbit comparisons showed agreements of about 0.1–0.25 m for Galileo, 0.1–0.2 m for BeiDou MEOs, 0.2–0.3 m for BeiDou IGSOs, and 0.2–0.4 m for QZSS. The BeiDou GEO orbits, however, have the worst agreements having a few meters differences. Clock comparisons of individual ACs have a consistency of 0.2–0.4 ns for Galileo, 0.2–0.3 ns for BeiDou IGSOs, 0.15–0.2 ns for BeiDou MEOs, 0.5–0.8 ns for BeiDou GEOs, and 0.4–0.8 ns for QZSS in general. The SLR validations demonstrated an accuracy of about 0.1 m for the current Galileo, BeiDou IGSO/MEO orbits, and about 0.2 m for QZSS orbits. However, the SLR residuals of BeiDou GEO orbits showed a systematic bias of about −0.5 m together with a standard deviation of 0.3 m. Solutions of PPP with different products mostly agree well with each other, which further confirms the good consistency of orbits and clocks among ACs. After convergence, an accuracy of 1 mm to 1 cm for static PPP and a few centimeters for kinematic PPP was achieved using multi-GNSS observations and MGEX orbit and clock products. However, it should be noted that a few exceptions may exist throughout the evaluations due to the insufficient models, different processing strategies, and ongoing updates applied by individual ACs.

The scope of another study is on the evaluation of the performance of Galileo from the user point of view, such as Rail Transportation Management System (ERTMS), by using public data, mostly made available by the IGS and its MGEX. The analysis focuses on the open service for dual and single frequency users and covers the satellite orbit and clock errors, the signal-in-space availability, the positioning accuracy, the ranging bounding parameters, the integrity risk and the continuity risk. The Galileo satellite orbit errors are evaluated for the F-NAV messages on E5a frequency and for the I-NAV message on E1 and E5b frequencies. The broadcast ephemerides are generated from real-time streams of about 30 IGS multi-GNSS stations. Precise orbit and clock parameters as well as differential code biases are also estimated by the German Aerospace Canter (DLR). The Signal In Space Ranging Error (SISRE) as 95% in nominal condition is described and selected anomalies are identified. Outlier's exclusion approaches are used in order to assess nominal performance also in presence of anomalies. The satellite clock stability is analyzed using various GNSS stations connected to Hydrogen masers and some to the UTC network. The clock error is evaluated over arcs of 3 days based on the overlapping Allan deviation.

The second part of the study focuses on the user performance in the position domain with a particular focus on future integrity service for aviation and other applications. Signal-in-space parameters which are relevant for the Advanced RAIM concept and the generation of the Integrity Support Message are monitored and analyzed. The study focuses on two aspects, for which novel monitoring methodologies are described and used. Firstly, the bounding of the ranging error is addressed. Several bounding definitions and methods can be used for the generation of the User Range Accuracy (URA) each of them solves differently the problem of assessing statistic characteristics of the SISRE distribution tails with a limited sample size. The strict aviation integrity requirements (even stricter for rail applications) require extrapolation strategies in the online ground monitoring. On the other side the ARAIM ground monitoring can take advantage of the fact that it has to perform a bounding monitoring rather than a bounding estimation, which allows reaching confidence on higher percentiles with smaller sample size. This method will be used on the real Galileo data and results are presented and compared to state of art techniques. Secondly, the study discussed the continuity and integrity risk of the user. So far, most integrity and continuity requirements have been tailored to the aviation user needs. The risks are interpreted in an average sense, by computing probabilities of events over a certain period of time and scaling them to the duration of the specific operation. These approaches don't take into account that the continuity risk has per definition an evolution over time. The extension of ARAIM to other applications (rail, automotive, UAVs) with longer operation durations and higher level of criticism of the continuity requirements need more accurate methods. The study presents a model for the computation of the continuity risk where each satellite health status is modelled with a Markov process using the GPS Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR). The user continuity risk resulting from the ARAIM FDE is then computed propagating over time of the user healthy status.

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SG 4.4.2: Modernized GNSS for Crustal Motions

Chair: *Jianghui Geng (China)*
Vice Chair: *Diego Melgar (USA)*

Members

- *Junbo Shi (China)*
- *Brendan Crowell (USA)*
- *Peng Fang (USA)*
- *Yehuda Bock (USA)*
- *Dana Caccamise (USA)*
- *Norman Teferle (Luxembourg)*
- *Yong Zheng (China)*
- *Radoslaw Baryla (Poland)*
- *Bob Wang (USA)*
- *Jennifer Haase (USA)*
- *Adrian Borsa (USA)*

Activities and publications during the period 2015-2019

1. Study Group Meeting at AGU Fall Meeting 2016

We had a joint study group meeting with READI (Real-time Earthquake Analysis for Disaster Mitigation Network) at AGU Fall Meeting in San Francisco in 2016. We discussed how we can use GNSS data in addition to seismic data to detect minor ground motions and identify real seismic signals. Dr. Yoaz Bar-Sever from JPL discussed their GREAT alert system in support of earthquake disaster mitigation. This system is composed of about 250 stations on a global scale, and is processing the GPS/GLONASS data with a latency of less than 10 s. Dr. Yehuda Bock from Scripps talked about the real-time integration of GPS data and MEMS accelerometer data. They have installed about 20 such units in southern California, and successfully captured two Mw4~5 earthquakes and identified P-wave arrivals, which cannot be achieved when only high-rate GPS is available. Dr. Brendan Crowell from University of Washington introduced their latest development on GPS-based early warning module, that is G-FAST. They used high-precision GPS data to calculate the peak ground displacements (PGD) and successfully determined the magnitude of large earthquake within a minute. Dr. Y Tony Song from JPL showed that they use static offsets derived from high-rate GPS to contribute to tsunami early warning. Dr. Geng from Wuhan University discussed how high-rate GLONASS data can augment high-rate GPS data to improve the noise spectrum over a wide band from 2 s to 0.5 days. They concluded that high-rate multi-GNSS can reduce more than the noise from multipath effects while sidereal filtering techniques only work on a narrowband from 50 to 2000 s (Geng et al. 2017).

2. International Seismogeodesy Workshop 2018 in Wuhan

We held International Seismogeodesy Workshop 2018 in Wuhan, China. More than 30 geodesists and seismologists from China, America and Hong Kong, China attended the meeting. This meeting aimed at engaging geodesists to know seismologists more for earthquakes, and focused on four issues: First, what observations do seismologists require to advance earthquake studies? Second, what can geodesists do to relieve the headaches of seismologists? Third, how can the headaches of seismologists be resolved by geodesists?

Fourth, can seismologists help to explain new geodetic observations? Around these issues, twelve reports were presented, and the experts and scholars attending the meeting had heated discussions and exchanges. This meeting had a positive meaning for international seismogeodesy research.

Fig. 1 Group photo of the seismogeodesy workshop

3. Science Application Session at IGS Workshop 2018

Dr. Geng chaired the session of Science Application at IGS Workshop 2018 in Wuhan, China. The session focused on scientific applications that benefit from IGS, including reference frame realization, Earth rotation, plate tectonics, plate boundary deformation, the earthquake cycle, seismology, glacial isostatic adjustment, sea level monitoring, low Earth orbiter positioning, time transfer, weather forecasting, climate monitoring, ionospheric science, atmospheric sounding, tsunami early warning, terrestrial water storage, snow depths, soil moisture, vegetation monitoring, and fundamental physics experiments. Six selected reports were presented in the plenary meeting: Dr. Zheng from Wuhan University talked about crustal deformation in the Kunlun Fault region from long-term GPS measurements; Dr. Kawamoto from Geospatial Information Authority of Japan introduced real-time coseismic fault model estimation based on RTK-GNSS analysis in Japan; Dr. Fernandes from SEGAL (UBI/IDL), Covilhã discussed the effect of colored noise on automatic offset detection in GNSS time series; Dr. Wickert from GFZ introduced GNSS-Reflectometry for Earth Observation, including history, results and prospects; Dr. Kuang from JPL talked about observing geocenter motion from LEO POD using onboard GPS tracking data; Dr. Ge from GFZ showed validating precipitable water vapor from shipborne GNSS observation using ground-based and spaceborne data.

4. A special issue at Remote Sensing on GNSS for Earth Observing System

Dr. Geng started a special issue at Remote Sensing on GNSS for Earth Observing System in December, 2018. This special issue calls for original researches and case studies focusing on recent developments in GNSS theories and algorithms and GNSS earth science applications. We encourage submissions that may include but are not limited to: High-precision GNSS and relevant algorithms; New methods and relevant challenging issues for retrieving troposphere and ionosphere delays; Co-/inter-/post-seismic crustal deformation, slow-deformation, and slip models of large earthquakes from GNSS or with other types of data (leveling data, InSAR, GRACE, etc.); Volcano, subsidence and landslide monitoring using GNSS; GNSS meteorology and its implications for large-scale climate phenomena, such as ESNO and East Asian Monsoon; Terrestrial-water-storage variation from GNSS and its effect on global sea-level change; GNSS reflectometry for ocean and land applications; Earthquake and tsunami early warning using real-time GNSS; Challenging issues and future directions. The website of this special issue is https://www.mdpi.com/journal/remotesensing/special_issues/GNSS_EOS.

5. An open-source software for PPP-AR

PRIDE-PPPAR originates in Dr. Maorong Ge's efforts on PPP-AR and later developed and improved by Dr. Jianghui Geng. It is an open-source software package which is based on many GNSS professionals' collective work in GNSS Research Center, Wuhan University. We would like to thank them all for their brilliant contributions to this software. We make this package open source with the goal of benefiting those professionals in their early career, and also advocate the geodetic and geophysical applications of PPP-AR. Especially, we hope that this package can contribute to high-precision applications in geosciences such as crustal motion and troposphere sounding studies. The entire open source project is funded by National Science Foundation of China (No. 41674033 and 41861134009) and is under the auspices of IAG JWG 4.4.1 "New GNSS Signals for Crustal Motion Studies".

PRIDE-PPPAR (Precise Point Positioning with Ambiguity Resolution) aims at post-processing of GPS data. It is worth noting that PRIDE-PPPAR is capable of processing high-rate GPS data (i.e. 1Hz, 5Hz, 10Hz), which will be useful to GNSS seismology. We are developing multi-GNSS version, and keep an eye on our website for future upgrade. We hope you enjoy the software and will keep attention to the copyright issues.

The copyright of this package is protected by GNU General Public License (version 3). Only a few source code are not open to the public due to technical restrictions and conflicts with existing commercial packages, and thus will be available as a dynamic link library. We note that the LAMBDA and DE405 module are provided as dynamic link libraries as well because of some potential or possible redistribution restrictions by their authors. Those who are interested in these two modules and want to know more information on them can refer to TUDelft:(https://www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-remote-sensing/research/lambda/lambda/) and NASA JPL (ftp://ssd.jpl.nasa.gov/pub/eph/planets/fortran/).

PRIDE-PPPAR requires the phase clock/bias products in the bias-SINEX format computed and released by Wuhan University (ftp://igs.gnsswhu.cn).

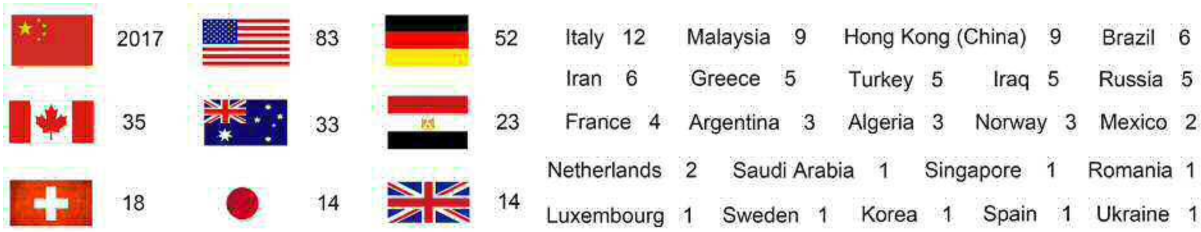

Fig. 2 Downloading countries and times of the PRIDE PPP-AR software

6. WG paper: "A Global Database of Strong-Motion Displacement GNSS Recordings and an Example Application to PGD Scaling" on SRL

This is abstract of the paper: "Displacement waveforms derived from Global Navigation Satellite System (GNSS) data have become more commonly used by seismologists in the past 15 yrs. Unlike strong-motion accelerometer recordings that are affected by baseline offsets during very strong shaking, GNSS data record displacement with fidelity down to 0 Hz. Unfortunately, fully processed GNSS waveform data are still scarce because of limited public availability and the highly technical nature of GNSS processing. In an effort to further the use and adoption of high-rate (HR) GNSS for earthquake seismology, ground-motion studies, and structural monitoring applications, we describe and make available a database of fully curated HR-GNSS displacement waveforms for significant earthquakes. We include data from HR-GNSS networks at near-source to regional distances (1–1000 km) for 29 earthquakes between Mw 6.0 and 9.0 worldwide. As a demonstration of the utility of this dataset, we model the magnitude scaling properties of peak ground displacements (PGDs) for these events. In addition to tripling the number of earthquakes used in previous PGD scaling studies, the number of data points over a range of distances and magnitudes is dramatically increased. The data are made available as a compressed archive with the article."

This paper is finished by the WG members Jianghui Geng, Diego Melgar, Brendan Crowell, Yehuda Bock and Sebastian Riquelme.

7. Studies on how integrated GPS/GLONASS can contribute to high-rate seismogeodesy

High-rate GPS has long been a valuable tool in source studies of moderate to large earthquakes due to its unclipping and unambiguous merits in recording both static and dynamic signatures of ground displacements, which is more than a favorable complement to classic broadband and strong-motion seismic sensors. In this case, it matters whether the positioning accuracy of high-rate GPS suffices in the identification of seismic signals, especially for relatively minor events. However, high-rate GPS is always obsessed by multipath effects. Although multipath effects can be partly mitigated through sidereal filtering, satellite orbits, atmosphere refractions, tides, etc. also contribute to the high-rate GPS noise. In fact, there is a potential risk that sidereal filtering will amplify these errors, which may consequently exceed multipath effects. In addition, we have already been in a multi-GNSS environment where Russia's GLONASS has been in a full constellation since 2012 and the quality of its satellite orbit products by IGS has evolved into the quite similar level to the GPS counterpart. In this study, we demonstrate that multi-GNSS will contribute significantly to or even excel in reducing noise of high-rate displacements as compared to sidereal filtering.

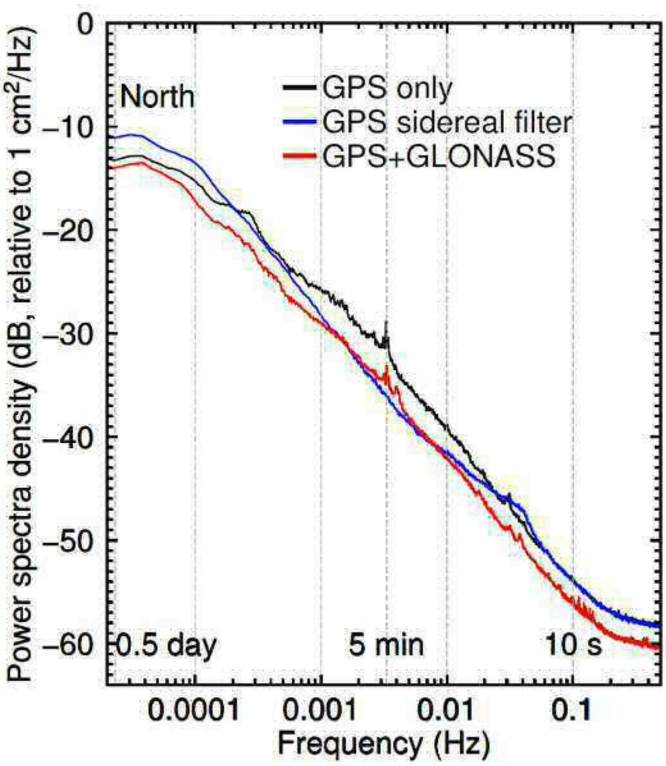

Fig. 3 Power spectral density (PSD) of 1-Hz displacements in the north component derived from GPS-only, sidereally filtered GPS-only and integrated GPS/GLONASS solutions

Fig. 1 shows the averaged PSD over about 2200 high-rate solutions on a wide frequency band from 2 s to about 0.5 days. Compared to the GPS only solutions (black curves), as expected, sidereal filtering (blue curves) is able to markedly reduce the power over the frequency band from about 50 to 2000 s for the north component. Unfortunately, over the higher frequency band from about 20 to 33 s and the lower band from about 1.4 hours to 0.5 days, sidereal filtering clearly increases, rather than reduces, the noise of high-rate GPS. We expect that the deterioration for the periods of 20–33 s can be alleviated if the shift period of “246 s” is adaptively changed in sidereal filtering as proposed by Choi et al. (2004) and Larson et al. (2007). Strikingly, introducing GLONASS (red curves), in contrast, can always reduce the noise of high-rate GPS over the entire frequency band for all three components. In particular, the power from the Nyquist period until about 1.4 hours is almost uniformly reduced by about 2–3 dB (a factor of 1.6 to 2.0) for the north and 1–2 dB (a factor of 1.3 to 1.6) for the east and up components, while such improvement is less for periods longer than a few hours.

Our conclusions are:

1) GPS sidereal filtering can potentially amplify errors on the lowest frequency band of a high-rate displacement time series.

2) Integration with GLONASS reduces the noise of high-rate GPS by up to 40% over the entire frequency band of a displacement time series.

3) High-rate multi-GNSS can be enhanced by sidereal filtering which should be carefully implemented to avoid complicating the noise spectrum.

8. Study crustal deformation in the India-Eurasia collision zone based on 25 years of GPS measurements

The India-Eurasia collision zone is the largest deforming region on the planet; direct measurements of present-day deformation from Global Positioning System (GPS) have the potential to discriminate between competing models of continental tectonics. But the increasing spatial resolution and accuracy of observations have only led to increasingly complex realizations of competing models. Here we present the most complete, accurate and up-to-date velocity field for India-Eurasia available, comprising 2576 velocities measured during 1991-2015. The core of our velocity field is from the Crustal Movement Observation Network of China (CMONOC-I/II): 27 continuous stations observed since 1999; 56 campaign stations observed annually during 1998-2007; 1000 campaign stations observed in 1999, 2001, 2004, 2007; 260 continuous stations operating since late 2010; 2000 campaign stations observed in 2009, 2011, 2013, 2015. We process these data and combine the solutions in a consistent reference frame with stations from the Global Strain Rate Model compilation, then invert for continuous velocity and strain-rate fields. We update geodetic slip rates for the major faults (some vary along strike), and find those along the major Tibetan strike-slip faults are in good agreement with recent geological estimates. The velocity field shows several large undeforming areas, strain focused around some major faults, areas of diffuse strain, and dilation of the high plateau. We suggest that a new generation of dynamic models incorporating strength variations and strain weakening mechanisms is required to explain the key observations. Seismic hazard in much of the region is elevated, not just near the major faults (Zheng et al., 2017).

Our Key Points:
1) We present the most complete and up-to-date velocity field in the India-Eurasia collision zone including 2576 GPS stations observed from 1991 to 2015.
2) Velocity field shows several large undeforming areas, strain around some major faults, areas of diffuse strain, dilation of high plateau.
3) There is no robust evidence for discrepancy between geological and geodetic slip rates of the major strike-slip faults in Tibet.

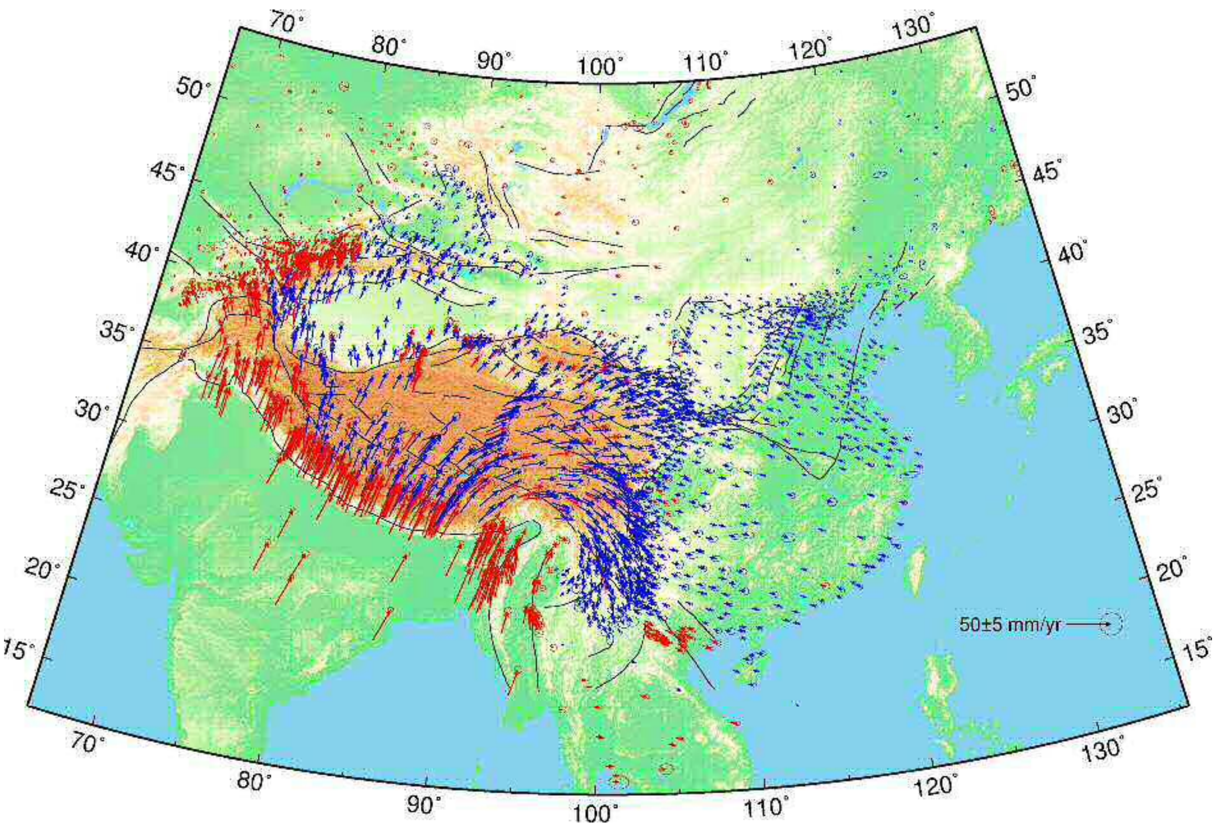

Fig. 4 Interseismic GPS velocity field covering the India-Eurasia collision zone with respect to stable Eurasia. The blue arrows indicate GPS velocities at CMONOC-I/II stations, and the red ones are those transformed from Global Strain Rate Model. Error ellipses are 95% confidence interval.

9. Forecast the shallow seismicity in the India-Eurasia collision zone based on geodetic strain rates

Geodetic strain rates from increasing GPS data provide a promising approach for seismicity forecast. With the strain rate field presented in Zheng et al. (2017, https://doi.org/10.1002/2017JB014465) derived from the most complete and up-to-date GPS dataset in the India-Eurasia collision zone, we forecast the shallow seismicity of this region, and infer that about 11 Mw≥7.5, 36 Mw≥7.0, 109 Mw≥6.5 and 326 Mw≥6.0 earthquakes may occur here every 100 years. We indicate that shallow seismicity forecast may be able to help us distinguish between block and continuum models, and block model cannot well describe the kinematics of the Tibetan Plateau, Tien Shan, West Mongolia, North China and Myanmar. We suggest that the regions with high forecasted earthquake rates but lack of historical earthquakes are undergoing high seismic risk, such as the west-central Himalaya (overdue for Mw≥7.5 earthquakes, possibly Mw≥8.0) and the central Altyn Tagh fault (overdue for Mw≥7.0 and Mw≥7.5 earthquakes) (Zheng et al., 2018).

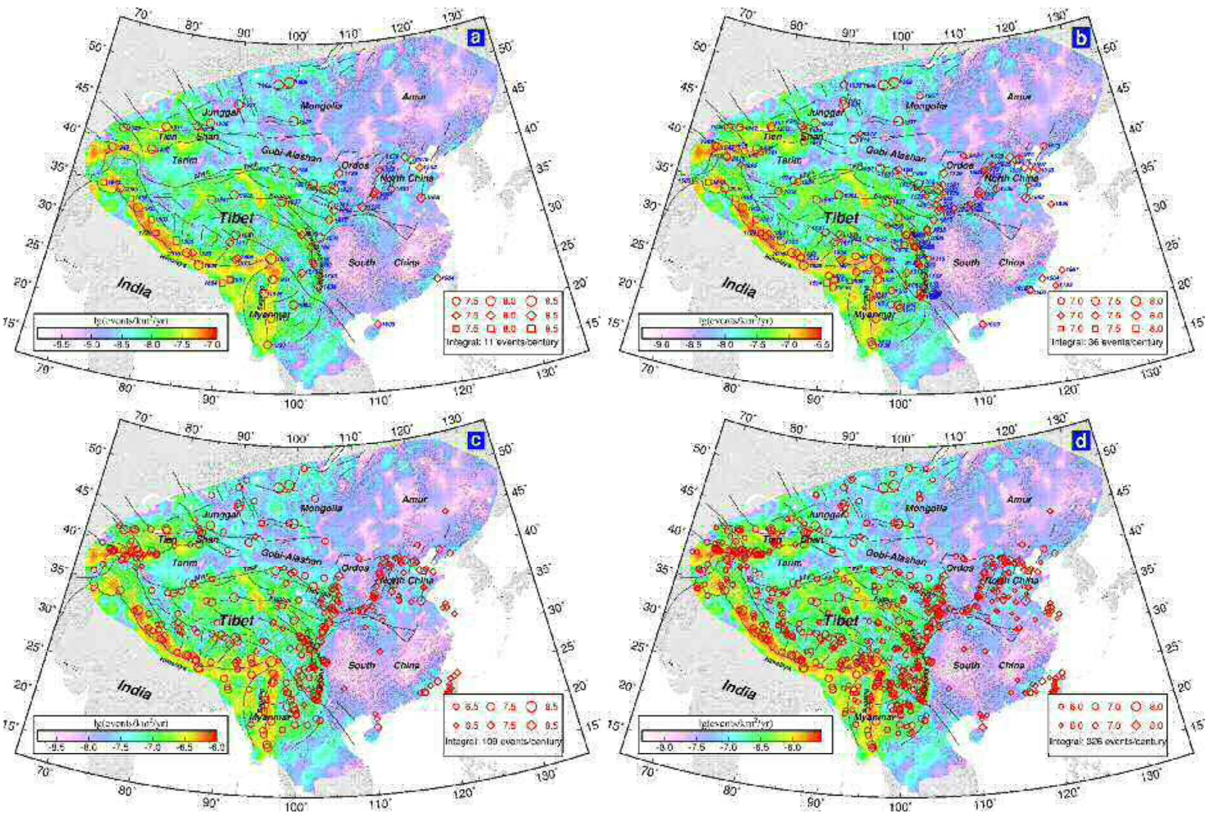

Fig. 5 The forecast result of the shallow seismicity in the India-Eurasia collision zone. Figures a, b, c and d are for Mw≥7.5, Mw≥7.0, Mw≥6.5 and Mw≥6.0 shallow earthquakes, respectively. The red symbols represent historical earthquakes, and the blue numbers indicate the years of the earthquakes. The forecast values represent the number of earthquakes per square kilometer per year

Our Key Points:

1) The India-Eurasia collision zone would suffer from about 11 Mw≥7.5, 36 Mw≥7.0, 109 Mw≥6.5 and 326 Mw≥6.0 shallow earthquakes per 100 years.
2) Shallow seismicity forecast provides a promising approach to help distinguish between block and continuum models for crustal deformation.
3) The west-central Himalaya and the central Altyn Tagh fault are undergoing high earthquake risk.

News Archive

- Diego Melgar became the associate editor of *Journal of Geophysical Research: Solid Earth.*
- Brendan Crowell became the assocaite editor of *Bulletin of the Seismological Society of America.*

Selected publications

Crowell, B. W., Schmidt, D. A., Bodin, P., Vidale, J. E., Gomberg, J., Hartog, J. R., et al. (2016). Demonstration of the cascadia g-fast geodetic earthquake early warning system for the nisqually, washington, earthquake. *Seismological Research Letters*, 87(4), 930-943.

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Goldberg, D. E., & Bock, Y. (2017). Self-contained local broadband seismogeodetic early warning system: detection and location. *Journal of Geophysical Research: Solid Earth*, 122(4), 3197-3220.

Hadas, T., Teferle, F. N., Kazmierski, K., Hordyniec, P., & Bosy, J. (2016). Optimum stochastic modeling for gnss tropospheric delay estimation in real-time. *GPS Solutions*, 21(3), 1-13.

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Wang, G., Turco, M., Soler, T., Kearns, T., & Welch, J. (2017). Comparisons of OPUS and PPP solutions for subsidence monitoring in the greater Houston area. *Journal of Surveying Engineering*, 143(4), 05017005.

Zheng, G., Wang, H., Wright, T. J., Lou, Y., Zhang, R., Zhang, W., et al. (2017). Crustal deformation in the India-Eurasia collision zone from 25 years of GPS measurements. *Journal of Geophysical Research: Solid Earth*, *122*(11), 9290-9312.

Zheng, G., Lou, Y., Wang, H., Geng, J., & Shi, C. (2018). Shallow seismicity forecast for the India-Eurasia collision zone based on geodetic strain rates. *Geophysical Research Letters*, 45(17), 8905-8912.

Working Groups of Sub-commission 4.4:

WG 4.4.1: Biases in Multi-GNSS data processing

Chair: *Xingxing Li (Germany)*
Vice Chair: *Jan Dousa (Czech Republic)*

Members

- Xingxing Li (GFZ German Research Center for Geosciences, Germany)
- Jan Dousa (Geodetic observatory Pecny, Czech Republic)
- Pavel Vaclavovic (Geodetic observatory Pecny, Czech Republic)
- Nigel Penna (Newcastle University, UK)
- Robert Weber (Vienna University of Technology, Austria)
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- Jinling Wang (University of New South Wales, Australia)
- Suqin Wu (RMIT University, Australia).
- Xiaoming Wang (RMIT University, Australia)
- Chris Rizos (University of New South Wales, Australia),
- Yang Gao (University of Calgary, Canada)
- Richard Langley (University of New Brunswick, Canada).
- Felipe Nievinski (Federal Institute of Santa Catarina, Brazil).
- Tianhe Xu (Xi'an Research Institute of Surveying and Mapping, China)
- Haibo He (Beijing Satellite Navigation Center, China)
- Fei Guo (Wuhan University, China)
- Yidong Lou (Wuhan University, China)
- Bofeng Li (Tongji University, China)
- Shuanggen Jin (Shanghai Astronomical Observatory, China)
- Zishen Li (Academy of Opto-Electronics, China)
- Ningbo Wang (Institute of Geodesy and Geophysics, China)

Activities and publications during the period 2015-2019

Main activities:

1. Multi-GNSS UPDs (uncalibrated phase dealys)

A GCRE four-system UPD estimation model and multi-GNSS UD PPP AR method were developed. With data acquired from MGEX, IGS, CMONOC and HongKong CORS stations, the UPDs of GCRE four systems are estimated and the quality of UPD products in terms of temporal stability and residual distributions are also investigated, and then we evaluated the benefits of multi-GNSS to PPP AR. Our results show, that GCRE four-system PPP-AR enables the fastest time to first fix (TTFF) solutions and the highest accuracy for all three coordinate components compared to the single- and dual-system. An average TTFF of 9.21 min with 7° cut-off elevation can be achieved for GCRE PPP AR, which is much shorter than that of GPS (18.07 min), GR (12.10 min), GE (15.36 min) and GC (13.21 min). With observations length of 10 minutes, the positioning accuracy of the GCRE fixed solution is (1.84, 1.11, 1.53) cm while the GPS-only result is (2.25, 1.29, 9.73) cm for the east, north and vertical components, respectively. When the cut-off elevation is increased to 30°, the GPS-only PPP AR results are very unreliable while 13.44 min of TTFF is still achievable for GCRE four-system solutions.

A dataset of 30 days from DOY001 to 030 of 2017 with a tracking network consisting of about 148 MGEX/IGS stations is used for GPS UPD estimation. The mean STD of the 30-day WL UPDs is 0.023 cycles while the mean STD of NL UPDs at DOY001 is 0.03 cycles. The percentage of residuals within ±0.15 cycles and within ±0.25 cycles are 94.8% and 98.7% for WL, 95.1% and 99.9% for NL, respectively. A global tracking network containing 67 MGEX stations are is used to estimate BDS UPDs. The influence of satellite-induced code biases is analyzed for BDS UPDs. Results show that the temporal stability of BDS WL UPDs is improved by 27.9%, 77.9% and 88.9% for GEO, IGSO and MEO satellites after code bias correction, while 1.7%, 17.6% and 22.6% are improved for BDS NL UPDs. Besides, the observations from the CMONOC and Hong Kong CORS network are also used for evaluate BDS UPDs. After the code bias correction, the mean STDs of CMONOC WL UPDs are improved by 16.7%, 27.6% and 85.9% for GEO, IGSO and MEO satellites and 11.7%, 12.1% and 74.4% are improved for Hong Kong CORS network. No obvious improvement is found for NL UPDs of regional network after code bias correction. When compared with global BDS NL UPDs, BDS NL UPDs estimated by Hong Kong CORS network is the more stable one with mean STDs of 0.031, 0.014 and 0.007 cycles for GEO, IGSO and MEO satellites. Thus, it is demonstrated that the higher temporal stability will be achieved for WL UPDs after the code bias correction and the small network will lead to a better results of NL UPDs. With a network of homogeneous receivers, the GLONASS UPDs were estimated with three mainstreaming types of receivers (TRIMBLE NETR9, JAVAD TRE_G3TH DELTA and LEICA) respectively. Results show that the WL UPDs estimated with TRIMBLE NETR9 all version receivers have the greatest stability with a mean STD of 0.0395 cycles, while the WL UPDs estimated with JAVAD TRE_G3TH DELTA version 3.6.7 receivers are the worst with a mean STD of 0.0565 cycles. For results of NL UPDs, UPDs estimated from LEICA receivers show the worst stability with the mean STD being of 0.117 cycles. For all type s of GLONASS UPDs, the percentages of NL residuals within ±0.25 cycles are close to 100%, while the percentages of WL residuals within ±0.25 cycles are 92.90%, 94.68%, 93.41% and 85.89% for TRIMBLE NETR9 all version receivers, TRIMBLE NETR9 5.15 receivers, LEICA receivers and JAVAD TRE_G3TH DELTA version 3.6.7 receivers, respectively. Although different version of receiver firmware has no influence on the temporal stability of GLONASS UPDs, it will cause a common deviation for NL UPDs comparing with the result of receivers with the same firmware version. It is necessary to select stations with the same receiver firmware version to conduct the GLONASS UPD estimation and PPP AR. Global and European networks are applied for the estimation of Galileo UPDs. The mean STD of global-network-derived WL UPDs is 0.01 cycles and that from European network is 0.02 cycles. The mean STDs of NL UPDs are 0.09 and 0.11 cycles for global and European networks, respectively. In terms of mean STD, global and European networks have comparable performance. However, the RMS of WL and NL residuals are 0.091 and 0.107 cycles for global network, 0.072 and 0.082 cycles for European network, which indicates that UPDs estimated by European network are more reliable.

The BDS observations from three different reference networks (Hong Kong, the CMONOC, and the MGEX networks) are employed to analyze the spatial-temporal characteristics of the BDS UPDs and evaluate the performance of PPP ambiguity resolution for GEO/IGSO/MEO satellites. For the GEO satellites, the mean STDs are 0.040, 0.017 and 0.069 cycles for Hong Kong, the CMONOC, and the MGEX networks, respectively, while the mean STDs of the IGSO satellites are 0.029, 0.020 and 0.028 cycles. For the MEO satellites, the STDs are on average 0.060, 0.024 and 0.029 cycles for Hong Kong, the CMONOC, and the MGEX networks. It can be observed that the CMONOC has the best stability among the three networks; the possible reason for this is that all the CMONOC stations are equipped with the same type of the receiver (TRIMBLE NETR9). Among the three types of satellites, the IGSO satellites show the best performance in terms of temporal stability, mainly because a continuous visible arc can be observed for IGSO satellites and the effect of the multipath is weaker than it is for GEO satellites. The NL UPD series of most BDS satellites are stable during a whole day and the NL UPDs of the Hong Kong network show the best temporal stability, while a subtle variation can be found for the NL UPDs of the MGEX networks. Except for the C05 and C12 satellites, the STDs of the NL UPDs for other BDS satellites are within 0.10 cycles. The STDs range from 0.006 to 0.13 cycles and are on average 0.037, 0.052 and 0.058 cycles for Hong Kong, the CMONOC, and MGEX networks, respectively. Different from the results of the WL UPDs, the NL UPDs of Hong Kong are better than the two other networks, since the distribution of the Hong Kong stations is denser, which means the orbit and atmospheric residual errors are almost the same for each station and can be absorbed by NL UPDs.

The multi-frequency UPD including EWL, WL and NL are also estimated for multi-frequency PPP ambiguity resolution. Benefiting from the long wavelength of EWL ambiguity, the EWL UPD series are more stable than WL and NL UPDs. It is interesting to find that the EWL UPDs of Galileo satellite are all close to zero while the values of WL UPDs of different Galileo satellites are different. In fact, we found that the fractional parts of EWL ambiguities for all Galileo satellites are almost the same values and can be absorbed by the receiver UPDs in the UPD estimation and thereby the resultant UPD corrections of Galileo satellites are zero. This phenomenon may be associated with the characteristic of the Alternative Binary Offset Carrier (Alt-BOC) signals. For BDS-3, B2a-B2b EWL UPDs were estimated to investigate the characteristics of phase biases of B2a/b signals. Eight stations able to track BDS-3 B2 signa were used for EWL UPD estimation. We can see that the fractional parts of different satellites agree with each other very well for both the data and pilot components. No differences can be observed between satellites C19~C22 manufactured by CAST and C27~C30 satellites manufactured by SECM. Since only eight stations are used for UPD estimation, the resultant EWL UPDs are not stable as the Galileo EWL UPD, however, we also found that the BDS-3 B2a-B2b satellite UPDs are close to the zero, which means that the phase biases of B2a are almost the same as those of B2b measurement.

2. BDS satellite-induced code bias

Since the satellite-induced and elevation-dependent code biases were observed for the 14 older BDS-2 satellites (C01-C14), an analysis and characterization of the code observations for the six newly launched satellites is required. The Multipath (MP) combination, Melbourne-Wübbena (MW) combination and Uncalibrated Phase Delays (UPDs) are calculated for all newly launched satellites on different frequencies. The results indicate that the newly launched BDS-2 satellite I6 has similar elevation-dependent code bias as the 14 older BDS-2 satellites while the satellite-induced code bias is negligible for the BDS-3 satellites. We also developed an improved elevation-dependent code bias correction model to mitigate satellite-induced code bias of the BDS satellites. The impact of code bias on MP combination, wide-lane ambiguity and UPD estimation were evaluated before and after the code bias correction. After applying the new correction model to the code observations, significant improvement is achieved in terms of the root mean square (RMS) of the MP series, the convergence time of the MW series and the quality of UPDs estimates for the I6 satellite and five older BDS-2 IGSO satellites C06-C10. No significant improvement is achieved for the results of MP series, MW series and UPD estimates for BDS-3 satellites since the derived correction values are nearly close to zero, which also indicates that the code biases are ignorable for the new-generation BDS-3 satellites on all frequency bands. This finding denotes a significant improvement for the new-generation BDS satellites and signals.

3. Inter-frequency Phase Bias

The triple-frequency carrier phase combination time series vary within 2 cm for all the satellites except G01, which reaches approximately 4 cm. Small bias variations, which reach up to ~2and 4cm respectively are observedfor C01 and G01. Such apparent bias variation, which is also known as inter-frequency clock bias (IFCB), signifies the difference of satellite clock offsets determined from two different signal pairs and provides an indication of thermally dependent inter-frequency biases. As the IFCBs for a certain satellite are identical for different receivers even though these are at different locations, the IFCBs could be completely eliminated as a common error by forming differences between receivers in precise relative positioning applications. However, without careful consideration of such biases, the satellite clock products derived from the first pair of carrier phase observations cannot be used for PPP using the second pair of carrier phase observations. This means that the presence of IFCB will limit the applicability of a common clock product for PPP applications. In line with our analysis, several researchers have also previously identified the presence of bias variations for GPS Block IIF and BeiDou-2 satellites. In contrast, no apparent bias variations can be recognized for the QZSS and Galileo satellites. Our findings for the first time indicate that all new-generation BeiDou-3 satellites show a good consistency of the B1C-B2b-B2a signals and exhibit no apparent bias variations. The absence of such bias variations simplifies the potential processing of multi-frequency PPP using observations from the new-generation BeiDou-3 satellites.

The IFCB estimation approaches for triple-frequency PPP based on either uncombined (UC) observations or IF combined observations within a single arbitrary combination are proposed. The key feature of the IFCB estimation approaches is that we only need to obtain a set of phase-specific IFCB (PIFCB) estimates between the L1/L5 and L1/L2 IF satellite clocks, and then, we can directly convert the obtained L1/L5 IF PIFCBs into L5 UC PIFCBs and L1/L2/L5 IF PIFCBs by multiplying individual constants. The mathematical conversion formula is rigorously derived. The UC and IF triple-frequency PPP models are developed. Datasets from 171 stations with a globally even distribution on seven consecutive days were adopted for analysis. After 24-h observation, the UC and IF triple-frequency PPP without PIFCB corrections can achieve an accuracy of 8, 6 and 13 mm, and 8, 5 and 13 mm in east, north and up coordinate components, respectively, while the corresponding positioning accuracy of the cases with PIFCB consideration can be improved by 38, 33 and 31%, and 50, 40 and 23% to 5, 4 and 9 mm, and 4, 3 and 10 mm in the three components, respectively. The corresponding improvement in convergence time is 17, 1 and 22% in the three components in UC model, respectively. Moreover, the phase observation residuals on L5 frequency in UC triple-frequency PPP and of L1/L2/L5 IF combination in IF triple-frequency PPP are reduced by about 4 mm after applying PIFCB corrections. The performance improvement in UC triple-frequency PPP over UC dual-frequency PPP is 7, 4 and 2% in terms of convergence time in the three components, respectively. The daily solutions of UC triple-frequency PPP have a comparable positioning accuracy to the UC dual-frequency PPP.

4. Differential code bias

Differential code biases (DCBs) of global navigation satellite system (GNSS) are required for code based positioning, ionospheric total electron content (TEC) extracting, as well as ambiguity resolution using code observation. In order to properly handle the code biases in GNSS data processing, the algorithm of IGGDCB (IGG stands for the Institute of Geodesy and Geophysics in Wuhan) has been developed for the estimation and analysis of the DBCs between all relevant signals of the currently changing GNSS environment. IGGDCB method is developed for the DCB estimation of current regional BDS satellites, which is also adaptable for GPS, GLONASS and Galileo constellations. The GNSS DCB processing activities and progresses conducted at IGG and Academy of Opto-Electronics (AOE) of the Chinese Academy of Sciences (CAS) include: (1) GPS and GLONASS DCB estimation in parallel with global ionospheric total electron content (TEC) modeling at the CAS ionosphere analysis center (IAC) of the IGS; and (2) routine CAS MGEX DCB products contribute to the IGS multi-GNSS experiment (MGEX) project.

CAS was nominated as a new IGS IAC during the IGS workshop 2016 held in Sydney, Australia. The global ionospheric maps (GIM) of CAS is generated by SHPTS (Spherical Harmonic plus generalized Trigonometric Series functions) method, which takes advantages of th e spherical harmonic and the generalized trigonometric series functions on global and local scales, respectively. The daily satellite and receiver DCBs between the legacy GPS and GLONASS C1, P1, P2 and C2 signals are also included in the rapid and final GIM products, which is confirmed to perform at the same level of the DCBs provided by the Center for Orbit Determination in Europe (CODE). CAS starts the routine upload of the rapid and final GIMs to the IGS from the beginning of 2017. CAS's GIM products covering the time span 1998-now are now available from CDDIS (cddis.gsfc.nasa.gov) and our own GIPP (ftp.gipp.org.cn/product/ionex/) ftp archives, with a latency of 1 and 3 days for rapid and final products, respectively.

The multi-GNSS DCBs generated at CAS also contribute to the IGS MGEX project in addition to the products provided by the German Aerospace Center (DLR). In spite of the legacy GPS and GLONASS signals, the new GPS civil signals as well as BDS and Galileo signals are also included in the data processing of CAS. It means that DCBs of all relevant signals of the GPS, GLONASS, BDS and Galileo satellites are determined in CAS's MGEX DCB products. Other than DLR's MGEX DCB product, which makes use of CODE's global ionosphere maps for ionospheric correction, CAS's product is derived on the basis of IGGDCB method, which employs local ionospheric model for the combined estimation of DCBs and ionospheric activities with the multi-GNSS observations. CAS's DCB product is generated on a daily with a new naming scheme proposed for future MGEX products, which has been routinely delivered to CDDIS and IGS repositories of the IGS since mid-October 2015, covering the time span 2013-now.

The BDS3 DCBs are estimated by using the iGMAS and MEGX networks and the performance of both satellite and receiver DCBs for BDS3 is evaluated with the observational data during the period of DOY 1–180, 2017. The characteristics of BDS3 and BDS2 DCB are compared, and the code ISB between BDS3 and BDS2 are also analyzed in detail. The comparison of our estimated BDS C2I-C6I and C2I-C7I DCBs and the DLR and IGG products shows a good agreement. For BDS2, the mean differences are within ±0.2 ns and STDs are within 0.15 ns. However, the BDS3 presents a larger difference, with the mean difference of about 0.35 ns, because fewer stations are included in the DLR/IGG processing. The comparison of BDS3 and BDS2 DCB shows that the receiver DCB differences between BDS3 and BDS2 are close to zero for the same network, i.e., iGMAS or MGEX. In other words, there is no significant systematic bias between BDS3 and BDS2 receiver DCB. However, when the iGMAS and MGEX networks are processed together, we found that the receiver DCB differences between BDS3 and BDS2 are not close to zero and present an obvious systematic bias between different networks. The further analysis of code ISB between BDS3 and BDS2 also shows a similar phenomenon. Therefore, the receiver DCB of BDS3 and BDS2 should be separately estimated or calibrated when iGMAS and MGEX networks are processed together.We also analyze the receiver DCB and code ISB between Galileo FOC and IOV satellites and found that there is no such systematic bias between Galileo FOC and IOV satellites. A 180-day analysis of estimated

BDS3 and BDS2 DCB shows that the satellite DCBs of BDS3 are fairly stable, with a mean STD of about 0.18 ns. For BDS2, the IGSO DCBs are the most stable with a mean STD of about 0.09 ns, and the GEO DCBs exhibit the worst stability with a mean STD of about 0.18 ns. The mean STDs of receiver DCBs for BDS3 and BDS2 are 0.38 and 0.41 ns, respectively, and the STD of receiver DCBs of BDS3 is smaller than that of BDS2 at most stations.

With the development of Low Earth Orbit satellites, DCBs estimation based on onboard observations has been widely studied. In this study, onboard observations of BDS and GPS satellites by the Chinese Fengyun-3D (FY-3D) and Fengyun-3C (FY-3C) satellites are applied to estimate BDS and GPS DCBs. Since only the code observations of C1C and C2W for GPS, and C2I and C7I for BDS are tracked by FY-3D and FY-3C, the DCB types of GPS C1C-C2W and BDS C2I-C7I are estimated with code multipath considered. First, the DCB estimates based on FY-3D onboard observations are analyzed. When jointly processing BDS + GPS onboard observations, the stability of satellite and receiver DCBs for both BDS and GPS has better consistency with the DCB products of the German Aerospace Center (DLR) and the Chinese Academy of Science than that for the single-system solutions (BDS-only solution and GPS-only solution). This is reasonable because more onboard observations are used in BDS + GPS solution, which can improve the strength of the DCB estimation. The variations of receiver DCB are analyzed as a function of geomagnetism and solar activity, but little relationship between them has been found. Compared with the FY-3C solution, the FY-3D solution can achieve a more stable satellite DCB with a stability improvement of 33%, 48%, 62% and 56% for GPS, BDS GEO, IGSO, and MEO satellites, respectively. Meanwhile, the receiver DCB of FY-3D is more stable than that of FY-3C as well. These improvements of satellite and receiver DCBs can be due to the enhancement of FY-3D GNSS Occultation Sounder (GNOS) instrument, which provides more observations with higher quality. Furthermore, both FY-3D and FY-3C onboard observations are processed together to estimate BDS and GPS DCBs. Compared with the FY-3D solution, the stability of satellite DCB can be improved by 16%, 9% and 7% for GPS, BDS GEO and IGSO satellites DCB, respectively, when both FY-3D and FY-3C onboard observations are jointly processed. The impact of DCB estimation on estimating the vertical total electron content (VTEC) is also investigated. Compared with FY-3D GPS-only and BDS + GPS solutions, the VTEC estimates along the FY-3D orbit can achieve more realistic results for FY-3D + FY-3C solution.

Meeting and communications during the period 2015-2019

1. A Special Issue of Advances in Space Research on "Multi-constellation GNSS: Methods, Benefits, Challenges, and Geosciences Applications";
2. A seminar on "multi-GNSS bias" with Dr. Maorong Ge from the GFZ, Dr. Peng Fang from the USA, Dr. Shuli Song, Dr. Xianglin Jia, Dr. Wenhai Jiao and colleagues of CAST and Microsat participated was hold on October 2018 IGS work shop;
3. A Special Issue of Remote sensing on "Sensing High-precision GNSS: Methods, Open Problems and Geoscience Applications";
4. Session: High-precision GNSS: methods, open problems and Geoscience applications. 8–13 April 2018, Vienna, Austria.
5. Session: Timing and Biases. IGS Workshop 2018, 29 October To 2 November, Wuhan, China.
6. Session: High-precision GNSS: methods, open problems and Geoscience applications. The General Assembly 2019 of the European Geosciences Union (EGU), 7–12 April 2019, Vienna, Austria.

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WG 4.4.2: Integer Ambiguity Resolution for Multi-GNSS PPP and PPP-RTK

Chair: *Xiaohong Zhang (China)*
Vice Chair: *Sue Lynn Choy (Australia)*

Members

- *Yang Gao (University of Calgary, Canada)*
- *Jianghui Geng (Wuhan University, China)*
- *Simon Banville (Natural Resources Canada, Canada)*
- *Sunil Bisnath (York University, Canada)*
- *José Miguel Juan (UPC, Spain)*
- *Baocheng Zhang (GNSS Research Centre, Curtin University, Australia)*
- *Pan Li (GFZ, Germany)*

Main activities and achievements during the period 2015-2019

1. Ambiguity resolved precise point positioning with GPS and BeiDou

A GPS + BDS fractional cycle bias (FCB) estimation method and a PPP AR model were developed using integrated GPS and BDS observations. For FCB estimation, the GPS + BDS combined PPP float solutions of the globally distributed IGS MGEX were first performed. When integrating GPS observations, the BDS ambiguities can be precisely estimated with less than four tracked BDS satellites. The FCBs of both GPS and BDS satellites can then be estimated from these precise ambiguities. For the GPS + BDS combined AR, one GPS and one BDS IGSO or MEO satellite were first chosen as the reference satellite for GPS and BDS, respectively, to form inner-system single-differenced ambiguities. The single-differenced GPS and BDS ambiguities were then fused by partial ambiguity resolution to increase the possibility of fixing a subset of decorrelated ambiguities with high confidence. To verify the correctness of the FCB estimation and the effectiveness of the GPS + BDS PPP AR, data recorded from about 75 IGS MGEX stations during the period of DOY 123-151 (May 3 to May 31) in 2015 were used for validation. Data were processed with three strategies: BDS-only AR, GPS-only AR and GPS + BDS AR. Numerous experimental results show that the time to first fix (TTFF) is longer than 6 h for the BDS AR in general and that the fixing rate is usually less than 35% for both static and kinematic PPP. An average TTFF of 21.7 min and 33.6 min together with a fixing rate of 98.6 and 97.0% in static and kinematic PPP, respectively, can be achieved for GPS-only ambiguity fixing. For the combined GPS+BDS AR, the average TTFF can be shortened to 16.9 min and 24.6 min and the fixing rate can be increased to 99.5 and 99.0%in static and kinematic PPP, respectively. Results also show that GPS + BDS PPP AR outperforms single-system PPP AR in terms of convergence time and position accuracy.

2. Multi-GNSS precise point positioning using raw observations

A joint-processing model for multi-GNSS (GPS, GLONASS, BDS and GALILEO) precise point positioning (PPP) is proposed, in which raw code and phase observations are used. In the proposed model, inter-system biases (ISBs) and GLONASS code inter-frequency biases (IFBs) are carefully considered, among which GLONASS code IFBs are modeled as a linear function of frequency numbers. To get the full rank function model, the unknowns are re-parameterized and the estimable slant ionospheric delays and ISBs/IFBs are derived and estimated simultaneously. One month of data in April, 2015 from 32 stations of the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) tracking network have been used to validate the proposed model. Preliminary results show that RMS values of the positioning errors (with respect to external double-difference solutions) for static/kinematic solutions (four systems) are 6.2 mm/2.1 cm (north), 6.0 mm/2.2 cm (east) and 9.3 mm/4.9 cm(up).One-day stabilities of the estimated ISBs described by STD values are 0.36 and 0.38 ns, for GLONASS and BDS, respectively. Significant ISB jumps are identified between adjacent days for all stations, which are caused by the different satellite clock datums in different days and for different systems. Unlike ISBs, the estimated GLONASS code IFBs are quite stable for all stations, with an average STD of 0.04 ns over a month. Single-difference experiment of short baseline shows that PPP ionospheric delays are more precise than traditional leveling ionospheric delays. The significant improvement of satellite visibility, spatial geometry, dilution of precision, convergence, accuracy, continuity and reliability that a combining utilization of multi-GNSS brings to precise positioning are also carefully analyzed and evaluated, especially in constrained environments.

3. Modeling and Assessment of Triple-frequency BDS Precise Point Positioning

The latest generation of GNSS satellites such as GPS BLOCK IIF, Galileo and BDS are transmitting signals on three or more frequencies, thus having more choices in practice. At the same time, new challenges arise for integrating the new signals. The modeling and assessment of triple-frequency PPP with BDS data were conducted. Firstly, three triple-frequency PPP models are developed. The observation model and stochastic model are designed and extended to accommodate the third frequency. In particular, new biases such as differential code biases and inter-frequency biases as well as the parameterizations are addressed. Then, the relationships between different PPP models are discussed. To verify the triple-frequency PPP models, PPP tests with real triple-frequency data were performed in both static and kinematic scenarios. Results show that the three triple-frequency PPP models agree well with each other. Additional frequency has a marginal effect on the positioning accuracy in static PPP tests. However, the benefits of third frequency is significant in situations of where there is poor tracking and contaminated observations on frequencies B1 and B2 in kinematic PPP tests.

4. Rapid initialization of real-time PPP by resolving undifferenced GPS and GLONASS ambiguities simultaneously

Rapid initialization of real-time precise point positioning (PPP) has constantly been a difficult problem. Recent efforts through multi-GNSS and multi-frequency data, though beneficial indeed, have not proved sufficiently effective in reducing the initialization periods to far less than 10 min. Though this goal can be easily reached by introducing ionosphere corrections as accurate as a few centimeters, a dense reference network is required which is impractical for wide-area applications. Leveraging the latest development of GLONASS PPP ambiguity resolution (PPP-AR) technique, we propose a composite strategy, where simultaneous GPS and GLONASS dual-frequency PPP-AR is carried out, and herein, the reliability of partial AR improves dramatically. We used 14 days of data from a German network and divided them into hourly data to test this strategy. We found that the initialization periods were shortened drastically from over 25 min when only GPS data were processed to about 6 min when GPS and GLONASS PPP-AR were accomplished simultaneously. More encouragingly, over 50% of real-time PPP solutions could be initialized successfully within 5 min through our strategy, in contrast to only 4% when only GPS data were used. We expect that our strategy can provide a promising route to overcoming the difficulty of achieving PPP initializations within a few minutes.

5. Three-frequency BDS precise point positioning ambiguity resolution based on raw observables

All Beidou navigation satellite system (BDS) satellites are transmitting signals on three frequencies, which brings new opportunity and challenges for high-accuracy precise point positioning (PPP) with ambiguity resolution (AR). We proposes an effective uncalibrated phase delay (UPD) estimation and AR strategy which is based on a raw PPP model. First, triple-frequency raw PPP models are developed. The observation model and stochastic model are designed and extended to accommodate the third frequency. Then, the UPD is parameterized in raw frequency form while estimated with the high-precision and low-noise integer linear combination of float ambiguity which are derived by ambiguity de-correlation. Third, with UPD corrected, the LAMBDA method is used for resolving full or partial ambiguities which can be fixed. This method can be easily and flexibly extended for dual-, triple-, or even more frequency. To verify the effectiveness and performance of triple-frequency PPP AR, tests with real BDS data from 90 stations lasting for 21 days were performed in static mode. Data were processed with three strategies: BDS triple-frequency ambiguity-float PPP, BDS triple-frequency PPP with dual-frequency (B1/B2) and three-frequency AR, respectively. Numerous experimental results showed that compared with the ambiguity-float solution, the performance in terms of convergence time and positioning biases can be significantly improved by AR. Among three groups of solutions, the triple-frequency PPP AR achieved the best performance. Compared with dual-frequency AR, additional the third frequency could apparently improve the position estimations during the initialization phase and under constraint environments when the dual-frequency PPP AR is limited by few satellite numbers.

Meeting and communications during the period 2015-2017

1. Session: Precise Point Positioning (PPP). IEEE / ION PLANS Conference, 11-14 April, Savannah, Georgia 2016.
2. Session: Advanced Technologies in High Precision GNSS Positioning. ION GNSS+ 2015, 14-18 September, Tampa, Florida.
3. Session: High precision GNSS-PPP. ION International Technical Meeting 2017, 30 January-02 February, Monterey, California.
4. Session: Multi-GNSS and GNSS specialities and Geo-Dynamics and GNSS Analysis. FIG Working Week, Sofia, Bulgaria, 17-21 May 2015
5. Session: GNSS and National Datum. FIG Working Week, Christchurch, New Zealand, 2-6 May 2016
6. Session: GNSS. FIG Working Week, Helsinki, Finland, 29 May-2 June 2017
7. Session: GNSS PPP. IGNSS, Gold Coast, Australia, 14-16 July 2016
8. Session: PPP. IGNSS, Sydney, Australia, 6-8 December 2016
9. Xiaohong Zhang become the CPGPS (the International Association of Chinese Professionals in Global Positioning Systems) President for 2018-2019
10. Organized a summer school at Xian, China in July 2018
11. Simon Banville. gave a talk "Updates to the CSRS-PPP online service" at IGS Workshop 2018
12. Lin Pan and Xiaohong Zhang gave a talk " Estimating a set of IFCBs to make IGS ionospheric-free clock product compatible with various triple-frequency PPP models" at IGS workshop 2018

Selected publications during the period 2015-2017:

Harima K, Choy S, Elneser L, Kogure S (2016) Local augmentation to wide area PPP systems: a case study in Victoria, Australia. In: IGNSS Symposium, Sydney, Australia, 6-8 December.

Duong V, Harima K, Choy S, Rizos C (2016) Performance of Precise Point Positioning using Triple-frequency GPS Measurements in Australia. In: IGNSS Symposium, Sydney, Australia, 6-8 December.

Harima K, Choy S, Rizos C, Satoshi K (2016) Performance of Real-Time Precise Point Positioning in New Zealand. In: Proceedings of FIG 2016, Christchurch, New Zealand, 2-6 May.

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Choy S, Harima K, Choudhury M, Rizos C, Kogure S (2015) Real-time Precise Point Positioning using QZSS LEX Augmentation Corrections in Australia. In: The International Symposium on GNSS, Kyoto, Japan, 16-19 November.

Harima K, Choy S, Choudhury M, Kogure S, Rizos C (2015) Quasi-Zenith Satellite Augmentation System for High Precision Positioning in Australia. In: IGNSS Symposium, Gold Coast, Australia, 14-16 July.

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Wickramasighe C, Choy S, Harima K (2015) Future of triple frequency PPP in the Asia Pacific region /Australia. In: The International Symposium on GNSS, Kyoto, Japan, 16-19 November.

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Aggrey J, S Bisnath (2017). Analysis of multi-GNSS PPP initialization using dual- and triple-frequency data. Proceedings of ION International Technical Meeting 2017, 30 January-02 February, Monterey, California, in press.

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Fei Guo, Xingxing Li, Xiaohong Zhang and Jinling Wang. (2017). Assessment of precise orbit and clock products for Galileo, BeiDou, and QZSS from IGS Multi-GNSS Experiment (MGEX). GPS Solutions, 21(1): 279-290.

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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 0.10:	High-rate GNSS
Joint Study Group 0.11:	Multiresolutional aspects of potential field theory
Joint Study Group 0.12:	Advanced computational methods for recovery of high-resolution gravity field models
Joint Study Group 0.13:	Integral equations of potential theory for continuation and transformation of classical and new gravitational observables
Joint Study Group 0.14:	Fusion of multi-technique satellite geodetic data
Joint Study Group 0.15:	Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy
Joint Study Group 0.16:	Earth's inner structure from combined geodetic and geophysical sources
Joint Study Group 0.17:	Multi-GNSS theory and algorithms
Joint Study Group 0.18:	High resolution harmonic analysis and synthesis of potential fields
Joint Study Group 0.19:	Time series analysis in geodesy
Joint Study Group 0.20:	Space weather and ionosphere
Joint Study Group 0.21:	Geophysical modelling of time variations in deformation and gravity
Joint Study Group 0.22:	Definition of next generation terrestrial reference frames (discontinued in 2017)

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. 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 structure of the ICCT is specified in the IAG by-laws.

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 2015-2019

President	*Pavel Novák* (Czech Republic)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Commission 1	*Geoffrey Blewitt* (USA)
Commission 2	*Roland Pail* (Germany)
Commission 3	*Manabu Hashimoto* (Japan)
Commission 4	*Marcelo Santos* (Canada)
GGOS	*Hansjörg Kutterer* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)

During the 2015-2019 period, the ICCT Steering Committee met during regular meetings of the IAG's Executive Committee as their memberships largely overlap. The ICCT President informed members of the two committees about the structure of the ICCT, activities of its joint study groups and about organization of the IX Hotine-Marussi Symposium on Mathematical Geodesy organized by ICCT in 2018, see below. The next (and last) meeting of the committee will be organized during the General Assembly of IAG and IUGG, Montreal, Canada, in July 2019.

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, 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 could be used by for fast and easy communication of ideas among the members of the Study Groups.

IX Hotine-Marussi Symposium

The IX Hotine-Marussi Symposium on Mathematical Geodesy was held from 18 to 22 June 2018. The symposium took place at the Faculty of Civil and Industrial Engineering of the Sapienza University of Rome, Italy, in the ancient Chiostro of the Basilica of S. Pietro in Vincoli.

The symposium was attended by 119 participants from 30 countries who contributed 120 papers (83 oral presentations and 37 posters). The scientific program of the symposium was organized in 10 sessions that were mainly modelled thematically after the ICCT study group topics and mostly convened by their chairs:

1. Geodetic methods in Earth system science (N. Sneeuw)
2. Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi)
3. Digital terrain modelling (R. Barzaghi)
4. Space weather and atmospheric modelling (K. Börger, M. Schmidt)
5. Global gravity field modelling and heights systems (D. Tsoulis, S. Claessens)
6. Theory of modern geodetic reference frames and Earth's rotation (Z. Altamimi)
7. Deformation and gravity field modelling at regional scales (J. Huang, Y. Tanaka)
8. Estimation theory and inverse problems in geodesy (A. Dermanis)
9. Advanced numerical methods in geodesy (R. Čunderlík)
10. Multi-sensor and time series data analysis (W. Kosek, K. Sosnica)

Additionally, a special session at the Accademia dei Lincei (the oldest scientific academy in the world, established in 1603 by Federico Cesi) was held on 19 June 2018. Its program consisted of 6 invited talks focused on interactions of geodesy and

- oceanography (M. H. Rio)
- glaciology (O. Francis, T. van Dam)
- atmosphere (R. Pacione, J. Douša)
- mathematics (W. Freeden, F. Sansò)
- solid Earth system structure from space (R. Haagmans)
- seismology (A. Peresan, M. Crespi, A. Mazzoni, G. Panza)

The special session was organized by Fernando Sansò, Emeritus at the Politecnico di Milano, member of the Accademia dei Lincei and long-term driving force behind the Hotine-Marussi symposia series.

The scientific program of the symposium was complemented with a social program including a night tour of the Vatican Museum and the Sistine Chapel.

The IX Hotine-Marussi Symposium was successful also due to the effort and organization skills of the local organizing committee chaired by Mattia Crespi (Rome), the vice-president of ICCT. The Hotine-Marussi symposium has been hosted by the Sapienza University of Rome already for the third time in a row. For more information on the IX Hotine-Marussi Symposium, please visit https://sites.google.com/uniroma1.it/hotinemarussi2018.

Participants of the IX Hotine-Marussi Symposium, 18-22 June 2018, in the Chiostro of the Basilica of S. Pietro in Vincoli, Rome, Italy.

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Sessions dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at the EGU General Assemblies 2016-2019 in Vienna. Other sessions on selected particular topics of theoretical geodesy related to joint study groups' activities were also organized at IAG's commissions meetings. Other meetings and/or session are listed within reports of individual joint study groups in the following text.

Summary on activities of study groups

The activities of the ICCT are related namely to research activities carried out by members of its joint study groups. Their final 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. The reports were (with few exceptions) standardized based on instruction concerning the length, structure and level of detail.

Most importantly, all chairmen delivered their reports in time which confirmed the main idea behind the current ICCT structure: involving young enthusiastic researchers as study group chairmen who actively cooperate internationally with research topics which matter to current geodesy. All study groups but one stayed active for the entire period 2015-2019. Moreover, new topics were identified (implications of new digital terrain models and namely of new instrumentation on geodetic theory) for future joint study groups within the ICCT structure 2019-2023.

Joint Study Group 0.10: High-rate GNSS

Chair: *Mattia Crespi (Italy)*
Affiliation: *Commissions 1, 3, 4 and GGOS*

Members

Juan Carlos Baez (Chile)
Elisa Benedetti (United Kingdom)
Geo Boffi (Switzerland)
Gabriele Colosimo (Switzerland)
Athanasios Dermanis (Greece)
Roberto Devoti (Italy)
Jeff Freymueller (USA)
Joao Francisco Galera Monico (Brazil)
Jianghui Geng (Germany)
Kosuke Heki (Japan)
Melvin Hoyer (Venezuela)
Augusto Mazzoni (Italy)
Nanthi Nadarajah (Australia)
Yusaku Ohta (Japan)
Ruey-Juin Rau (Taiwan)
Eugenio Realini (Italy)
Chris Rizos (Australia)
Giorgio Savastano (USA)
Nico Sneeuw (Germany)
Peiliang Xu (Japan)

1. Activities

1.1 Summary

Since the very beginning of the GNSS era, the goal has been pursued to widen as much as possible the range in space (from local to global) and time (from short to long term) of the observed phenomena, in order to cover the largest possible field of applications, both in science and in engineering.

Obviously, two complementary, but primary as well, goals were to get this information with the highest accuracy and in the shortest time: they are the key goals pursued by high-rate GNSS. Starting from the noble birth in seismology, and the very first experiences in structural monitoring, high-rate GNSS had already demonstrated its usefulness and power in providing precise positioning information in fast time-varying environments.

Nevertheless, the contemporary technological evolution both impacting GNSS and other IoT (Internet of Things) sensors able to provide kinematic parameters, thus a continuously increasing heap of data, asked for due attention, in order both to define the approaches for the optimal data processing and integration, and to assess the actually achievable accuracies in different applications.

Exactly these objectives were pursued during the activities of this JSG, covering a variety of applications: monitoring of ground shaking and displacement during earthquakes and tracking the fast variations of the ionosphere, also for contribution to tsunami early warning; real-time controlling landslides and the safety of structures; providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of (high) dynamic platforms such as airborne sensors, high-speed terrestrial vehicles, athlete and sport vehicles, and even pedestrians and human gesture.

1.2 Research

GNSS seismology, ionospheric seismology

- ground shaking, seismic waveforms and coseismic displacements: [5, 8, 16, 17, 18, 19, 20, 21, 22, 24, 26, 29, 30, 32, 44, 54, 56, 61, 72 and 73]
- seismic inversion, focal mechanism, magnitude estimation: [2, 25, 34, 36, 37, 52, 58, 62 and 63]
- tsunami early warning: [4, 35, 46, 53 and 60]
- Earthquake early warning: [23, 38, 39, 40, 41, 42 and 43]
- sensors, infrastructures and databases: [1, 3, 9 and 10].

Integration of GNSS with other sensors

- IoT sensors integration [6, 7, 27, 28, 33, 55, 57, 59, 64 and 71].

Navigation

- methodology [49, 50, 51 and 70]
- kinematic estimation of position and velocity [11, 12, 13, 14, 15, 31, 45, 47, 48, 65, 66, 67, 68 and 69].

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session *Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *High-precision GNSS: methods, open problems and Geoscience applications* at the European Geoscience Union General Assembly (Vienna, Austria) in 2017, 2018 and 2019.

1.4 Editorial activity

- Special Issue of Advances in Space Research on *High-rate GNSS: Theory, Methods, and Engineering/Geophysical Applications* 59(11): 2689-2830; Editor: Peiliang X; see http://www.sciencedirect.com/science/journal/02731177/59/11.
- Special Feature of Measurement Science and Technology on *High-Precision Multi-Constellation GNSS: Methods, Selected Applications and Challenges* (Eds: Paziewski J, Crespi M, see https://iopscience.iop.org/journal/0957-0233/page/High-Precision-Multi-Constellation-GNSS)
- Special Issue of Remote Sensing on *High-precision GNSS: Methods, Open Problems and Geoscience Applications* (Eds: Li X, Paziewski J, Crespi M, see https://www.mdpi.com/journal/remotesensing/special_issues/GNSS_rs)

1.5 Technology transfer and relevant applications in science and engineering

- VADASE algorithm implemented by Leica in the firmware of GR series GNSS receiver since 2 September 2015 (http://blog.leica-geosystems.com/leica-vadase-is-worlds-first-autonomous-gnss-monitoring-solution-onboard-a-stand-alone-receiver)
- VARION algorithm under incorporation into JPL's Global Differential GPS System as a novel contribution to future integrated operational tsunami early warning systems (https://www.nasa.gov/feature/jpl/scientists-look-to-skies-to-improve-tsunami-detection)

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 3
- SC 3.5: Tectonics and Earthquake Geodesy – Chair: *Haluk Ozener* (Turkey)

Commission 4
- SC 4.1: Emerging Positioning Technologies and GNSS Augmentation – Chair: *Vassilis Gikas* (Greece)
- SC 4.2: Geo-spatial Mapping and Geodetic Engineering – Chair: *Jinling Wang* (Australia)
- SC 4.3: Atmosphere Remote Sensing – Chair: *Michael Schmidt* (Germany)
- SC 4.4: Multi-constellation GNSS – Chair: *Pawel Wielgosz* (Poland)

GGOS
- Geohazards Monitoring Focus Area – Chair: *John LaBrecque* (USA)

Report: Global Navigation Satellite System to Enhance Tsunami Early Warning Systems (Editors: John LaBrecque, John Rundle, Gerald Bawden), see http://www.ggos.org/media/filer_public/64/36/6436cc04-00cf-407a-a365e79ce26378f2/gtews2017.pdf

3. Future prospects

3.1 Research

High-rate GNSS general problems
- Full GNSS multi-constellations integration for real-time solutions (functional and stochastic models).
- Accuracy assessment and stochastic modeling of very high rate (low-cost) multi-frequency multi-constellation GNSS receivers.
- Optimal models for real-time monitoring of GNSS permanent stations measurements noise and clocks.

GNSS seismology, structural monitoring
- Optimal statistical testing for reliable real-time detection of significant velocities/displacements.

Ionospheric seismology
- Optimal filtering for real-time ionospheric disturbance detection.
- GEO/MEO GNSS satellites integration, also with LEO occultation satellites.
- Further investigations on ionospheric total electron content variations prior to major earthquakes.

Sensors integration
- Functional and stochastic modeling of low-cost dual frequency GNSS receivers and newest IoT sensors for enhanced kinematic solutions.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on high-rate GNSS at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of the session *High-precision GNSS: methods, open problems and Geoscience applications* at next European Geoscience Union General Assemblies.

3.3 Editorial activity

- Special Issues on peer-review journals on high-rate GNSS.
- JSG publications: proposal for two (one science and the other engineering oriented) state-of-the-art review papers on high-rate GNSS co-authored by the JSG members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography in high-rate GNSS.
- Questionnaire within the Members of the JSG for starting an inventory of methodologies, technologies and applications in high-rate GNSS.

4. Publications

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Joint Study Group 0.11: Multiresolutional aspects of potential field theory

Chair: *Dimitrios Tsoulis (Greece)*
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1. Activities

1.1 Summary

Potential field theory defines the theoretical backbone of gravity field modelling and interpretation. The mathematical description and numerical computation of the gravity signal of finite distributions enters a series of applications from terrain effects and geoid computations over finite geographical regions to reduction and downward continuation of global satellite data. The study of the field induced by ideal geometrical bodies, such as the cylinder, the rectangular prism or the generally shaped polyhedron expresses the formal aspect of this bundle of activities and are linked to local or regional datasets. At the same time integral expressions and theorems of potential theory as well as the utilization of spectral tools permit the incorporation of global data, such as digital terrain or crustal databases and the realization of the corresponding global solutions.

The development, numerical implementation and validation of analytical, numerical, spectral, hybrid and multiresolutional tools for the evaluation of the different potential field quantities in the view of and related to the currently available global terrain and density information as well as satellite data, especially direct observations of second order derivatives of the potential, was the core motivation and key objective behind the activities of JSG 0.11. The considered research topics were pursued both in the context of forward and inverse potential field modelling.

The performed activities covered a wide range of applications including the gravity signal of ideal sources, in particular polyhedrons and spherical prisms, global topographic reduction and Bouguer maps, geoid, third-order gravitational tensor, spectral gravity forward modelling, mass transport, inverse gravimetric problem and approximation methods.

1.2 Research

Gravity signal of ideal sources

- Polyhedral gravity signal (D'Urso 2015, D'Urso and Trotta 2017).
- Spherical prismatic gravity signal (Roussel et al. 2015).

Global terrain and crustal data

- Spherical harmonic analysis of global crustal database CRUST 1.0, related gravity field signal and Moho signature implications (Tenzer et al. 2015).
- Global gravimetric terrain corrections at 3-arcsec spatial resolution (Hirt et al. 2019).
- Topographic potential and its derivatives compared with numerical integration (Hirt et al. 2016, Kuhn and Hirt 2016).

Potential satellite data

- Processing and interpolation of GOCE gradiometric data for the production of gradient grids (Bouman et al. 2016, Tsoulis and Moukoulis 2019).

Integral expressions

- Third-order gradients of the potential using integral formulas (Šprlák and Novák 2015).
- Integral transforms for potential and gradients in the frame of boundary value problems (Novák et al. 2017).

Spectral techniques

- Spectral gravity forward modelling, methodological aspects and convergence issues (Root et al. 2016, Bucha et al. 2019a, b).
- Gravity anomalies (Tenzer et al. 2019) and geoid computations (Tenzer et al. 2015, Tenzer et al. 2016, Foroughi et al. 2019).
- Third-order gradients of the potential using spherical harmonic synthesis (Hamáčková et al. 2016).

Mass transport and regional forward modelling

- Glacier and ice sheet mass variations using GRACE data (Harig and Simons 2015, 2016, Beveridge et al. 2018, Bevis et al. 2019).
- Glacial isostatic adjustment using the observed gravity field to enhance geophysical models (Root et al. 2015).

Inverse modelling

- Separation of gravity and magnetic data and inversion for the determination of 3D hidden crustal structures (Michel 2015a, Prutkin et al. 2017), planetary magnetic field determination by inversion and downward continuation taking into account regional characteristics of data (Plattner and Simons 2015), inversion of electric and magnetic data for an object with spherical symmetry (Leweke et al. 2018a), theory of inverse gravimetric and inverse magnetic problems as ill-posed problems with emphasis on the Earth (Michel and Orzlowski 2016, Leweke et al. 2018b).
- Inversion of satellite gravity data for source depth determination by means of Slepian functions (Galanti et al. 2019), guideline methodology for the utilization of Slepian functions for inverse problems with regional data (Michel and Simons 2017).
- Inversion of potential fields sampled in terms of vector observations at satellite altitude using gradient vector Slepian functions as local base functions (Plattner and Simons 2015, 2017), spherical signal estimation and spectral analysis (Simons and Plattner 2015).
- Matching pursuit-type greedy algorithms for linear inverse problem solving (Michel 2015b, Kontak and Michel 2018a) and for the non-linear inverse gravimetric problem, i.e., given a gravity field, determine the surface of the gravitating object (Kontak and Michel 2018b), regularization parameters and convergence in matching pursuit algorithms

(Gutting et al. 2017, Michel and Orzlowski 2017), decrease of iterations by introducing an orthogonal projection step, leading to better gravity modelling and downward continuation results (Michel and Telschow 2016).

Estimation and approximation methods

- Trial functions for approximation on the sphere (Freeden et al. 2018), techniques and quality measures for uniform distributions of points on the sphere (Ishtiaq and Michel 2017, Ishtiaq et al. 2019), spatially concentrated and spectrally band-limited vector trial functions (Slepian functions) on the sphere (Leweke et al. 2018c).
- Using a learning algorithm for the construction of an optimal basis for gravity field modelling out of spherical harmonics and radial basis functions (Michel and Schneider 2019), a sparse estimate of a probability density on the sphere applying a greedy algorithm (Gramsch et al. 2018).
- Spin-weighted or generalized spherical harmonics and their geodetic applications (Michel and Seibert 2018).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of Session G1.3 *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions (D. Tsoulis, M. Sideris, P. Novák, V. Michel)* at the European Geoscience Union General Assembly (Vienna, Austria) in 2017.
- Organization of Session *global gravity field modelling and height systems (D. Tsoulis, S. Claessens)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Organization of Inter-Association Symposium *JG02 Theory and methods of potential fields (IAG, IAGA; D. Tsoulis, S. Claessens, M. Fedi)* at the 27th IUGG General Assembly (Montreal, Canada) in 2019.

2. Future prospects

2.1 Research

All considered research topics define open scientific areas with numerous open questions emerging from the efficient and accurate numerical implementation of the individual theoretical developments and the utilization of current and upcoming terrestrial and satellite global datasets. An indicative list of themes for further consideration would include:

Forward modelling

- Numerical evaluation and validation of third order potential derivatives with an attempt to evaluate them alternatively (analytically or numerically) over bounded regions.
- Thorough review, numerical implementation and comparison of different available forward modelling algorithms.
- Spectral and multiresolutional computations of the potential function and its derivatives for known distributions and comparisons with available numerical and analytical solutions.

Inverse modelling

- Inclusion in existing and evolving inverse problem solving algorithms of high and very high degree gravity field models to represent the observed gravity signal.
- Validation of inverse algorithms by incorporating accurate geometric modelling of the hidden sources and exact computation of their gravity signal in the frame of closed loop simulations with the available forward modelling methods.

2.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on theory and methods of potential fields at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of a session on theory and methods of potential fields at the next European Geoscience Union General Assembly.

2.3 Editorial activity

- Special Issues on peer-review journals on potential fields.
- JSG publications: proposal for several state-of-the-art review papers on potential fields co-authored by the JSG members.

3. Publications

1. Beveridge AK, Harig C, Simons FJ (2018) The changing mass of glaciers on the Tibetan Plateau, 2002-2016, using time-variable gravity from the GRACE satellite mission. *Journal of Geodetic Science*, 15 pp, http://dx.doi.org/10.1515/jogs-2018-0010.
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Joint Study Group 0.12: Advanced computational methods for recovery of high-resolution gravity field models

Chair: *Róbert Čunderlík (Slovak Republic)*
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1. Activities

1.1 Research

Activities of the JSG-0.12 during the whole period 2015−2019 have been mainly focused on further development of the advanced computational methods for recovery of high-resolution gravity field models. The numerical approaches based on (i) the discretization methods like the boundary element method (BEM), finite element method (FEM) and finite volume method (FVM), or on (ii) meshless methods like the method of fundamental solution (MFS) and singular boundary method (SBM), or on (iii) others weak solution concepts, have been used:

- to solve numerically the geodetic boundary-value problems (GBVPs), see e.g., (*Čunderlík 2016b*), (*Čunderlík et al. 2016a,b, 2018*), (*Holota 2018*), (*Holota and Nesvadba 2019a,b*), (*Macák et al. 2016*) and (*Medľa et al. 2018*),
- to process the GOCE satellite measurements, see (*Čunderlík 2016*),
- to develop nonlinear diffusion filtering of various geodetic data, see, e.g., (*Kollár et al. 2016*) and (*Čunderlík et al. 2016*).

To solve such problems in spatial domains while obtaining high-resolution numerical solutions, such approaches require parallel implementations and large-scale parallel computations on clusters with distributed memory using the MPI (Message Passing Interface). In the following the main activities are briefly described.

In case of FVM approach, an iterative approach to solve the nonlinear satellite-fixed GBVP has been developed. In this approach an unknown direction of the actual gravity vector together with the disturbing potential is updated in every iteration (*Macák et al. 2016*). An original method to treat the oblique derivative problem using an up-wind based FVM has been proposed. Namely, the second order up-wind numerical scheme has been derived for non-uniform grids above the real Earth's topography (*Medľa and Mikula 2016*). Such an approach has involved a construction of the non-uniform hexahedron 3D grids above the Earth's surface that is based on an evolution of a surface, which approximates the Earth's topography, by its mean curvature. To obtain optimal shapes of non-uniform 3D grid, the proposed evolution has been accompanied by a tangential redistribution of grid nodes. Afterwards, the Laplace equation has been discretized using the FVM developed for such a non-uniform grid. The oblique derivative boundary condition has been treated as a stationary advection equation resulting to a new up-wind type discretization suitable for non-uniform 3D grids (*Medľa et al. 2018*).

To reduce a numerical complexity of the boundary integral approaches, e.g., the direct BEM with collocation or MFS and SBM as meshless methods, we have focused on elimination of the far zones interactions using the Hierarchical matrices (H-matrices). To compress the "far field parts" of the system matrices, the Adaptive Cross Approximation (ACA) algorithm have been implemented. It is based on the idea that numerically rank-deficient sub-blocks, which correspond to interactions of well-separated groups, can be efficiently compressed through an approach very similar to the column-pivoted LU decomposition. The first experiments show that the ACA algorithm effectively reduces memory requirements and computational costs while giving practically the same results. It means that implementations of the H-matrices as a compression technique allow to increase a level of the discretization considerably w.r.t. available memory of the accessible HPC facilities. This is promising for further development of the boundary integral approaches for high-resolution gravity field modelling.

In case of nonlinear diffusion filtering, the existing method based on the regularized Perona-Malik model has been extended in order to avoid undesirable smoothing of local extremes. This has been treated by a modification of the diffusivity coefficient, which now depends on a combination of the edge detector and a mean curvature of the filtered function. A semi-implicit numerical scheme has been derived for this approach (*Kollár et al. 2016*), which is based on a numerical solution of partial differential equations on closed surfaces using the surface FVM. Sensitivity parameters of the proposed "edge and extremes detector" have been experimentally tuned for different types of filtered data (*Čunderlík et al. 2016*). The similar semi-implicit numerical scheme has been also derived for data given on 2D rectangular grids.

The achieved results of all activities have been published in several papers (see below) and they were presented at the major geodetic conferences, e.g. at the *EGU General Assemblies* in Wien (every year), during the Joint Commission 2 and IGFS Meetings – *GGHS-2016* (Thessaloniki, Greece, 2016) and *GGHS-2018* (Copenhagen, Danmark, 2018), at the *IAG-IASPEI Scientific Assembly* (Kobe, Japan, 2017) or at the *IX Hotine-Marussi Symposium* (Rome, Italy, 2018).

1.2 Sessions organization at international congresses/symposia/workshops:

- Organization of the session *Advanced numerical methods in geodesy (R. Čunderlík)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *Recent Developments in Geodetic Theory (P. Holota, N. Sneeuw, B. Heck, R. Čunderlík, O. Nesvadba)* at the European Geoscience Union General Assemblies (Wien, Austria) in 2016, 2017, 2018 and 2019.

2. Publications:

1. Čunderlík R (2016) Precise modelling of the static gravity field from GOCE second radial derivatives of the disturbing potential using the method of fundamental solutions. *IAG Symposia Series* 144: 71-81
2. Čunderlík R, Kollár M, Mikula K (2016) Filters for geodesy data based on linear and nonlinear diffusion. *International Journal on Geomathematics* 7(2): 239-274
3. Čunderlík R, Macák M, Medľa M, Mikula K, Minarechová Z (2018a) Numerical methods for solving the oblique derivative boundary value problems in geodesy. In: Freeden W, Rummel R (eds.) *Handbuch der Geodäsie*. Springer Reference Naturwissenschaften. Springer Spektrum, Berlin, Heidelberg, pp.1-48; doi: 10.1007/978-3-662-46900-2_105-1.
4. Čunderlík R, Mikula K, Minarechová Z, Macák M (2018b) Computational methods for high-resolution gravity field modeling. In: Grafarend E (eds) *Encyclopedia of Geodesy*. Encyclopedia of Earth Sciences Series. Springer, Cham.
5. Holota P (2018) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. *IAG Symposia Series* 147: 47-52
6. 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

7. Holota P, Nesvadba O (2019b) Boundary complexity and kernel functions in classical and variational concepts of solving geodetic boundary value problems. *IAG Symposia Series* 149: 31-41
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10. Medľa M, Mikula K (2016) New second order up-wind scheme for oblique derivative boundary value problem. In: ALGORITMY-2016 – 20th Conference on Scientific Computing, Proceedings of contributed papers, ISBN: 978-80-227-4544-4, pp. 254-263.
11. Medľa M, Mikula K, Čunderlík R, Macák M (2018) Numerical solution to the oblique derivative boundary value problem on non-uniform grids above the Earth topography. *Journal of Geodesy* 92: 1-19
12. Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. *IAG Symposia Series* 144: 93-100
13. Nesvadba O, Holota P (2016) An OpenCL implementation of ellipsoidal harmonics. *IAG Symposia Seriers* 142: 195-203
14. Roese-Koerner L, Schuh WD (2016) Effects of different objective functions in inequality constrained and rank-deficient least-squares problems. *IAG Symposia Series* 142: 325-331

Joint Study Group 0.13: Integral equations of potential theory for continuation and transformation of classical and new gravitational observables

Chair: *Michal Šprlák (Australia)*
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Robert Tenzer (China)
Guyla Tóth (Hungary)

1. Activities

1.1 Summary

The description of the Earth's gravitational field and its temporal variations belongs to the fundamental pillars of modern geodesy. Various observational techniques for collecting gravitational data have been invented based on terrestrial, marine, airborne and more recently, satellite sensors. Different parametrization methods of the gravitational field were established in geodesy, including those based on solving boundary/initial value problems of potential theory, through Fredholm's integral equations.

Traditionally, Stokes's, Vening-Meinesz's and Hotine's integrals have been of main interest as they accommodated geodetic applications in the past. In recent history, new geodetic integral transformations were formulated as new gravitational observables became gradually available with the advent of precise GNSS (Global Navigation Satellite Systems) positioning, satellite altimetry and aerial gravimetry/gradiometry. The family of integral transformations has enormously been extended with satellite-to-satellite tracking and satellite gradiometric data available from recent gravity-dedicated satellite missions.

This study group aims at systematic treatment of geodetic integral transformations. Many solutions are based on spherical approximation that cannot be justified for globally distributed satellite data and with respect to requirements of various data users requiring gravitational data to be distributed at the reference ellipsoid or at constant geodetic altitude. On the other hand, the integral equations in spherical approximation possess symmetric properties and also motivate for adopting a generalized notation. New numerically efficient, stable and accurate methods for upward/downward continuation, comparison, validation, transformation, combination and/or for interpretation of gravitational data are also of high interest with increasing availability of large amounts of new data.

1.2 Research

Spherical integral transformations

- Geoid determination (Afrasteh et al. 2018, Foroughi et al. 2017, 2018, 2019, Goli et al. 2018b, Janák et al. 2017, Sheng et al. 2018)
- New integral transformations and their mathematical properties
    - Satellite-to-satellite tracking observables (Eshagh and Šprlák 2016, Šprlák and Eshagh 2016)
    - 2^{nd} order gravitational tensor components (Romeshkani and Eshagh 2015, Šprlák and Novák 2017, Šprlák et al. 2015)
    - 3^{rd} order gravitational tensor components (Šprlák and Novák 2015, 2016, 2017, 2018).
- Spectral combination of 3^{rd} order gravitational tensor components (Pitoňák et al. 2018).
- Geophysical applications
    - Forward modelling (Tenzer et al. 2017b, Šprlák et al. 2018, Yang et al. 2018)
    - Estimation of volumetric density (Ye et al. 2018)
    - Determination of Moho, elastic thickness and sub-crustal stress (Eshagh 2015, 2016a, 2016b, 2017, Eshagh and Hussain 2015, 2016, Eshagh and Pitoňák 2019, Eshagh and Romeshkani 2015, Eshagh and Tenzer 2015, Eshagh et al. 2016a, 2016b, 2017, 2018a, 2018b, 2019, Šprlák and Eshagh 2016, Tenzer and Eshagh 2015, Tenzer et al. 2015, 2017a).
- Systematic classification and overview of integral transformations (Novák et al. 2017).

Boundary value problems

- Approximations of the linear boundary value problem (Holota 2016).
- Solution of the spherical curvature boundary value problem (Šprlák and Novák 2016, 2018, Šprlák et al. 2016).
- Solution of the spheroidal Neumann boundary value problem (Holota 2015, Holota and Nesvadba 2018, 2019, Nesvadba and Holota 2016, Šprlák and Tangdamrongsub 2018).
- Solution of the spheroidal horizontal boundary value problem (Šprlák and Tangdamrongsub 2018).

Numerical solutions and formulations of inverse problems:

- Inversion of gravity anomalies for geoid determination (Goli et al. 2018a).
- Inversion of satellite-to-satellite tracking observables, 2^{nd} or 3^{rd} order gravitational tensor components (Eshagh 2017, Eshagh and Pitoňák 2019, Eshagh and Romeshkani 2015, Eshagh and Šprlák 2016, Eshagh et al. 2018a, 2019, Pitoňák et al. 2016, 2017a, 2017b, 2019, Šprlák and Eshagh 2016).
- Inversion of satellite-to-satellite tracking observables and 2^{nd} tensor components in spheroidal approximation (Novák and Šprlák 2018).

1.3 Sessions organization at international congresses/symposia/workshops

- Scientific committee of the IX Hotine-Marussi Symposium, Rome, Italy, 18-22 June 2018 (P. Novák, M. Šprlák, R. Tenzer).
- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2017 (EGU2017), Vienna, Austria, 23-28 April 2017 (P. Holota, O. Nesvadba).
- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2018 (EGU2018), Vienna, Austria, 8-13 April 2018 (P. Holota, O. Nesvadba).

- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2019 (EGU2019), Vienna, Austria, 7-12 April 2019 (P. Holota, O. Nesvadba).

1.4 Editorial activity

- Proceedings of the IX Hotine-Marussi Symposium, Italy, 18-22 June 2018, IAG Symposia Series, Springer (Editor: P. Novák).
- On Significant Applications of Geophysical Methods, Proceedings of the 1st Springer Conference of the Arabian Journal of Geosciences (CAJG-1), Tunisia 2018, (Editor: M. Eshagh).

2. Cooperation/Interactions with IAG Commissions and GGOS

- Commission 2: Working Group 2.2.2 "1 cm geoid experiment", Chair: Y.M. Wang (USA)
- GGOS: Focus Area "Unified Height System", Chair: L. Sánchez (Germany)

3. Future prospects

3.1 Research

Integral transformations:
- Propagation of random and systematic errors through spherical integral transformations
- Efficient and accurate numerical evaluation and effects of the distant zones for spherical integral transformations.
- Extension and overview of the spheroidal integral transformations for oblate planetary bodies.

Boundary value problems:
- Formulation and solution of the spheroidal gradiometric and spheroidal curvature boundary value problems.

Solution of inverse problems:
- Optimal combination of various observations (terrestrial, airborne, satellite) for an accurate gravitational field determination.

3.2 Technology transfer and relevant applications in science and engineering

- Reference bibliography on geodetic integral transformations.

4. Publications

1. Afrasteh Y, Safari A, Sheng MB, Kingdon R, Foroughi I (2018) The effect of noise on geoid height in Stokes-Helmert method. *IAG Symposia Series* 148: 25-29, Springer, Cham; doi: 10.1007/1345_2017_25.
2. Eshagh M (2015) On the relation between Moho and sub-crustal stress induced by mantle convection. *Journal of Geophysics and Engineering* 12: 1-11
3. Eshagh M (2016a) Integral approaches to determine sub-crustal stress from terrestrial gravimetric data. *Pure and Applied Geophysics* 173: 805-825
4. Eshagh M (2016b) On Vening-Meinesz-Moritz and flexural theories of isostasy and their comparison over Tibet Plateau. *Journal of Geodetic Science* 6: 139-151
5. Eshagh M (2017) Local recovery of lithospheric stress tensor from GOCE gravitational tensor. *Geophysical Journal International* 209: 317-333
6. Eshagh M, Hussain M (2015) Relationship amongst gravity gradients, deflection of vertical, Moho deflection and the stresses derived by mantle convections-a case study over Indo-Pak and surroundings. *Geodynamics, Research International Bulletin* 3(4): I-XIII
7. Eshagh M, Romeshkani M (2015) Determination of sub-lithospheric stress due to mantle convection using GOCE gradiometric data over Iran. *Journal of Applied Geophysics* 122: 11-17

8. Eshagh M, Tenzer R (2015) Sub-crustal stress determined using gravity and crust structure models. *Computational Geoscience* 19: 115-125
9. Eshagh M, Hussain M (2016) An approach to Moho discontinuity recovery from on-orbit GOCE data with application over Indo-Pak region. *Tectonophysics* 690B: 253-262
10. Eshagh M, Hussain M, Tenzer R, Romeshkani M (2016a) Moho density contrast in central Eurasia from GOCE gravity gradients. *Remote Sensing* 8: 1-18
11. Eshagh M, Hussain M, Tiampo KF (2016b) Towards sub-lithospheric stress determination from seismic Moho, topographic heights and GOCE data. *Journal of Asian Earth Sciences* 169: 1-12
12. Eshagh M, Šprlák M (2016) On the integral inversion of satellite-to-satellite velocity differences for local gravity field recovery: A theoretical study. *Celestial Mechanics and Dynamical Astronomy* 124: 127-144
13. Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24
14. Eshagh M, Ashagrie A, Bedada TB (2018a) Regional recovery of gravity anomaly from the inversion of diagonal components of GOCE gravitational tensor: a case study in Ethiopia. *Artificial Satellites* 53: 55-74
15. Eshagh M, Steinberger B, Tenzer R, Tassara A (2018b) Comparison of gravimetric and mantle flow solutions for lithospheric stress modelling and their combination. *Geophysical Journal International* 213: 1013-1028
16. Eshagh M, Pitoňák M (2019) Elastic thickness determination from on-orbit GOCE data and CRUST1.0. *Pure and Applied Geophysics* 176: 685-696
17. Eshagh M, Pitoňák M, Tenzer R (2019) Lithospheric elastic thickness estimates in central Eurasia. *Terrestrial, Atmospheric and Oceanic Sciences Journal* 30: 73-84
18. Foroughi I, Afrasteh Y, Ramouz S, Safari A (2017) Local evaluation of Earth gravitational models, case study: Iran. *Geodesy and Cartography* 43: 1-13
19. Foroughi I, Vaníček P, Novák P, Kingdon RW, Sheng M, Santos MC (2018) Optimal combination of satellite and terrestrial gravity data for regional geoid determination using Stokes-Helmert's method, the Auvergne test case. *IAG Symposia Series* 148: 37-43, Springer, Cham; doi: 10.1007/1345_2017_22.
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21. Goli M, Foroughi I, Novák P (2018a) On estimation of stopping criteria for iterative solutions of gravity downward continuation. *Canadian Journal of Earth Sciences* 55: 397-405
22. Goli M, Foroughi I, Novák P (2018b) The effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. *Studia Geophysica et geodetica* 63: 35-54
23. Holota P (2015) Summation of series and an approximation of Legendre's functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy-Mathematic-Physics-Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In: Leibniz Online, Jahrgang 2015, Nr. 19, 12 pp. Zeitschrift der Leibniz-Sozietät e.V., ISSN 1863-3285; http://leibnizsozietaet.de/wp-content/uploads/2015/06/holota.pdf).
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26. Holota P, Nesvadba O (2019) 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: 1-34
27. Janák J, Vaníček P, Foroughi I, Kingdon R, Sheng M, Santos M (2017) Computation of precise geoid model of Auvergne using current UNB Stokes-Helmert's approach. *Contribution to Geodesy and Geophysics* 47: 201-229
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29. Novák P, Šprlák M, Tenzer R, Pitoňák M (2017). Integral formulas for transformation of potential field parameters in geosciences. *Earth-Science Reviews* 164: 208-231
30. Novák P, Šprlák M (2018) Spheroidal integral equations for geodetic inversion of geopotential gradients. *Surveys in Geophysics* 39: 245-270
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32. Pitoňák M, Šprlák M, Novák P, Tenzer R (2017a) Regional gravity field modelling from GOCE observables. *Advances in Space Research* 59: 114-127
33. Pitoňák M, Šprlák M, Tenzer R (2017b) Possibilities of inversion of satellite third-order gravitational tensor onto gravity anomalies: a case study for central Europe. *Geophysical Journal International* 209: 799-812
34. Pitoňák M, Eshagh M, Šprlák M, Tenzer R, Novák P (2018) Spectral combination of spherical gravitational curvature boundary-value problems. *Geophysical Journal International* 214: 773-791

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36. Romeshkani M, Eshagh M (2015) Deterministically-modified integral estimators of tensor of gravitation. *Boletim de Ciências Geodésicas* 21: 189-212
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39. Šprlák M, Novák P (2015) Integral formulas for computing a third-order gravitational tensor from volumetric mass density, disturbing gravitational potential, gravity anomaly and gravity disturbance. *Journal of Geodesy* 89: 141-157
40. Šprlák M, Eshagh M (2016) Local recovery of sub-crustal stress due to mantle convection from satellite-to-satellite tracking data. *Acta Geophysica* 64: 904-929
41. Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 90: 727-739
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43. Šprlák M, Novák P (2017) Spherical integral transforms of second-order gravitational tensor components onto third-order gravitational tensor components. *Journal of Geodesy* 91: 167-194
44. Šprlák M, Novák P (2018) Correction to: spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 92: 573
45. Šprlák M, Han S-C, Featherstone W (2018) Forward modelling of global gravity fields with 3D density structures and an application to the high-resolution (~2 km) gravity fields of the Moon. *Journal of Geodesy* 92: 847-862
46. Šprlák M, Tangdamrongsub N (2018) Vertical and horizontal spheroidal boundary-value problems. *Journal of Geodesy* 92: 811-826
47. Tenzer R, Eshagh M (2015) Subduction generated sub-crustal stress in Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences* 26: 261-268
48. Tenzer R, Eshagh M, Jin S (2015) Martian sub-crustal stress from gravity and topographic models. *Earth and Planetary Science Letters* 425: 84-92
49. Tenzer R, Eshagh M, Shen W (2017a) The subcrustal stress estimation in central Eurasia from gravity, terrain and crustal structure models. *Geoscience Journal* 21: 47-54
50. Tenzer R, Foroughi I, Pitoňák M, Šprlák M (2017b) Effect of the Earth's Inner Structure on the Gravity in Definitions of Height Systems. *Geophysical Journal International* 209: 297-316
51. Yang M, Hirt C, Tenzer R, Pail R (2018) Experiences with the use of mass density maps in residual gravity forward modelling. *Studia Geophysica et Geodaetica* 62: 596-623
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4.1 Selected oral and poster presentations

Foroughi I, Janák J, Kingdon RW, Sheng M, Santos M, Vaníček P (2015) Illustration of how satellite global field should be treated in regional precise geoid modelling. 12th EGU General Assembly, Vienna, April 2015.

Foroughi I, Vaníček P, Kingdon RW, Novák P, Sheng M, Santos M (2016) Poisson downward continuation of scattered Helmert's gravity anomalies to mean values on a raster on the geoid using Least Square. 13th EGU General Assembly, Vienna, April 2016.

Foroughi I, Vaníček P, Kingdon RW, Sheng M, Santos M (2015) Assessment of discontinuity of Helmert's gravity anomalies on geoid. Canadian Geophysical Union Meeting, Montreal, Canada.

Foroughi I, Vaníček P, Novák P, Kingdon RW, Goli M, Sheng M, Santos M (2016) Harmonic downward continuation of scattered point gravity anomalies to mean anomalies on a mesh on the geoid. Canadian Geophysical Union meeting, Fredericton, Canada.

Ghobadi-Far K, Han S-C, Šprlák M (2018) A pocket guide to physical geodesy: constructing a unified scheme for representation of geopotential functionals. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Hamáčková E, Šprlák M, Pitoňák M, Novák P (2015). Comparison of third order potential derivatives based on recent satellite-based GGMs and on global isostatic topographic models. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P (2015) Summation of series and an approximation of Legendre's functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy-Mathematic-Physics-Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In:

Kolloquium der Leibniz-Sozietät am 13. 02. 2015 zum Thema "Geodäsie-Mathematik-Physik-Geophysik": Kurzbericht [on-line]. Leibniz-Sozietät der Wissenschaften zu Berlin, e.V.
Holota P (2017) Geodesy and Mathematics: Recent Developments in the Deep Rooted Relationship. Presented at the Wissenschaftliches Kolloquium „Die Förderung der wissenschaftlichen Geodäsie seit Friedrich Robert Helmert (1843-1917)" organized by the Leibniz-Sozietät der Wissenschaften zu Berlin e.V. in cooperation with the Helmholtz-Zentrum Potsdam – GFZ, DVW Berlin-Brandenburg e.V. and the TU Berlin, Institut für Geodäsie und Geoinformationstechnik, Potsdam, Germany, 7 April 2017.
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, Potsdam, Germany, 15 February 2019.
Holota P, Nesvadba O (2015) Differential geometry of equipotential surfaces and its relation to parameters of Earth's gravity field models. 26th IUGG General Assembly, Prague, June-July 2015.
Holota P, Nesvadba O (2015) Domain transformation and the iteration solution of boundary value problems in gravity field studies. 26th IUGG General Assembly, Prague, June-July 2015.
Holota P, Nesvadba O (2015) Elementary potentials and Galerkin's matrix for an ellipsoidal domain in the recovery of the gravity field. 26th IUGG General Assembly, Prague, June-July 2015.
Holota P, Nesvadba O (2015) Fundamental solution of Laplace's equation in oblate spheroidal coordinates and Galerkin's matrix for Neumann's problem in Earth's gravity field studies. 12th EGU General Assembly, Vienna, April 2015.
Holota P, Nesvadba O (2016) Combining terrestrial data and satellite-only models in Earth's gravity field studies: optimization and integral kernels. Living Planet Symposium of the European Space Agency, Prague, May 2016.
Holota P, Nesvadba O (2016) Construction of Galerkin's matrix for elementary potentials and an ellipsoidal solution domain based on series developments and general relations between Legendre's functions of the first and the second kind: application in Earth's gravity field studies. 13th EGU General Assembly, Vienna, April 2016.
Holota P, Nesvadba O (2016) Modification of ellipsoidal coordinates and successive approximations in the solution of the linear gravimetric boundary value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Holota P, Nesvadba O (2016) Small modifications of curvilinear coordinates and successive approximations applied in geopotential determination. AGU Fall Meeting, San Francisco, December 2016.
Holota P, Nesvadba O (2017) Boundary complexity in classical and variational concepts of solving geodetic boundary value problems. IAG-AESPEI Joint Scientific Meeting, Kobe, July-August 2017.
Holota P, Nesvadba O (2017) Laplacian versus topography in the solution of the linear gravimetric boundary value problem by means of successive approximations. 14th EGU General Assembly, Vienna, April 2017.
Holota P, Nesvadba O (2017) Weak solution concept and Galerkin's matrix for the exterior of an oblate ellipsoid of revolution in the representation of the Earth's gravity potential by buried masses. 14th EGU General Assembly, Vienna, April 2017.
Holota P, Nesvadba O (2018) Green's function method extended by successive approximations and applied to Earth's gravity field recovery. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.
Holota P, Nesvadba O (2018) Neumann's function and its derivatives constructed for the exterior of an ellipsoid and adapted to an iteration solution of the linear gravimetric boundary value problem. 15th EGU General Assembly, Vienna, April 2018.
Holota P, Nesvadba O (2018) Transformation of topography into the structure of Laplace's operator and an iteration solution of the linear gravimetric boundary value problem. 15th EGU General Assembly, Vienna, April 2018.
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. 16th EGU General Assembly, Vienna, April 2019.
Holota P, Nesvadba O (2019) Using the Green's function method for solution domains with a complicated boundary in Earth's gravity field studies. 16th EGU General Assembly, Vienna, April 2019.
Nesvadba O, Holota P (2016) An improved methodology for precise geoid/quasigeoid modelling. 13th EGU General Assembly, Vienna, April 2016.
Nesvadba O, Holota P (2016) On the downward continuation stability in dependence of the topography roughness. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.
Novák P (2017) Properties of gravity-field curvatures and their applications in geophysics. IAG-AESPEI Joint Scientific Meeting, Kobe, July-August 2017.
Novák P, Pitoňák M, Šprlák M (2015) Regional recovery of the disturbing gravitational potential from satellite observations of first-, second- and third-order radial derivatives of the disturbing gravitational potential. AGU Fall Meeting, San Francisco, December 2015.
Novák P, Pitoňák M, Šprlák M, Tenzer R (2018) Gravitoscopy of Earth's mass density distribution based on higher-order gradients of the gravitational potential. 15th EGU General Assembly, Vienna, April 2018.
Novák P, Pitoňák M, Tenzer R, Šprlák M (2018) Local gravitational field modelling through spectral combination of satellite higher-order radial derivatives of the disturbing gravitational potential and a global gravitational model. AGU Fall Meeting, Washington, D.C., December 2018.

Novák P, Šprlák M, Tenzer R, Pitoňák M (2016) Integral formulas for analysis of current and future satellite gravitational observations. AGU Fall Meeting, San Francisco, December 2016.

Novák P, Šprlák M, Pitoňák M, Tenzer R (2018) Classical solutions to boundary-value problems of the potential theory for current and future gravity field observables. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Accuracy of classical definition of the geoid-to-quasigeoid separation. 13th EGU General Assembly, Vienna, April 2016.

Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Effect of crustal and mantle density structure on the quasigeoid-to-geoid separation. 13th EGU General Assembly, Vienna, April 2016.

Pitoňák M, Eshagh M, Novák P, Šprlák M, Tenzer R (2018) Recovery of the gravitational potential at the Earth's surface by spectral combination of first-, second- and third-order radial derivatives of the gravitational potential measured by satellite sensors. 15th EGU General Assembly, Vienna, April 2018.

Pitoňák M, Eshagh M, Novák P, Šprlák M, Tenzer R (2018) Spectral downward continuation of the first-, second- and third-order radial derivatives of the gravitational potential measured by satellite sensors. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Pitoňák M, Eshagh M, Šprlák M, Tenzer R (2017) Spectral downward continuation of gravitational curvatures and its implications for future gravity field missions. 12th Slovak Geophysical Conference, Comenius University, Bratislava, Slovakia, September 2017.

Pitoňák M, Eshagh M, Šprlák M, Tenzer R, Novák P (2017). Spectral combination of spherical gravitational curvature boundary-value problems. 14th EGU General Assembly, Vienna, April 2017.

Pitoňák M, Novák P, Šprlák M, Eshagh M (2018) Local spectral downward continuation of the first-, second- and third-order radial derivatives of the gravitational potential onto gravity disturbances on the Earth surface. International Association of Geodesy Symposium: Gravity, Geoid and Height Systems, Copenhagen, Denmark, September 2018.

Pitoňák M, Novák P, Šprlák M, Tenzer R (2018) Combination of spherical gravitational curvatures boundary value problem using the condition adjustment model. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Pitoňák M, Šprlák M, Hamáčková E, Novák P (2015) The effect of topographic and atmospheric masses on inversion of a satellite third-order gravitational tensor onto gravity anomalies. 26th IUGG General Assembly, Prague, June-July 2015.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Possibilities of the regional gravity field recovery from first-, second- and third-order radial derivatives of the disturbing gravitational potential measured on moving platforms. 13th EGU General Assembly, Vienna, April 2016.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Regional determination of gravity disturbances by inverting satellite gravitational gradients. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Pitoňák M, Šprlák M, Novák P (2018) Regional recovery of the disturbing gravitational potential from GOCE observables. 10 Years of the Czech Republic in ESA, Prague, November 2018.

Pitoňák M, Šprlák M, Sebera J, Novák P, Hamáčková E (2016) Comparative study of the far zones effect on the spherical downward continuation. Living Planet Symposium of the European Space Agency, Prague, May 2016.

Pitoňák M, Šprlák M, Tenzer R (2018) Inversion of satellite third-order gravitational tensor. Geodetic and Remote Sensing Methods for Earth's and Planetary Studies, Hong Kong, January 2018.

Šprlák M, Hájková J, Pitoňák M, Novák P, Tenzer R (2016) An analysis of geoid determination based on terrestrial observations of the radial gravity potential derivatives. 13th EGU General Assembly, Vienna, April 2016.

Šprlák M, Han S-C, Featherstone W (2018) Is the spheroidal approximation of the Moon important for high-resolution global gravitational field modelling? COSPAR 42nd Assembly, Pasadena, USA, July 2018.

Šprlák M, Han S-C, Featherstone W (2018) Regional lunar gravitational field modelling from GRAIL line-of-sight gravitation observables. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Šprlák M, Han S-C, Featherstone W (2018) Regional Recovery of the lunar gravitational field by inverting GRAIL line-of-sight gravitation observables. COSPAR 42nd Assembly, Pasadena, USA, July 2018.

Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Solution of the boundary value problems with boundary conditions in the form of gravitational curvatures. AGU Fall Meeting, San Francisco, December 2015.

Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Spherical harmonic analysis of third-order gravitational tensor components and its implications for future gravity-dedicated satellite mission designs. 26th IUGG General Assembly, Prague, June-July 2015.

Šprlák M, Petrš J, Pitoňák M, Novák P, Hamáčková E (2016) Possibilities of validation for GRACE satellite-to-satellite tracking data by integral transformations. Living Planet Symposium of the European Space Agency, Prague, May 2016.

Joint Study Group 0.14: Fusion of multi-technique satellite geodetic data

Chair: *Krzysztof Sośnica (Poland)*
Affiliation: *Commissions 1, 3 and 4, and GGOS*

Members

Toshimichi Otsubo (Japan)
Daniela Thaller (Germany)
Mathis Bloßfeld (Germany)
Andrea Grahsl (Switzerland)
Ulrich Meyer (Switzerland)
Grzegorz Bury (Poland)
Radosław Zajdel (Poland)
Claudia Flohrer (Germany)
Agnieszka Wnek (Poland)
Kamil Kazmierski (Poland)
Sara Bruni (Italy)
Mateusz Drożdżewski (Poland)
Karina Wilgan (Switzerland)

1. Activities

1.1 Summary

The activities of the JSG0.14 study group were concentrated around the identification of systematic effects between different techniques of satellite and space geodesy and the combination of various techniques to derive geodetic parameters. Proper identification and handling of systematics should in result improve the consistency between different observational techniques and should help us to mitigate artifacts in the geodetic time series. Therefore, different observational techniques of space geodesy, which are capable of deriving the same parameters, were cross-validated and combined. Geodetic parameters that can be determined when employing different techniques of space geodesy are thus here the fundamental subject of interest.

All of the new GNSS systems have been equipped with laser retroreflector arrays (LRA) dedicated to SLR tracking of new GNSS systems. The International Laser Ranging Service (ILRS) initiated a series of special tracking campaigns dedicated to tracking new Galileo spacecraft as well as tracking of the whole GNSS constellation. SLR observations to GNSS satellites allow for the validation of microwave-derived GNSS orbits, for the determination of GNSS orbital parameters, co-location in space on-board GNSS spacecraft and for the determination of global parameters, such as pole coordinates, length-of-day, geocenter motion, etc. The fusion of GNSS and SLR observations requires a profound investigation of biases and systematic effects affecting both techniques. Neglecting of systematic effects may lead to a degradation of solutions and the absorption of various systematic effects by global geodetic parameters.

In the framework of this Study Group, various analyses were performed including processing SLR observations to new GNSS systems, SLR observations to LEO satellites, as well as an attempt to unification and harmonization of the troposphere delay models for SLR and GNSS. For the purpose of the investigation of SLR-GNSS biases, a new on-line service has been launched (Zajdel et al. 2017): multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS, www.govus.pl) as an element of the new ILRS Associated Analysis Center.

1.2 Research

Harmonization of the atmospheric delay models between SLR and GNSS

- Modeling of horizontal gradients in SLR solutions
  - Analysis of the sensitivity of SLR observations to the atmospheric asymmetry and horizontal gradients of troposphere delay
  - Estimation of horizontal gradients using SLR observations to LAGEOS-1/2 (Drożdżewski and Sośnica 2018)
  - Using GNSS-derived gradients to account for the atmosphere asymmetry in SLR solutions
  - Deriving horizontal gradients on the basis of numerical weather models (a joint activity within the framework of Joint Working Group 1.3: Troposphere ties)
- Improving mapping functions of troposphere delays
  - Using Potsdam Mapping Function (PMF) for SLR (in the framework of cooperation with GFZ Potsdam), (Sośnica et al. 2018c)
  - Using Vienna Mapping Function (VMFo) for SLR (in the framework of cooperation with TU Vienna), (Boisits et al. 2018)
  - Assimilation of numerical weather models and GNSS delays using least squares collocation (Wilgan et al. 2017a, 2017b, Wilgan and Geiger 2019)

Processing SLR observations to new GNSS systems: Galileo, GLONASS, BeiDou, QZSS

- Determination of global geodetic parameters
  - Determination of station coordinates, geocenter, and Earth rotation parameters using SLR observations to multi-GNSS satellites (Sośnica et al. 2019)
  - Determination of global geodetic parameters using SLR observations to multi-GNSS and LAGEOS satellites (Sośnica et al., 2018b)
- Analysis of the consistency between SLR and GNSS solutions
  - Analysis of the Blue-Sky effect and non-tidal surface loading displacements for SLR observations to GNSS (Bury et al. 2019a)
  - Determination of precise orbits of GNSS satellites using SLR observations (Bury et al. 2019b)
  - Development of the on-line service GOVUS.PL for the validation of multi-GNSS satellite orbits (Zajdel et al. 2017)
  - Validation and analysis of the impact of ambiguity resolution of Galileo orbits using SLR data (Katsigianni et al. 2019)
  - Quality assessment of multi-GNSS orbits using SLR for real-time Precise Point Positioning (Kaźmierski et al. 2018a, 2018b)

Integration of SLR observations to different low- and high-orbiting satellites

- Determination of the Earth's gravity field.
- Combining SLR observations with LEO data (SWARM and GRACE) to derive time-variable Earth's gravity field models (Meyer et al. 2019).
- Combining SLR solutions derived from different analysis centers in the framework of the EGSIEM-Follow-On activities (Bloßfeld et al. 2019).
- Applying global gravity field models for a proper georeferencing of remote sensing and GNSS data (Osada et al. 2017).

Processing of SLR observations to LEO and geodetic satellites

- Validation and calibration of SLR biases using SLR observations to LEO missions (Arnold et al. 2019).
- Validation of GOCE orbits and the sensitivity analysis of GOCE orbits to the ionospheric activity using SLR data (Strugarek et al. 2017).

- Summary on the scientific contribution of SLR observations to geodetic satellites and the quality control of SLR data (Pearlman et al. 2019, Otsubo et al. 2019).
- Determination of geocenter coordinates using GNSS-based GRACE orbits (Tseng et al. 2017).
- Determination of TOPEX/Poseidon spin parameters using high-rate SLR data (Kucharski et al. 2017).

1.3 Sessions organization at international congresses/symposia/workshops

- Co-organization of the session *X. Multi-sensor and time series data analysis (W. Kosek, K. Sośnica)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *Geophysical Signal Separation in Global Geodesy, Observing and Separation of geophysical signals in the Climate and Earth System through Geodesy,* at the European Geoscience Union General Assembly (Vienna, Austria) in 2018 and 2019.

1.4 Technology transfer and relevant applications in science and engineering

- GOVUS (www.govus.pl): multi-GNSS Orbit Validation Visualizer Using SLR.
- GNSS-WARP: development of the software in terms of processing multi-GNSS observations in real-time (adding the possibility of processing Galileo, and BeiDou data, Kaźmierski et al. 2018a, 2018b).
- EPOS-PL: construction of co-located sites in Poland in the framework of the European Plate Observing System (EPOS), Task 8 - GGOS++. The co-located sites include: (1) precise multi-GNSS receivers, (2) tidal gravimeters gPhone-X, (3) InSAR reflectors, (4) seismometers, (5) microwave radiometers, all of which are installed in the same place. The test area is located in Southern Poland in Upper Silesia with two external reference stations in Wroclaw and Borowa Góra (Sośnica and Bosy 2019).

2. Cooperation/Interactions with IAG Commissions and GGOS

- IAG Joint Working Group 1.3: Troposphere ties – Chair: R. Heinkelmann (Germany), Vice Chair: J. Douša (Czech Republic).
- Cooperation with the ILRS and IGS MGEX (via running the GOVUS service and the Associated ILRS Analysis Center for the validation of multi-GNSS orbits).

3. Future prospects

3.1 Research

Determination of global geodetic parameters using combined SLR-GNSS observations

- Determination of geocenter motion from Galileo, GPS, GLONASS, and BeiDou.
- Analysis of daily pole coordinates and length-of-day variations using combined SLR-GNSS observations to Galileo.
- Determination of sub-daily Earth Rotation Parameters from SLR, Galileo and other GNSS systems.
- Co-location in space between SLR and GNSS using Galileo and GLONASS satellites.
- Precise orbit determination of GNSS satellites using combined SLR and microwave observations.
- Deriving geodetic parameters using GNSS employing time-variable gravity field models derived from SLR and GRACE.

Integration of SLR observations to active LEO, geodetic, and GNSS satellites

- Combination of SLR observations to various LEO missions: Sentinel-3A/3B, GRACE, GRACE-FO, GOCE, SWARM-A/B/C, Jason-2/3 to derive global geodetic parameters and to realize the terrestrial reference frames.
- Time-variable gravity field determination using SLR observation to passive geodetic satellites (LAGEOS-1/2, LARES-1/2, Starlette, Stella, Ajisai, Larets, BLITS-M, BLITS).
- Orbit simulations and processing data from new satellite missions planned for 2019: LARES-2, BLITS-M, and launched in 2018: Sentinel-3B, GRACE-FO.
- Time-variable gravity field determination using SLR observation to passive geodetic satellites and GNSS-based orbits of LEO satellites to fill the gap between GRACE and GRACE-FO missions.
- Combinations between GRACE-FO results and SLR for the improvement of degree-2 gravity field parameters.

Atmospheric delay modeling issues

- Development of a simple model of troposphere horizontal gradients for SLR solutions (which is important in the context of including LARES-1 into the operational ILRS products).
- Homogenization of troposphere delay models for co-located space geodetic stations. Using the same troposphere parameters for estimating the hydrostatic delay in SLR and GNSS solutions.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on the integration of space geodetic techniques at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of the session at next *European Geoscience Union General Assembly* and *IAG Commission 4 Symposium*.

3.3 Editorial activity

- Special issues on peer-review journals on the integration of SLR, multi-GNSS, LEO and gravity field data.
- JSG publications: proposal for review papers on integration of various techniques of space geodesy co-authored by the JSG members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography on multi-GNSS, SLR, LEO, and time-variable gravity
- Publication of Galileo, GLONASS, and BeiDou orbits derived using combined SLR and GNSS observations (contribution to IGS MGEX and ILRS)
- Extension of the on-line service GOVUS

4. Publications

1. Arnold D, Montenbruck O, Hackel S, Sośnica K (2019) Satellite laser ranging to low Earth orbiters: orbit and network validation. *Journal of Geodesy*; doi: 10.1007/s00190-018-1140-4.
2. Bloßfeld M, Meyer U, Sośnica K, Jäggi A (2019) Combined SLR gravity field time series for continuous Earth System Monitoring. European Geosciences Union General Assembly 2019, Vienna, Austria, 7-12 April 2019. *Geophysical Research Abstracts.*
3. Boisits J, Landskron D, Sośnica K, Drożdżewski M, Böhm J (2018) VMF3o: enhanced tropospheric mapping functions for optical frequencies. 21st International Workshop on Laser Ranging, Canberra, Australia, 4-9 November 2018.
4. Bury G, Sośnica K, Zajdel R (2019a) 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*: 1-17; doi: 10.1109/TGRS.2018. 2885845.

5. Bury G, Sośnica K, Zajdel R (2019) Multi-GNSS orbit determination using satellite laser ranging. *Journal of Geodesy*; doi: 10.1007/s00190-018-1143-1.
6. Drożdżewski M, Sośnica K (2018) Satellite laser ranging as a tool for the recovery of tropospheric gradients. *Atmospheric Research* 212: 33-42; doi: 10.1016/j.atmosres.2018. 04.028.
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Joint Study Group 0.15: Regional geoid/quasi-geoid modelling – theoretical framework for the sub-centimetre accuracy

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1. Activities

1.1 Summary

A theoretical framework for the regional geoid/quasi-geoid modelling is a conceptual structure to solve a geodetic boundary value problem regionally. They consist of, but are not limited to, the following components:

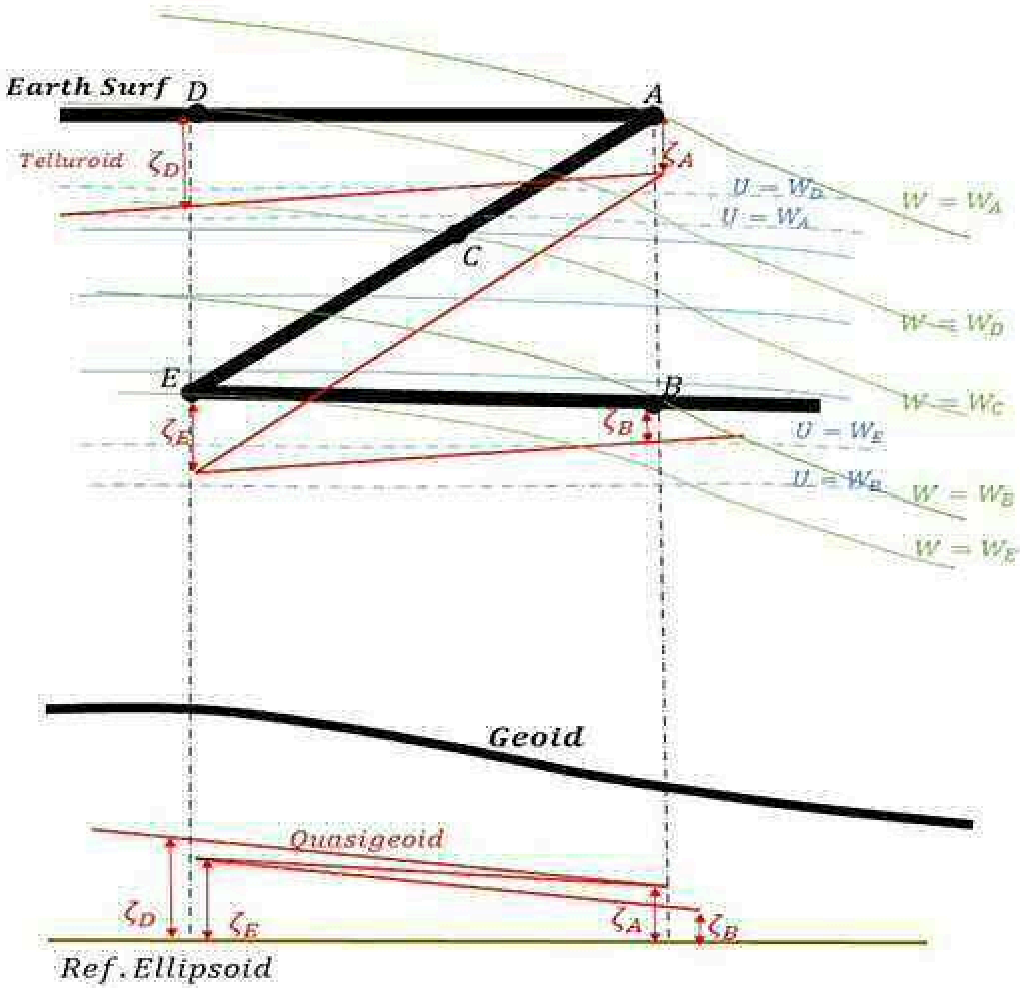
- Physical constant GM
- W0 convention and changes
- Geodetic Reference Systems and Frames such as GRS80 and ITRF
- Formulation of the geodetic boundary value problem (GBVP)
- Numerical methods
- Data type, distribution and quality requirements
- Gravity reduction
- Data interpolation and extrapolation methods
- Combination of different types of gravity data
- Estimation of the geoid/quasi-geoid model error
- Validation of geoid/quasi-geoid models
- Transformation between the geoid and quasi-geoid models
- Time-variable geoid/quasi-geoid modelling
- New theories and methods such as the radial basis functions (RBFs).

For the period of 2015-2019, members of the JSG have contributed to seven of these components which are highlighted in Section 1.2.

1.2 Research

Formulation of the geodetic boundary-value problem (GBVP)

- When computing the geoid for Auvergne, Janak et al. (2017) and Foroughi et al. (2017a) were naturally interested in comparing their results with the best results for the quasigeoid. They reported that the geoid appears to be determinable to a higher accuracy than the quasigeoid. One of the first things they discovered is showed in the figure below; referred as folded quasigeoid. This research continues in (Kingdon et al. 2018).



Data type, distribution and quality requirements

- Huang et al. (2017) compared GRAV-D data with terrestrial gravity data in three survey blocks that cross the Canada-US border, and showed that differences between GRAV-D and terrestrial gravity data are 3.6 mGal for AN04, 1.8 mGal for EN05 and 2.3 mGal for EN08 in terms of Root Mean Square (RMS) at the mean flight height.
- Barzaghi et al. (2018) computed geoid models for the Mediterranean using the remove-compute-restore Stokes-FFT method, and shipborne gravity or altimetry inferred gravity data over sea and land gravity data. The remove step over sea does not include residual terrain correction (bathymetry), which leads to slightly worse results. The models were compared to an independent geoid constructed by subtracting the Mean Dynamic Topography from the Mean Sea Surface, and secondly to drifter-observed current speeds. Results revealed significant errors in the gravimetric geoid at smallest scales, and analysis of the results of this intermediate model showed that improvement is required in the gravity data preprocessing, specifically the de-biasing of marine data, as well as the gridding (interpolation) procedure.

Gravity reduction

- Kingdon et al. (2015) studied least-squares downward continuation of gravity anomalies in Helmert's space, introducing the concept and showing some sample applications.
- Vaníček et al. (2016) discovered that during the iterative solution of the downward continuation problematic unique inverse problem – the solution stays within physically meaningful boundaries. As starting from some iteration, the process starts to model the effect of random errors and thus it makes no sense to seek an exact solution; instead the most probable solution in statistical sense should be preferred.

- Tavakoli et al. (2016) did a study of an application of Kouba's refined form of Poisson's partial differential equation of the gravity potential to the problem of topographical density determination.
- Vaníček et al. (2018) have done some additional thinking about the origin of the secondary indirect topographical effect (SITE).
- Foroughi et al. (2018a, b) developed an algorithm to get the minimum quadratic norm values (least-squares estimates) of downward continued Helmert's gravity anomalies, which under the assumption of Gaussian distribution of errors are the most probable estimates of the real downward continued anomalies. In application for Auvergne in France, the mean standard deviations of the geoidal heights are only 0.6 cm. As one should expect, the main contributing factors to these uncertainties are the Poisson probabilistic downward continuation process, with the maximum standard deviation just short of 6 cm (the average value of 2.5 mm) and the topographic density uncertainties, with the maximum value of 5.6 cm (the average value of 3.0 mm).
- Sheng et al. (2019a) have produced a global laterally-varying topographical density model with 30 arc-second, 5 arc-minute, and 1 arc-degree angular grid resolutions by associating a global lithology model with appropriate densities determined from geological databases.
- Lin and Denker (2019) investigated the computation of topographic and atmospheric effects with tesseroids.

Combination of different types of gravity data

- Wang et al. (2016) discussed two methods of combination: the spectral combination and the least-squares collocation with emphasis on the first. The method was applied for satellite, airborne and terrestrial gravity data in the US NGS's GSVS11 (Jiang and Wang 2016).
- Gerlach and Ophaug (2017) derived combined geoid solutions from state-of-the-art satellite only models (based on Release-5 GOCE data) and terrestrial information. Combination was performed in the spectral domain using Wenzel's stochastic method as well as more deterministic methods like the classical Wong&Gore modification. Wenzel's approach was chosen, because it is considered to be optimal in a certain sense. Thereby it is important to stress, that correlated noise for both satellite and terrestrial data have been assumed. Comparison with older geoid models shows the general improvement brought by the satellite missions GRACE and GOCE from around 8 cm before GRACE and GOCE, to currently around 3 cm.
- Huang and Véronneau (2017) studied the spectral response of Stokes's integral to its modification and truncation. They suggest that the unmodified Stokes's integral is spectrally unstable when being arbitrarily truncated, and a modification to Stokes's kernel is required for a smooth geoid model.

Estimation of the geoid/quasi-geoid model error

- Featherstone et al. (2018) published the first Australian gravimetric quasigeoid model with location-specific uncertainty estimates. The gravimetric quasigeoid errors (one sigma) are 50–60 mm across most of the Australian landmass, increasing to ~100 mm in regions of steep horizontal gravity gradients or the mountains, and are commensurate with external estimates.
- Gerlach et al. (2019) have tried to derive general measures for the errors of geoid and gravity anomalies based on different sets of input data (a coarse and dense grid of scattered gravity data in a test area in Norway, point dsitance around 6 and 2-3 km, respectively). The main focus is on the representation error. The error estimates, derived by least-squares collocation, are general in the sense that we used a band-pass filtered global covariance function instead of empirical regional functions. Validation with independent data shows, that the signal variance in the area fits our general model and

that formal error estimates for gravity anomalies and geoid heights correspond well with the empirical errors. Finally, we expect that the denser gravity dataset can improve the geoid from around 2 to almost 1 cm.

Validation of geoid/quasi-geoid models

- Santos et al. (2015) reported a series of comparisons of geoidal heights derived from several GOCE models with (1) geoidal heights derived from GPS on benchmarks (referred to as geometric geoidal heights) over Mexico and Canada, and with (2) geoidal heights derived from the latest geoidal maps of Mexico (GGM2010) and Canada (PCGG2013). The omission errors in Mexico and in Canada show a similar behavior, with a near zero mean and a standard deviation at the order of ˙50 cm in Mexico and ˙45 cm in Canada.
- In the Great Lakes region, the improvement of the geoid model by GRAV-D reaches decimetres using the lake surface height measured by satellite altimetry as an independent data set over Lake Michigan where the legacy gravity data have significant errors (Li et al. 2016).
- In Perth, Western Australia, a modern digital astro-geodetic field campaign was completed in February 2017. Along a ~40 km long east-west traverse crossing the Perth Basin, vertical deflection data were collected at 37 field stations using two Q-Daedalus digital astronomical measurement systems (Guillaume and Bürki 2014; Hauk et al. 2016). The initial analysis of these new vertical deflection data indicates a precision of 0.2 arc-sec.

New theories and methods

- Ophaug and Gerlach (2017) investigated the equivalence of these three methods (Stokes integration, least-squares collocation and representation in spherical splines) in regional applications both from a theoretical as well as from a numerical point of view. They found that all methods agree on the sub-millimeter to millimeter level, where the largest deviations are due to discretization errors of Stokes integral equation.
- Lin et al. (2019) compared the fixed and free-positioned point mass methods for the RBF modeling of regional gravity fields, and suggested that the latter outperforms the former in regions with rough field features.
- While attempting to provide a solution to the polar gap problem that contaminates the GOCE mission data, Sheng et al. (2019b) extended the work of Paul (1973) and developed two theorems for formulating the global spherical harmonic series exactly from any number of sub-regions (of any arbitrary shape) completely covering the globe without overlap; the first theorem for the 2D case and the second dealing with the more general 3D case. They also investigated the numerical evaluation of these theorems using synthetic data to demonstrate that the inconsistencies between theory and practice do not unduly contaminate the results.

1.3 Sessions organization at international congresses/symposia/workshops

- Co-organization of the session *Deformation and gravity field modelling at regional scales (J. Huang, Y. Tanaka) a*t the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.

2. Cooperation/Interactions with IAG Commissions and GGOS

The JSG0.15 has been collaborating closely with the following groups and sub-commissions (SC) in organizing an international cooperation on determining the best ways to combine satellite gravity models and terrestrial/airborne gravity data in geoid modelling and work towards a 1 cm accuracy goal in Colorado, USA:

- GGOS JWG: Strategy for the Realization of the IHRS (chair L. Sánchez)
- IAG SC 2.2: Methodology for geoid and physical height systems (chair J. Agren)
- IAG JWG 2.2.2: The 1 cm geoid experiment (chair Y. M. Wang)

3. Publications

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4. Foroughi I, Vaníček P, Kingdon R, Sheng M, Santos MS (2018a) Investigating the accuracy of the Poisson's downward continuation using least squares technique. IX Hotine-Marussi Symposium, Rome, Italy, June 18-22.
5. Foroughi I, Vaníček P, Kingdon R, Goli M, Sheng M, Afrasteh Y, Novák P, Santos M, (2018b). Sub-centimetre geoid, *Journal of Geodesy*, https://doi.org/10.1007/s00190-018-1208-1.
6. Gerlach C, Ophaug V (2017) Accuracy of Regional Geoid Modelling with GOCE. *IAG Symposia Series* 148: 17-23; doi: 10.1007/1345_2017_6.
7. Gerlach C, Ophaug V, Omang O, Idzanovic M (2019) Quality and distribution of terrestrial gravity data for precise regional geoid modeling: a generalized setup. *IAG Geodesy Symposia Series* (submitted).
8. Huang J, Véronneau M (2017) The spectral response of Stokes's integral to modification and truncation, a commemorative publication for Bernhard Heck. KIT, 117-121; doi: Einzelbeitrag:10.5445/KSP/1000080220.
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12. Kingdon R, Vaníček P, Zhong D (2015) Least squares downward continuation, fusion and gridding of airborne and terrestrial gravity observations. Presented at the IUGG General Assembly, Prague, June 22 to July 2.
13. Kingdon R, Vaníček P, Santos MC (2018) The shape of the quasi-geoid. IX Hotine-Marussi Symposium, oral presentation, Rome, Italy, June 18-22.
14. Lin M, Denker H. Müller J (2019) A comparison of fixed- and free-positioned point mass methods for regional gravity field modelling. *Journal of Geodynamics* 125: 32-47; doi: 10.1016/j.jog.2019.01.001.
15. Lin M, Denker H (2019) On the computation of gravitational effects for tesseroids with constant and linearly varying density. *Journal of Geodesy* 93: 723-747; https://doi.org/ 10.1007/s00190-018-1193-4.
16. Ophaug V, Gerlach C (2017) On the equivalence of spherical splines with least-squares collocation and Stokes's formula for regional geoid computation. *Journal of Geodesy*; doi: 10.1007/s00190-017-1030-1.
17. Santos MC, Avalos D, Peet T, Sheng M, Kim D, Huang J (2015) Assessment of GOCE models over Mexico and Canada and impact of omission errors. *IAG Symposia Series*143; doi:10.1007/1345_2015_28, Springer International Publishing Switzerland.
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19. Sheng MB, Shaw C, Vaníček P, Kingdon RW, Santos M, Foroughi I (2019) Formulation and validation of a global laterally varying topographical density model. *Tectonophysics* (in press).
20. Sheng MB, Vaníček P, Novák P, Santos MC, Kingdon RW, Foroughi I (2019b) Per partes integration of potential coefficients in global spherical harmonic series. Submitted to *Journal of Geodesy*.
21. Tavakoli A, Safari A, Vaníček P (2016) A special case of the Poisson PDE for formulated Earth's surface and its capability to approximate the terrain mass density employing land-based gravity data, a case study in the south of Iran. *Geophysical Journal International* 207(3): 1529-1553
22. Vaníček P, Novák P, Sheng MB, Kingdon R, Janák J, Foroughi I, Martinec Z, Santos MC (2016) Does Poisson's downward continuation give physically meaningful results? *Studia Geophysica et Geodaetica*; doi: 10.1007/s11200-016-1167-z.
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Joint Study Group 0.16: Earth's inner structure from combined geophysical sources

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1. Activities

1.1 Summary

Seismological, gravity, magnetotelluric and heat flow measurements are mainly used to investigate Earth's inner structure. Seismic tomography (especially surface waves) and seismic reflection and refraction experiments provide images of inner structure, importantly of density interfaces (sediment basements, Moho, lithosphere-asthenosphere boundary LAB, core-mantle boundary zone). Seismic velocities could also be inverted for density and temperature, and seismic attenuation and seismic anisotropy are correlated with temperature and strain, respectively. Global heat flow measurements help constrain the lithospheric geotherm and Earth's energy budget. Magnetotelluric studies image Earth's electrical conductivity. Gravity field manifests Earth's density structure and this information is used in studies of isostasy, lithospheric stresses, basement morphology, seafloor relief, or lithospheric elastic thickness.

Scientific activities of the members of this study group reflect their expertise primarily in gravimetry and seismology. The study group focused on theoretical and practical research aspects, involving developments and applications of theoretical models for gravity inversion, seismic data processing and analysis, the combination of seismic and gravity data, and the facilitation of various geophysical and geodetic data in studies of Earth's structure and processes. They extensively applied existing and newly developed theoretical models in geodynamic and geophysical interpretations of Earth's interior. Studies (listed below) involve, for instance, the modelling of Moho interface, LAB, lithospheric stresses, or oceanic slabs. Moreover, they investigated oceanic lithosphere, mantle structure, inner-inner core equatorial anisotropy, orogenic formations and crustal melting beneath them, mantle viscosity, sedimentary basins, metallogenic zones in cratonic formations, and many other phenomena. In addition to terrestrial studies, their research involved some planetary applications. Selected research outcomes are briefly summarized next.

1.2 Research

In selected examples from scientific outputs, we demonstrate global and regional gravity images of Earth's crust and upper mantle, the Moho models from combined processing of gravity and seismic data, global maps of stress field of Venus, Mars and Earth, and the regional study of horizontal stresses in Fennoscandia. Theoretical examples are given for the definition of height reference systems and the computation of Bouguer gravity field of telluric planets (and Earth's Moon). We also present the recent development in the Bayesian gravity inversion and its application.

Global gravimetric studies

Chen and Tenzer (2019) compiled and interpreted global mantle and sub-lithosphere mantle gravity maps, see Fig. 1. They identified global lateral thermal distribution within the asthenosphere and negative thermal anomalies of subducted slabs in West Pacific, see Fig. 1d.

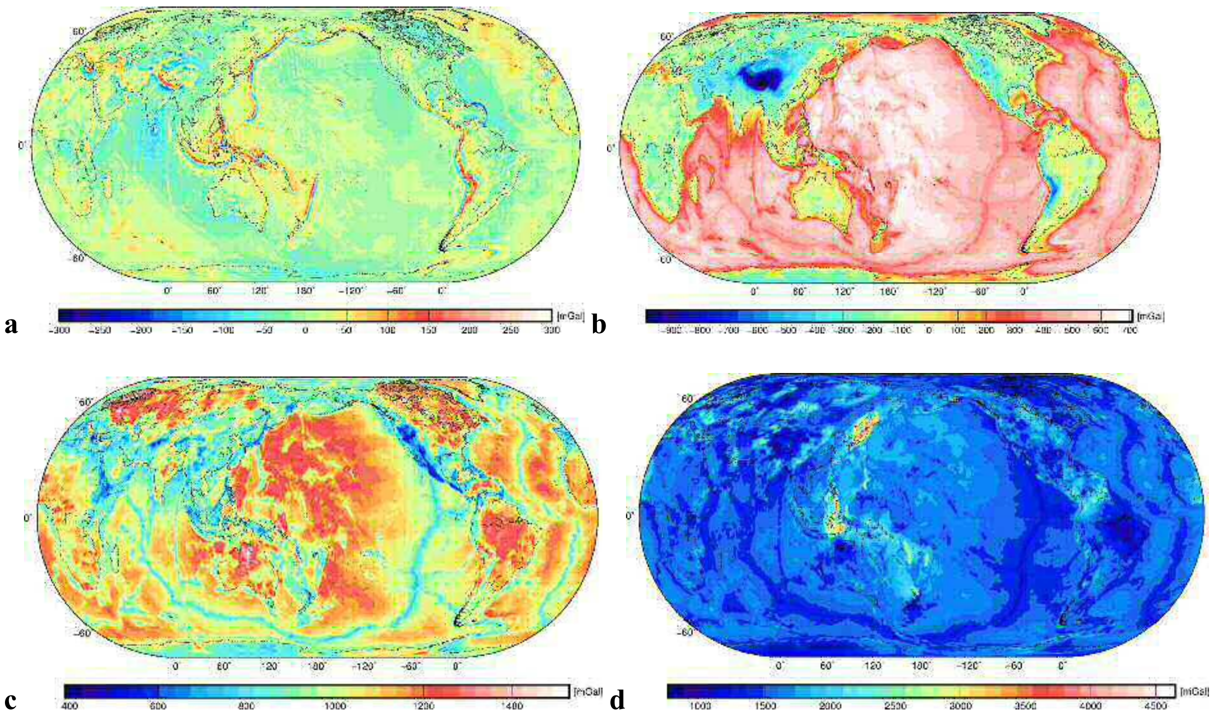


Figure 1: Global gravity: (**a**) free-air, (**b**) Bouguer, (**c**) mantle and (**d**) sub-lithosphere mantle.

Detailed regional gravimetric studies

Numerous studies were dedicated to investigate geologically and tectonically significant regions, such as Tibet, West Pacific, the South China Sea, or Iran. We also conducted large-scale studies. Rathnayake et al. (2019) compiled and interpreted the Bouguer and mantle gravity maps of the Indian Ocean, see Fig. 2. They demonstrated that the southern Nubian-Somalian plate boundary, i.e., the Lwandle plate, and the Indo-Australian plate boundary, i.e., the Capricorn plate, are not manifested in the mantle gravity map by a thermal signature, confirming that these tectonic margins are diffuse zones of convergence, characterized by low deformation and seismicity due to very slow rates of relative motions accommodated across these boundaries. They also show that a thermal signature of intraplate hotspots in the mantle gravity map is almost absent. This finding agrees with the evidence from direct heat flow measurements that do not indicate the presence of a significant positive temperature anomaly compared to the oceanic lithosphere of a similar age.

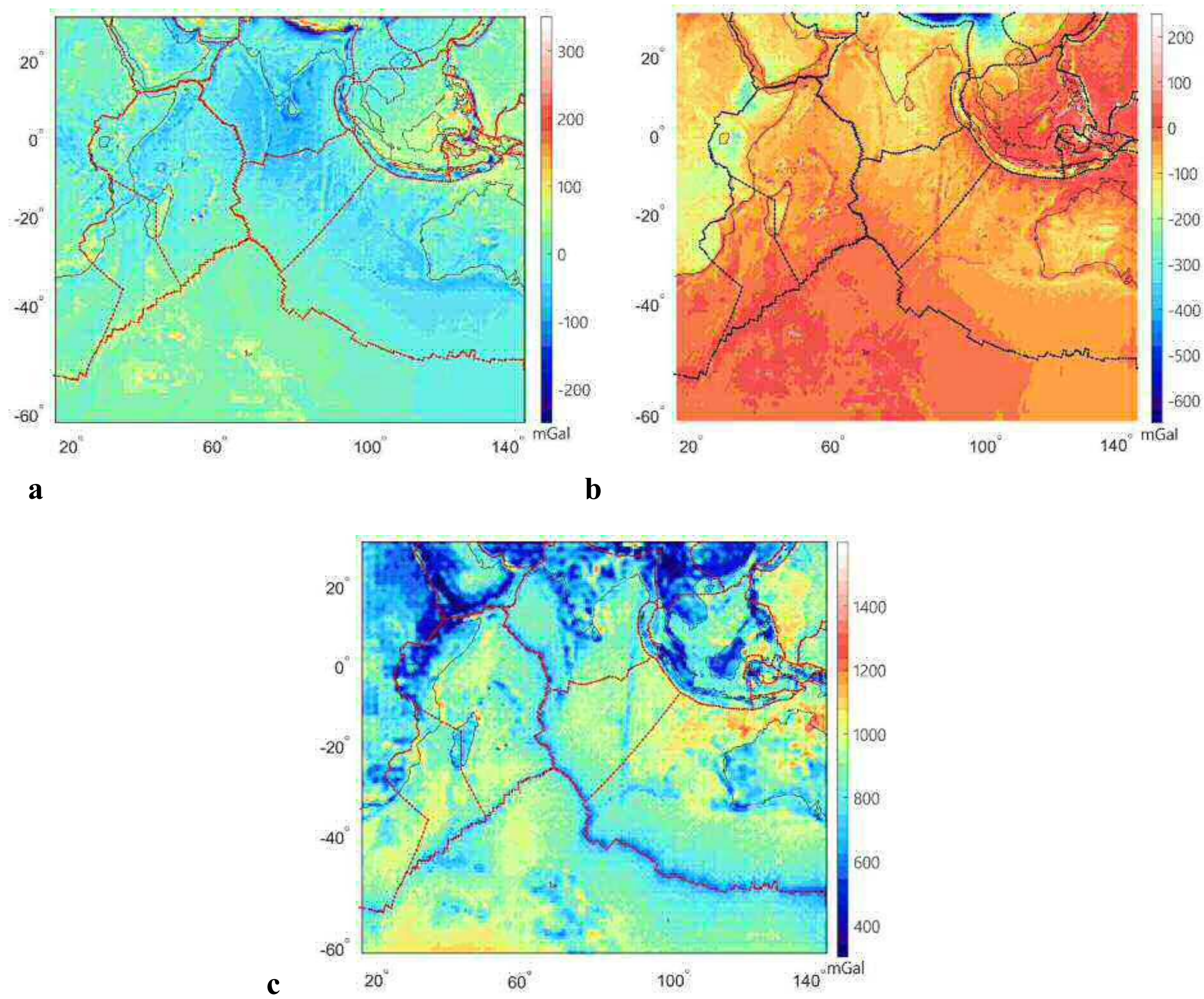


Figure 2: Gravity of the Indian Ocean: (a) free-air, (b) Bouguer and (c) mantle gravity data.

Regional crustal models

We compiled several regional Moho models using gravity and seismic data, and conducted similar continental-scale studies. In Figs. 3 and 4, the example is shown for the Moho depth in Antarctica estimated by Baranov et al. (2018). Bagherbandi et al. (2017) investigated the contribution of the lithospheric thermal state on the Moho geometry in South America, see Fig. 5. Another area of study of density modeling incorporating seismic velocity models or information was the Alps, as well as the Chad basin (manuscripts in preparation stage).

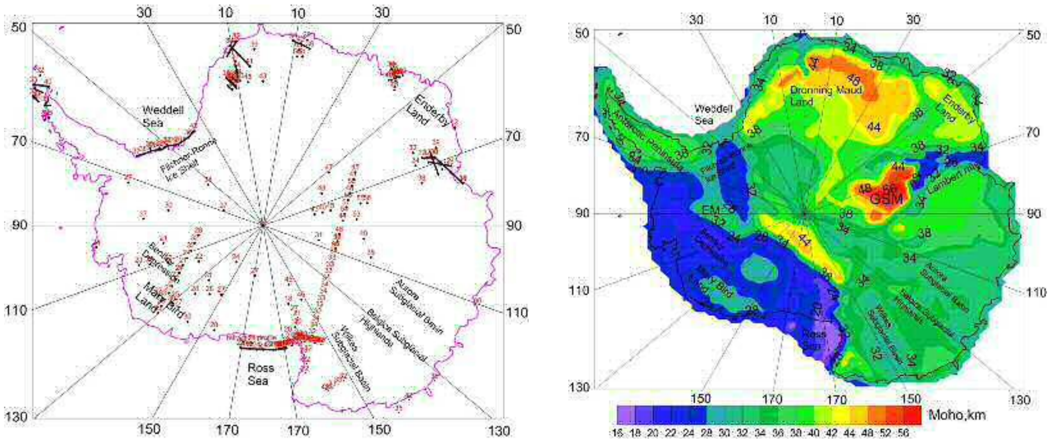


Figure 3: Seismic data (left) and the seismic Moho model (right) of Antarctica.

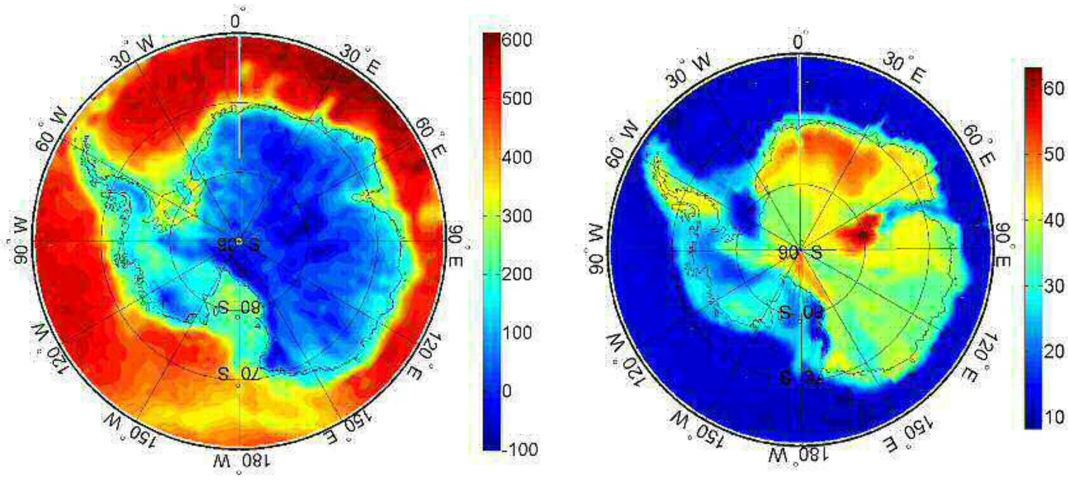


Figure 4: Bouguer gravity data (left) and the **c**ombined Moho model (right) of Antarctica.

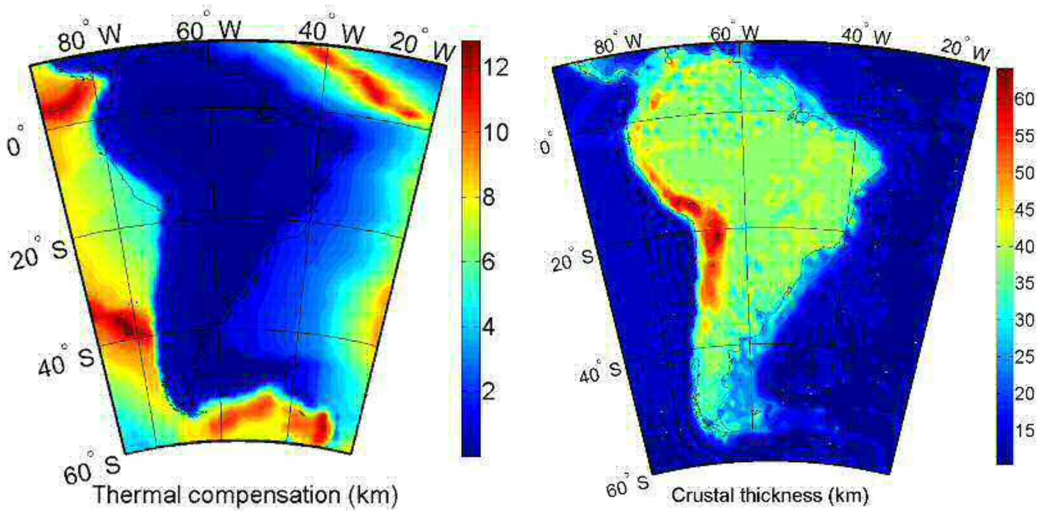


Figure 5: The lithospheric thermal-pressure compensation on the Moho depth (left) and the Moho model (right) of South America.

Stress field studies

Tenzer et al. (2015), Eshagh and Tenzer (2015) and Zampa et al. (2018) investigated a possible evidence of global tectonism on Venus and Mars. They used gravity and topographic models to compute stress field. According to their results, the signature of global tectonism on Mars and Venus is absent, see Fig. 6a, b, while the global tectonic configuration is clearly manifested in terrestrial stress field anomalies, see Fig. 6c.

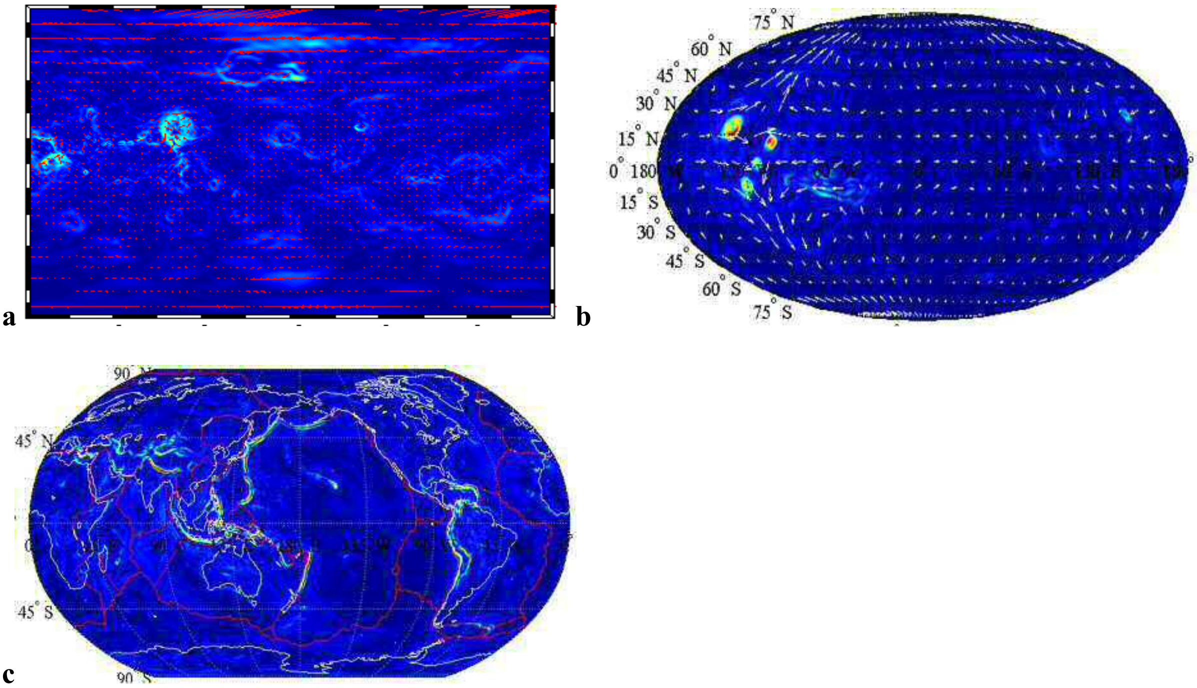
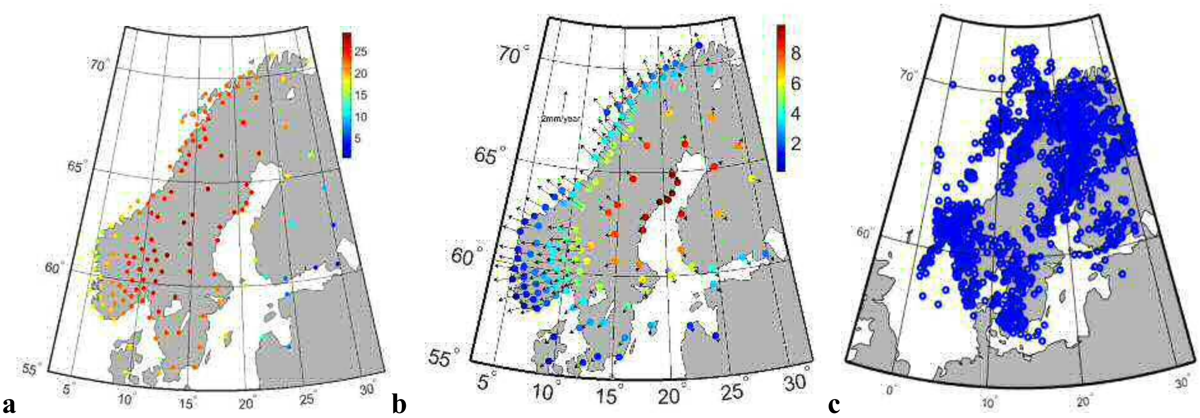
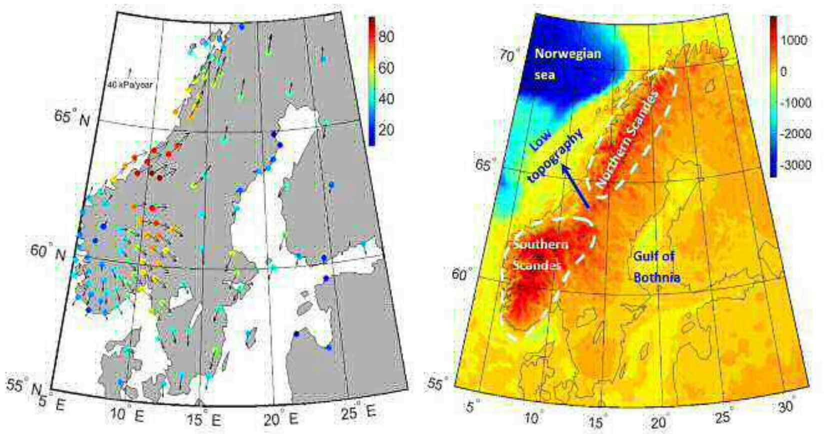


Figure 6: The global stress maps of (**a**) Venus, (**a**) Mars and (**c**) Earth.

Gido et al. (2018) determined the horizontal stress field induced by mantle convection in Fennoscandia using gravity data, see Fig. 7. The result is consistent with tectonism and seismicity of the region. In addition, the secular rate of change of the horizontal stress, which is within 95 kPa/year, is larger outside the uplift dome than inside.





d

Figure 7: Horizontal stress field in Fennoscandia: (**a**) the absolute horizontal stress (in MPA) from gravity data, (**b**) the vertical (color circles) and horizontal (black arrows) velocities (in mm/yr) from GPS results and ICE-5G-FEM model (Kierulf et al. 2014), (**c**) the seismic activity between 2007-2017 according to FENTEC (Finnish Institute of Seismology, University of Helsinki) database, and (**d**) the secular rate of horizontal stress (tectonics) shown in color circles (in kPa/yr) and its direction changes with black arrows (in mm/yr). Right panel shows topography (in m).

Planetary studies

In theoretical study by Tenzer et al. (2018), authors discussed definitions of height systems for telluric planets (and Earth's Moon). They proposed a more accurate approach for defining the physical (orthometric) heights with respect to the geoid surface, see Fig. 8. They also demonstrated that the accuracy of computing physical heights could be improved, see Fig. 9.

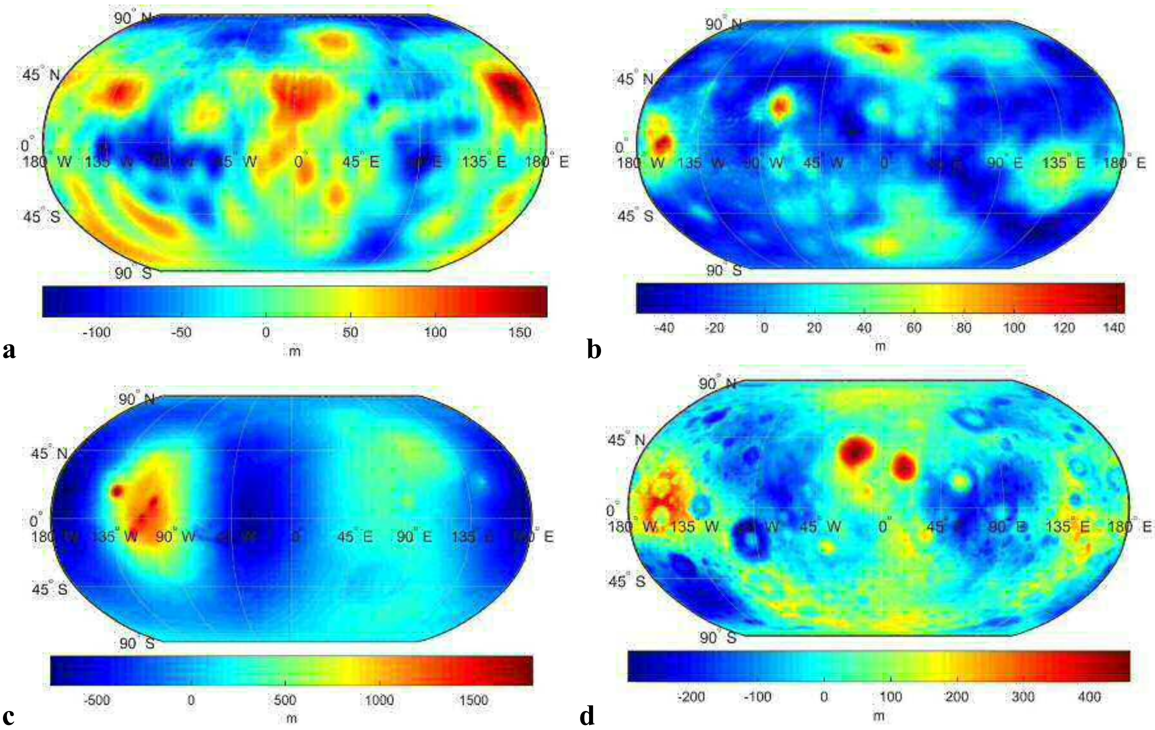


Figure 8: Geoidal heights on (a) Mercury, (b) Venus, (c) Mars and (d) Earth's Moon.

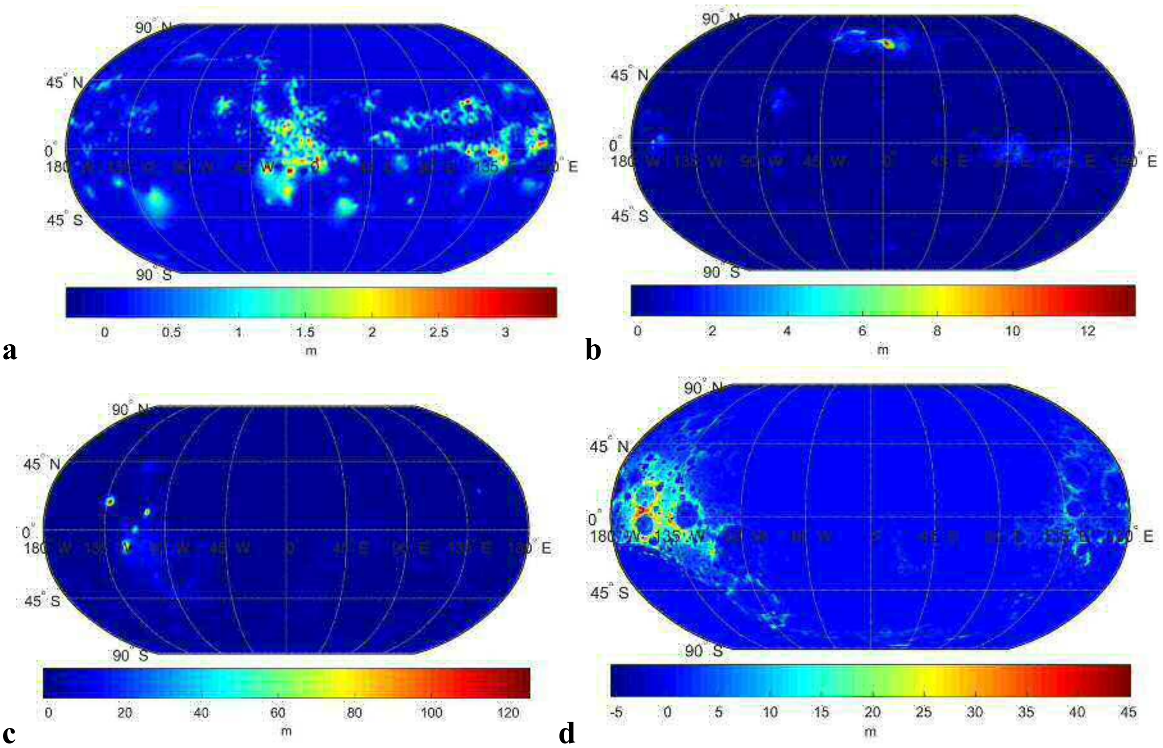
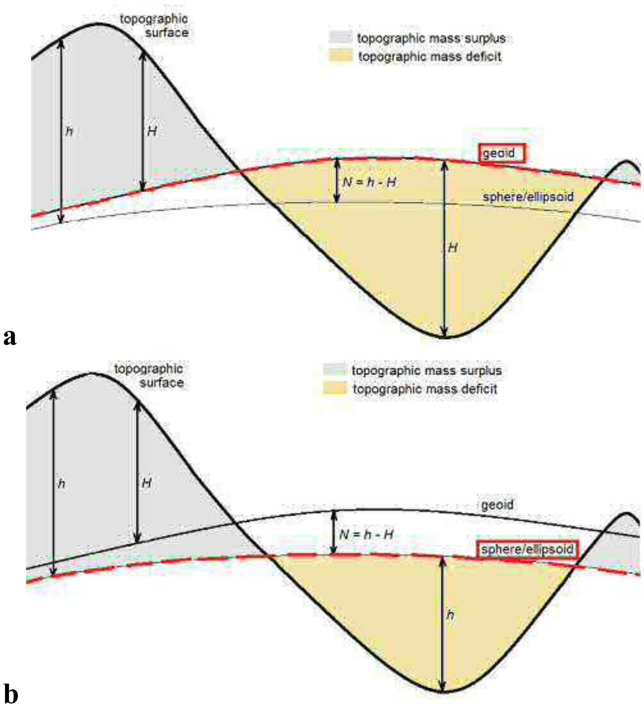
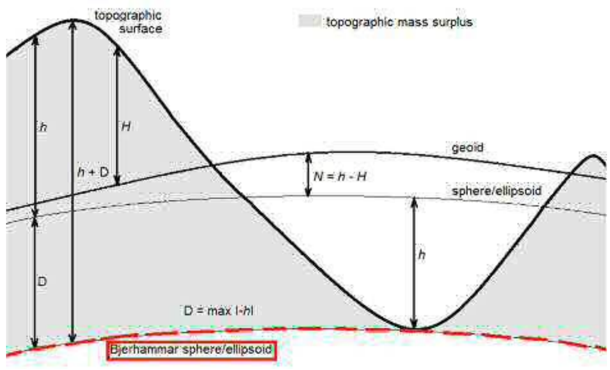


Figure 9: Differences between the accurate and approximate orthometric heights on (**a**) Mercury, (**b**) Venus, (**c**) Mars and (**d**) Earth's Moon.

In another theoretical study for planetary applications, Tenzer et al. (2019) proposed and examined numerically three possible schemes, see Fig. 10, how to compute the topographic gravity correction, and concluded that the optimal choice for computing the Bouguer gravity data, see Fig. 11, is based on the geoid-referenced surface.





c

Figure 10: Possible scenarios of computing the topographic gravity correction for a height reference surface represented by (**a**) the geoid, (**b**) the geometric reference surface and (**c**) the Bjerhammar sphere/ellipsoid. Used notation: h the geometric height, H the physical height, N the geoidal height and D the (constant) depth of the Bjerhammar sphere/ellipsoid.

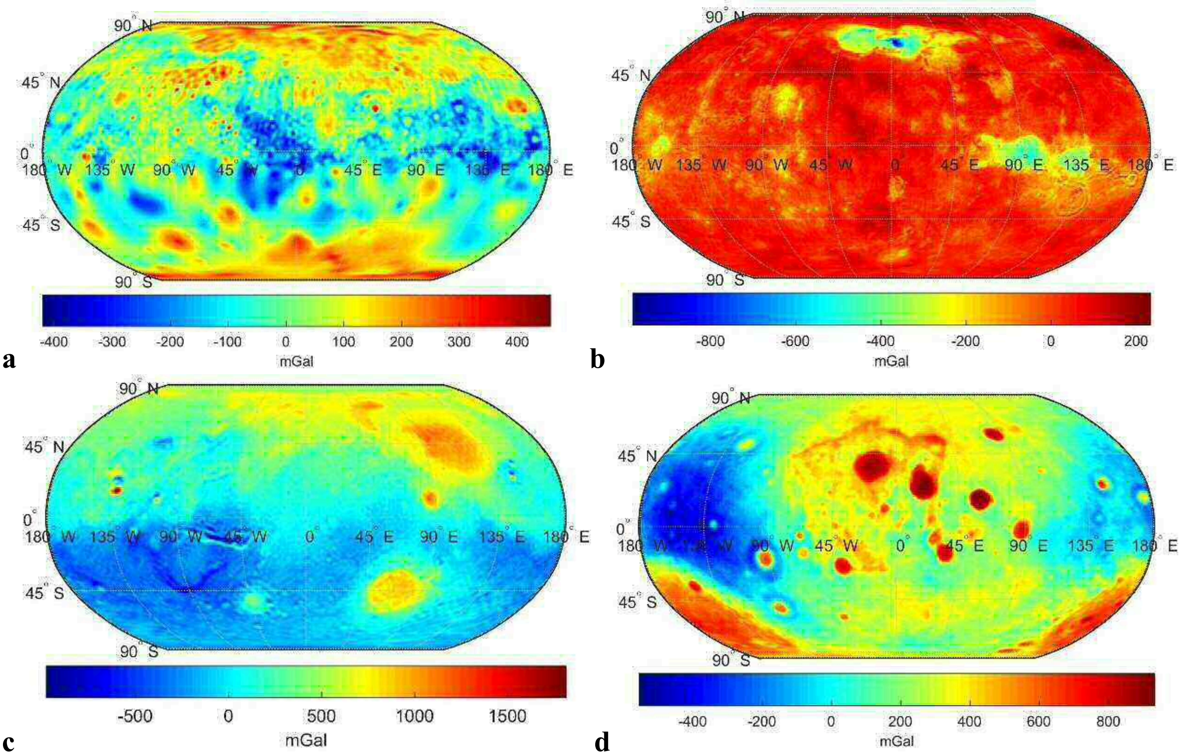


Figure 11: Bouguer gravity maps of (**a**) Mercury, (**b**) Venus, (**c**) Mars and (**d**) Earth's Moon computed for the geoid-referenced surface.

Gravity inversion techniques

Rossi et al. (2015) studied and implemented a Bayesian gravity inversion algorithm constrained on a-priori geological information. Reguzzoni et al. (2019) tested this approach below the Jiangmen Underground Neutrino Observatory (JUNO), currently under construction in the Guangdong Province (China). Since the geoneutrino signal measured by a liquid scintillator detector placed on the continental crust is dominated by the natural radioactivity of the closest geological units, they aimed at investigating the crustal structure that lies within ~300 km from the detector. The solution maximizing the posterior probability is the GIGJ (GOCE Inversion for Geoneutrinos at JUNO) crustal model for the Guangdong Province, see Fig. 12. The GIGJ model is consistent with the input geological and seismic information, and fits the GOCE gravity data with a standard deviation of 1 mGal. The model has been used to estimate the geoneutrino signal expected at JUNO and produced by unitary abundances of U and Th in the crustal layers.

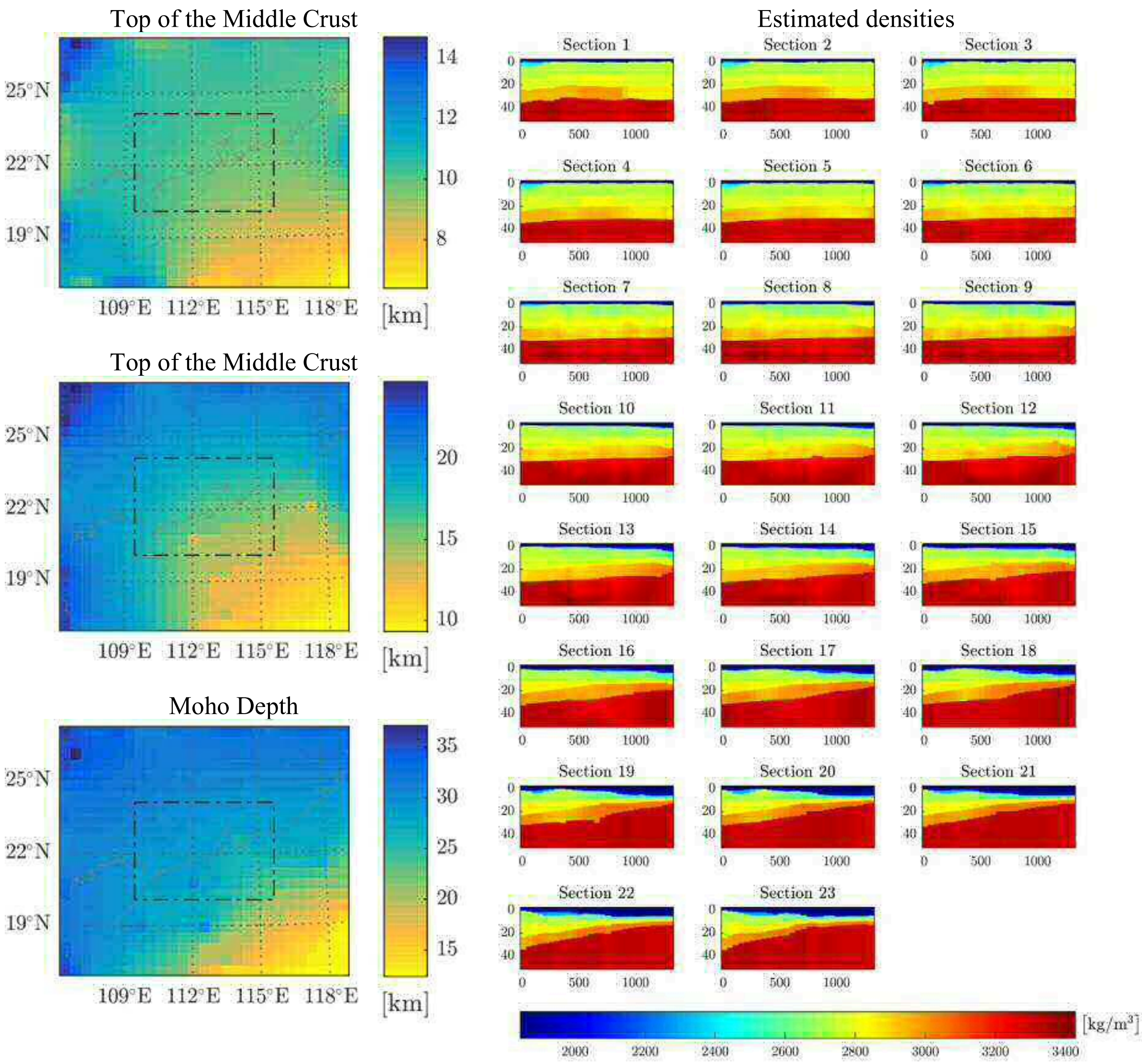


Figure 12: Estimated GIGJ model under the JUNO detector by the Bayesian inversion of GOCE data. Discontinuity surfaces on the left, density distribution on the right. Note that the top of the Upper Crust (i.e., the basement) is not estimated. Note also that the sections are numbered from North (1) to South (23), and cut the model from West to East.

<u>Earth's core studies</u>

Xin et al. (2015), Wang et al. (2015) and Wang and Song (2018) provided the evidence of equatorial anisotropy of Earth's inner-inner core.

1.3 Sessions organization at international congresses/symposia/workshops

Except for scientific activities, the members of JSG0.16 have been involved in organizing international conferences. R. Tenzer was the member of scientific committee of the 9th International Workshop on TibXS organized in Zhangye, China, August 6-10, 2018 and of the IX Hotine-Marussi Symposium in Rome, June 18-22, 2018. He is the IAG co-convener of the joint IAGA-IASPEI-IAG-ILP-IAVCEI session JA08: Probing the Earth's lithosphere and its dynamics using geophysical modelling at the IUGG General Assembly in Montreal, 8-18 July, 2019. L. Sjöberg and M. Bagherbandi are organizing the First International School on Geoid Modelling, Gravity Inversion and its Application at the University of Gävle, Gävle, Sweden, 9-13 September, 2019.

1.4 Technology transfer and relevant applications in science and engineering

The proposed Bayesian algorithm (Rossi et al., 2015; Reguzzoni et al., 2019), which has been engineered into a set of software tools by a spin-off company of Politecnico di Milano, has been applied to oil exploration for scenarios with more than 1.5 million voxels and in presence of complex geological structures.

2. Future prospects

We expect to deliver the density model of the whole mantle based on the combined analysis of seismic and gravity data with additional geophysical and geochemical constraints that would serve as the Earth's synthetic model for testing numerical approaches for gravimetric forward and inverse modelling. This model will also serve to provide gravimetric images of the Earth's structure down to the core-mantle boundary zone. Special emphasis will be given to improve existing models of the asthenosphere and transition zone in the mantle.

2.1 Research

Gravimetric interpretation of the Earth's inner structure

- Spatial and spectral analysis of Earth's gravity field.
- Regional and continental-scale gravimetric studies of Antarctica, Indian Ocean, parts of Eurasia, South America and Africa.
- Studies of equatorial anisotropy of Earth's inner-inner core.
- Gravimetric studies of telluric planets and Earth's Moon.
- Compilation of Bouguer and mantle gravity maps of planets and moons.
- Studies of lithospheric stress field.

Numerical models

- Optimal numerical models for gravimetric forward and inverse modelling of lithospheric and deep mantle structures.

Density structure models

- Development and improvement of density model of Earth's lithosphere and asthenosphere.
- Compilation of new density model of continental sedimentary basins.

3. Publications

Members of JSG0.16 have extensively published their scientific results in peer-reviewed international journals. They also actively presented their results at major international conferences, such as IUGG 2015, ESA Living Planet 2016, IAG Gravity, Geoid and Height Systems 2016 Symposium, or the annual meetings organized by EGU and AGU. The members have usually participated and reported their results in sessions on gravity field modelling, lithospheric structure, solid Earth, planetary remote sensing, and vertical reference systems. The list of selected publications and presentations is below.

1. Abrehdary M, Sjöberg LE, Bagherbandi M (2016) The spherical terrain correction and its effect on the gravimetric-isostatic Moho determination. *Geophysical Journal International* 204(1): 262-273
2. Abrehdary M, Sjöberg LE, Bagherbandi M, Sampietro D (2017) Towards the Moho depth and Moho density contrast along with their uncertainties from seismic and satellite gravity observations. *Journal of Applied Geodesy*; https://doi.org/10.1515/jag-2017-0019.
3. Álvarez O, Gimenez M, Folguera A, Spagnotto S, Bustos E, Baez W, Braitenberg C (2015) New evidence about the subduction of the Copiapó ridge beneath South America, and its connection with the Chilean-Pampean flat slab, tracked by satellite GOCE and EGM2008 models. *Journal of Geodynamics* 91: 65-88
4. Bagherbandi M, Tenzer R, Abrehdary M, Sjöberg LE (2015) A New Fennoscandian crustal thickness model based on CRUST1.0 and gravimetric isostatic approach. *Earth-Science Review* 145: 132-145

5. Bagherbandi M, Sjöberg LE, Tenzer R, Abrehdary M (2015) On the rock equivalent topography effect in the gravimetric Moho determination. *Journal of Geodynamics* 83: 28-36
6. Bagherbandi M, Bai Y, Sjöberg LE, Abrehdary M, Tenzer R, Miranda S, Sanchez JMA (2017) Effect of the lithospheric thermal state on the Moho interface. *Journal of South American Earth Sciences* 76: 198-207
7. Bao X, Song X, Li J (2015) High-resolution lithospheric structure beneath Mainland China from ambient noise and earthquake surface-wave tomography. *Earth and Planetary Science Letters* 417:132-141
8. Bao X, Sun X, Xu M, Eaton DW, Song X, Wang L, Ding Z, Mi N, Li H, Yu D, Huang Z, Wang P (2015) Two crustal low-velocity channels beneath SE Tibet revealed by joint inversion of Rayleigh wave dispersion and receiver functions. *Earth and Planetary Science Letters* 415:16-24
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10. Baranov A, Tenzer R, Bagherbandi M (2018) Combined gravimetric-seismic crustal model for Antarctica. *Surveys in Geophysics* 39(1): 23-56
11. Barzaghi R, Reguzzoni M, Borghi A, De Gaetani CI, Sampietro D, Marotta A (2015) Global to local Moho estimate based on GOCE geopotential models and local gravity data. *IAG Symposia Series* 142: 275-282
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13. Braitenberg C, Pivetta T, Barbolla DF, Gabrovšek F, Devoti R, Nagy I (2019) Terrain uplift due to natural hydrologic overpressure in karstic conduits. *Scientific Reports* 9(1): 3934
14. Caporali A, Braitenberg C, Montone P, Rossi G, Valensise G, Viganò A, Zurutuza J (2018) A quantitative approach to the loading rate of seismogenic sources in Italy. *Geophysical Journal International* 213(3): 2096-2111
15. Chen W, Braitenberg C, Serpelloni E (2018) Interference of tectonic signals in subsurface hydrologic monitoring through gravity and GPS due to mountain building. *Global and Planetary Change* 167: 148-159
16. Chen W, Tenzer R (2015) Harmonic coefficients of the Earth's Spectral Crustal Model 180 - ESCM180. *Earth Science Informatics* 8(1): 147-159
17. Chen W, Tenzer R, Li H (2018) A regional gravimetric Moho recovery under Tibet using gravitational potential data from a satellite global model. *Studia Geophysica et Geodaetica* 62(4): 624-647
18. Chen W, Tenzer R (2017) Moho modelling in spatial domain: a case study under Tibet *Advances in Space Research* 59(12): 2855-2869
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20. Chen W, Tenzer R (2019) Mantle and sub-lithosphere mantle gravity maps from the LITHO1.0 global lithospheric model. *Surveys in Geophysics* (submitted)
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29. Eshagh M, Tenzer R (2017) Lithospheric stress tensor from gravity and lithospheric structure models. *Pure and Applied Geophysics* 174(7), pp 2677-2688
30. Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24
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36. Li H, Song X, Lü Q, Yang X, Deng Y, Ouyang L, Li J, Li X, Jiang G (2018) seismic imaging of lithosphere structure and upper mantle deformation beneath East-Central China and their tectonic implications. *Journal of Geophysical Research – Solid Earth* 123(4): 2856-2870
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44. Reguzzoni M, Rossi L, Baldoncini M, Callegari I, Poli P, Sampietro D, Strati V, Mantovani F et al. (2019) GIGJ: a crustal gravity model of the Guangdong Province for predicting the geoneutrino signal at the JUNO experiment. *Journal of Geophysical Research – Solid Earth,* doi: 10.1029/2018JB016681.
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53. Tenzer R, Foroughi I (2018) On the applicability of Molodensky's concept of heights in planetary sciences. Special Issue: Gravity field determination and its temporal variation, *Geosciences* 8(7): 239
54. Tenzer R, Chen W, Baranov A, Bagherbandi M (2018) Gravity maps of Antarctic lithospheric structure from remote-sensing and seismic data. *Pure and Applied Geophysics* 175(6): 2181-2203
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61. Tenzer R, Eshagh M, Jin S (2015) Martian sub-crustal stress from gravity and topographic models. *Earth and Planetary Science Letters* 425: 84-92
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65. Tenzer R, Chen W, Ye Z (2015) Empirical model of the gravitational field generated by the oceanic lithosphere *Advances in Space Research* 55(1): 72-82
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71. Xia HH, Song X, Wang T (2016) Extraction of triplicated PKP phases from noise correlations. *Geophysical Journal International* 205(1): 499-508
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78. Wang T, Song X, Xia HH (2015) Equatorial anisotropy in the inner part of Earth's inner core from autocorrelation of earthquake coda. *Nature Geoscience* 8(3): 224-227

4.1 Presentations

Capponi M, Sampietro D, Reguzzoni M (2019) Earth crust regional modelling by Bayesian gravity inversion. Poster presentation at 3D Earth Science Meeting, 12-14 March 2019, Dublin, Ireland.

Mansi AH, Reguzzoni M, Sampietro D (2015) Modelling of subduction plates from GOCE gravity gradients along the satellite orbit. TopoEurope 2015, 4-7 October 2015, Antibes, France.

Marchetti P, Sampietro D, Capponi M, Rossi L, Reguzzoni M, Porzio F, Sansò F (2019) Lithological Constrained Gravity Inversion: A Bayesian Approach. Oral presentation at the 81st EAGE Conference and Exhibition, 3-6 June 2019, London, GB.

Reguzzoni M, Sampietro D (2019) The gravimetric contribution to the Moho estimation. Invited oral presentation at the International Conference: Earth's gravity field and Earth sciences, 22 March 2019, Accademia dei Lincei, Rome, Italy.

Rossi L, Reguzzoni M, Sampietro D (2015) Bayesian gravimetric inversion for local crustal model refinement in the Guangdong province, South China. EGU General Assembly 2015, 12-17 April 2015, Vienna, Austria.

Rossi L, Reguzzoni M, Sampietro D (2015) Guangdong province crustal modelling by applying a Bayesian inversion on a GOCE-based gravity model. TopoEurope 2015, 4-7 October 2015, Antibes, France.

Rossi L, Mansi AH, Reguzzoni M, Sampietro D (2017) Gravity inversion of the Kermadec-Tonga subduction zone by GOCE data and seismic information. EGU General Assembly 2017, 23-28 April 2017, Vienna, Austria.

Rossi L, Reguzzoni M, Baldoncini M, Callegari I, Poli P, Sampietro D, Strati V, Mantovani F (2018) GIGJ: a crustal model of the Guangdong Province using GOCE gravity data for predicting geoneutrinos. Oral presentation at EGU General Assembly 2018, 8-13 April 2018, Vienna, Austria.

Rossi L, Reguzzoni M, Sampietro D (2018) A parallel algorithm for the Bayesian gravity inversion. Poster presentation at the IX Hotine-Marussi Symposium, 18-22 June 2018, Rome, Italy.
Sampietro D, Mansi AH, Rossi L, Reguzzoni M (2016) Combining GOCE gravity gradients and seismic information to model subducting plates. Living Planet Symposium 2016, 9-13 May 2016, Prague, Czech Republic.
Sampietro D, Capponi M (2018) East Mediterranean Sea crustal structure from GOCE-based global gravity data. Poster presentation at MED 2018, 11-12 December 2018, ESA–ESRIN, Frascati, Rome, Italy.
Tenzer R, Zampa L, Eshagh M, Pitoňák M (2018) Origin of Venusian surface deformations from gravity and topographic models. The IX Hotine-Marussi International Symposium on Theoretical and Computational Geodesy, June 18-22, 2018, Rome, Italy (invited)
Tenzer R, Foroughi I, Sjöberg LE, Bagherbandi M, Hirt C, Pitoňák M (2018) Theoretical and practical aspects of defining the heights for planets and moons. Session 7: Theoretical aspects of height system realization, The IX Hotine-Marussi International Symposium on Theoretical and Computational Geodesy, June 18-22, 2018, Rome, Italy
Tenzer R (2018) Lithospheric Structure of West Antarctic Rift Zone. SE28-A055: General Contributions in Solid Earth. Asia Oceania Geosciences Society (AOGS), 15th Annual Meeting, June 3-8, 2018, Honolulu, Hawaii
Tenzer R, Pitoňák M, Foroughi I (2018) Physical Heights for Telluric Planets. PS09-A034: Science and Exploration of Mars and Venus. Asia Oceania Geosciences Society (AOGS), 15th Annual Meeting, June 3-8, 2018, Honolulu, Hawaii
Tenzer R, Foroughi I (2017) Height systems for planets. International Symposium on Planetary Remote Sensing and Mapping, Hong Kong, 13-16 August, 2017
Tondi R, Borghi A, Reguzzoni M, Vuan A, Klin P (2015) Gravity data for a 3-D density model of the Po plain and the surrounding region. EGU General Assembly 2015, 12-17 April 2015, Vienna, Austria.

Joint Study Group 0.17: Multi-GNSS theory and algorithms

Chair: *Amir Khodabandeh (Australia)*
Affiliation: *Commissions 1, 4 and GGOS*

Members

Peter J.G. Teunissen (Australia)
Pawel Wielgosz (Poland)
Bofeng Li (China)
Simon Banville (Canada)
Nobuaki Kubo (Japan)
Ali Reza Amiri-Simkooei (Iran)
Gabriele Giorgi (Germany)
Thalia Nikolaidou (Canada)
Robert Odolinski (New Zealand)

1. Activities

1.1 Summary

This report presents an overview of activities undertaken towards the objectives of the JSG 0.17 since 2015. The aim of the study group is to identify and investigate challenges posed by processing/integrating data of the next generation satellite navigation systems, developing optimal methods capable of multi-GNSS data processing, thereby articulating new algorithms and findings through journals, conferences and group discussions.

We had a group discussion on the inter-system-biases (ISBs). The ISBs pop up in the multi-GNSS measurement setup, because the receiver instrumental delays are experienced in a way that is 'different' from system to system (the term 'system' refers to a satellite constellation). The members were invited to give their opinions about 1) significance, 2) estimation and 3) outlook of the ISBs for multi-GNSS positioning and non-positioning applications. A few members contributed to the discussion and provided their feedback. A summary is given as follows. A conservative way of dealing with the ISBs is to treat them as unknown and estimate them on the fly, often without any temporal constraints. Although this approach leads to a slightly weaker solution, but then one does not have to worry about any unit-specific bias that would not be properly accounted for by calibration values or by possible intra-day variations due to, e.g., temperature changes. In this perspective, the benefits of calibrating ISBs and the potential applications are limited to controlled environments where equipment (receiver type and firmware version) are well defined. On the other hand, there are methods that offer ISBs calibration. In particular, for networks of a large number of receivers, a-priori ISBs calibration enables one to take a common pivot satellite among multiple systems, thus considerably increasing the GNSS network model's redundancy. The outlook would be that as part of the IGS analysis centers' work, all receiver manufacturers will be aligned to employ the same standards, presenting receiver instrumental delays with no ISBs. Several scenarios on properly handling the ISB parameters in the GNSS network models are presented in (Khodabandeh and Teunissen 2016a).

1.2 Research

<u>Undifferenced, uncombined multi-frequency formulation</u>: Most of the current methods for GNSS data processing are based on forming combined observations (e.g., ionosphere-free, wide-lane and Melbourne-Wubbena combinations). These methods are therefore restrictive in the light of the development of new multi-frequency GNSS constellations. Odijk et al. (2015)

presented an undifferenced, uncombined multi-frequency formulation of the GNSS observation equations and showed how one should interpret *estimable* forms of the GNSS parameters. They further applied their method to integer ambiguity resolution-enabled precise point positioning (PPP-RTK) and presented the positioning performance improvements that can be expected by multi-GNSS PPP-RTK setup. Further results on mutli-GNSS positioning are provided in (Odolinski and Khodabandeh 2016). As to the non-positioning applications, Khodabandeh and Teunissen (2016b) applied the method to the GNSS array model and analysed the estimability and precision of multi-frequency GNSS-derived slant Total Electron Content (TEC), showing that the variance of the TEC solutions follows the 1-over-n (1-over-f) rule and decreases the more the number of antennas/frequencies (n: number of array antennas, f: number of frequencies).

The advent of multi-GNSS mass-market receivers: A vast number of low-cost receivers, tracking satellites of multiple systems, have entered the market. Odolinski and Teunissen (2017a, b) showed, in contrast to their single-GNSS counterparts, that these receivers can offer high-precision positioning if one rigorously integrates their multi-GNSS data, see also the smartphone implementation of such receivers (Odolinski and Teunissen 2018).

The triple-frequency BeiDou signals: Following the study on the stochastic model of triple-frequency BeiDou signals (Li 2016), (Li et al. 2017) investigated the RTK performance of the extra-wide-lane observations available through the BeiDou triple frequencies. Given fast successful ambiguity resolution, the extra-wide-lane observations were shown to provide RTK solutions with a horizontal accuracy of 10 cm.

GLONASS FDMA signals: Banville (2016) presented a strategy for long-baseline ambiguity resolution applicable to the GLONASS L1/L2 FDMA signals. Benefiting from the frequency-spacing of the signals, ionosphere-free ambiguities were defined, improving the repeatability of static PPP solutions by more than 20 %, see also (Banville et al. 2018).

GLONASS CDMA signals: Zaminpardaz et al. (2017) presented world-first results of the GLONASS L3 signals. They studied the noise characteristics, the integer ambiguity resolution performance, and the positioning performance. In particular, the GLONASS data were shown to have a lower noise level than that of GPS, particularly in case of the code data.

Integrity monitoring: Teunissen (2017) presented a new distributional theory for the combination of testing and estimation with applications to GNSS integrity, see also (Imparato et al. 2018) and (Zaminpardaz et al. 2018 and 2019).

Distributed estimation and filtering for GNSS: Khodabandeh et al. (2018) applied a consensus-based distributed Kalman filter to a network of GNSS receivers. It was shown how single-receiver, but collaborative, GNSS users can achieve high-precision solutions without the need of relying on centralized computing centers, see (Khodabandeh and Teunissen 2019).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi) at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.

1.4 Editorial activity

- Guest editors of Special issue (2019) in Journal of Spatial Science of “Multi-GNSS processing, positioning and applications”, open for submissions until 1 May (R. Odolinski, P.J.G. Teunissen, B. Zhang).

2. Future prospects

Integration of multiple navigation satellite systems (multi-GNSS) will be a vital part of low-cost GNSS RTK receivers. Morevover, design and development of low-cost antennas, mitigating the impact of multipath, would benefit low-cost multi-GNSS receivers.

The following areas need addressing in the coming period:

- GNSS integrity: development of proper theory as current theory is still not adequate.
- Mass-market dense networks: with the combination of multi-GNSS (=lot of satellites) and low-cost receivers (=having many receivers becomes affordable) real advantage should be taken of the much denser sampling of the atmosphere.
- Computational efficiency of estimation and testing: with the huge increase of GNSS data real challenges exits to perform rigorous testing and estimation efficiently.
- Determination of the stochastic model of low-cost multi-frequency and multi-GNSS equipment. This includes estimation of temporal-and cross-correlation of multi-GNSS measurements as well as other probabilistic parameters like measumement distributions.
- Characterization of the inter-system, inter-/intra-frequency biases and inter-satellite-type-biases for low-cost mass-market receivers.

3. Selected publications

1. Banville S, Collins P, Lahaye F (2018) Model comparison for GLONASS RTK with low-cost receivers. *GPS Solution* 22: 52, https://doi.org/10.1007/s10291-018-0712-3.
2. Laurichesse D, Banville S (2018) Instantaneous centimeter-level multi-frequency precise point positioning. *GPS World*, July 2018.
3. Banville S (2016) GLONASS ionosphere-free ambiguity resolution for precise point positioning. *Journal of Geodesy* 90: 487; doi:10.1007/s00190-016-0888-7.
4. Giorgi G (2016) Attitude determination. In: *Encyclopedia of Geodesy*. Edited by EW Grafarend, Earth Sciences Series, Springer; doi: 10.1007/978-3-319-02370-0_2-1.
5. Imparato D, Teunissen PJG, Tiberius CCJM (2018) Minimal detectable and identifiable biases for quality control. *Survey Review*. https://doi.org/10.1080/00396265.2018.1437947
6. Khodabandeh A, Teunissen PJG (2019) Distributed least-squares estimation applied to GNSS networks (*invited paper*), Measurement Science and Technology, Special issue of *High-Precision Multi-Constellation GNSS: Methods, Selected Applications and Challenges* (Editors: J. Paziewski and M. Crespi); doi: https://doi.org/10.1088/1361-6501/ab034e.
7. Khodabandeh A, Teunissen PJG, Zaminpardaz A (2018) Consensus-based distributed filtering for GNSS. Chapter in *Kalman Filters-Theory for Advanced Applications*, 273-304; doi: 10.5772/intechopen.71138
8. Khodabandeh A, Teunissen PJG (2016a) PPP-RTK and inter-system biases: the ISB look-up table as a means to support multi-system PPP-RTK. *Journal of Geodesy* 90(9): 837-851
9. Khodabandeh A, Teunissen PJG (2016b) Array-aided multifrequency GNSS ionospheric sensing: estimability and precision analysis. *IEEE Transactions on Geoscience and Remote Sensing* 54(10): 5895–5913
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11. Li B, Zhang L, Verhagen S (2016) Impacts of BeiDou stochastic model on reliability: overall test, w-test and minimal detectable bias. *GPS Solutions*; doi: 10.1007/s10291-016-0596-z.
12. Li H, Li B, Lou L, Yang L, Wang J (2016) Impact of GPS differential code bias in dual- and triple-frequency positioning and satellite clock estimation. *GPS Solutions*; doi: 10.1007/s10291-016-0578-1.
13. Li B (2016) Stochastic modeling of triple-frequency BeiDou signals: estimation, assessment and impact analysis. *Journal of Geodesy* 90: 593-610
14. Nardo A, Li B, Teunissen PJG (2016) Partial ambiguity resolution for ground and space-based applications in a multi-GNSS scenario: a simulation study. *Advances in Space Research* 57(1): 30-45
15. Li B, Feng Y, Gao W, Li Z (2015) Real-time kinematic positioning over long baselines using triple-frequency BeiDou signals. *IEEE Transactions on Aerospace and Electronic Systems* 51(4): 3254-3269
16. Odijk D, Khodabandeh A, Nadarajah N, Choudhury M, Zhang B, Li W, Teunissen PJG (2016) PPP-RTK by means of S-system theory: Australian network and user demonstration, *Journal of Spatial Science*; doi:10.1080/14498596.2016.1261373

17. Odijk D, Zhang B, Khodabandeh A, Odolinski R, Teunissen PJG (2015) On the estimability of parameters in undifferenced, uncombined GNSS network and PPP-RTK user models by means of S-system theory. *Journal of Geodesy* 90(1): 15-44
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Joint Study Group 0.18: High resolution harmonic analysis and synthesis of potential fields

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1. Activities

1.1 Summary

The gravitational fields of the Earth and other celestial bodies in the Solar System are customarily represented by a series of spherical, spheroidal or ellipsoidal harmonic coefficients. The maximum degree and order (d/o) of harmonic series of the Earth's gravitational potential has risen steadily over the past decades. This has posed and continues to pose both theoretical and practical challenges for the geodetic community. Members of this study group have achieved progress on several of these challenges.

The computation of associated Legendre functions (ALFs) of the first kind, which are required for spherical harmonic analysis and synthesis, has traditionally been subject to numerical instabilities and underflow/overflow problems. These problems have successfully been solved, and efficient, stable and accurate computation of ALFs of extremely high d/o is now possible thanks to new algorithms. Progress has also been made on spherical harmonic analysis given a number of different functionals on various surfaces. Software for ultra-high degree harmonic analysis and synthesis has been developed and made publicly available.

Ultra-high degree models (up to d/o ~46,000) of topography and its constituents and of topographic potential have been generated using improved techniques. This shows a clear advance over earlier models, and it has led to new insights. One example is the improved understanding of the correlation between gravitational and topographic potential at small spatial scales.

The divergence of harmonic series inside the Brillouin surface has been shown to be a significant challenge for ultra-high degree harmonic models. For example, traditional spherical harmonic series of the Earth's gravitational potential start to diverge at the Earth's surface at degrees that are now achievable, and for other celestial bodies divergence has been observed at much lower degrees. Some advances have been made on dealing with this challenge, but further research is required.

1.2 Research

Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis

- Algorithms for precise and stable computation of associated Legendre functions of the first and second kind (or ratios thereof), plus its derivatives and integrals [10, 12, 13, 14 and 18].
- Software development for ultra-high degree surface harmonic analysis and synthesis [6] [13, 14, 28 and 29].
- Algorithms for harmonic analysis using input data of various types and on various surfaces [8, 9, 11, 19, 25, 35 and 36].

Convergence vs divergence in spherical and spheroidal harmonic series

- Convergence/divergence of spherical harmonic synthesis on the Earth's surface [21].
- Divergence effect and amplified omission errors on the Moon and other celestial bodies [5, 23 and 26].

High-resolution spherical and spheroidal models and degree variance models

- High-resolution harmonic models of topography and its constituents [20 and 29].
- High-resolution harmonic models of topographic or topographic-isostatic potential fields and their computation [1, 2, 3, 15, 16, 17, 31, 32 and 33].
- High-resolution harmonic models of the global or local gravitational potential field [4, 22 and 30].

Applications of high-resolution harmonic models

- Computation of spherical harmonic Bouguer gravity anomalies [21].
- Correlation between gravitational and topographic potential [24].
- The spectral filter problem in residual terrain modelling [34].

1.3 Sessions organisation at international congresses/symposia/workshops

- Organisation of the session *Global gravity modelling and height systems (D. Tsoulis, S. Claessens)* at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.
- Organisation of the session *Theory and methods of potential fields (D. Tsoulis, S. Claessens, M. Fedi)* at the IUGG General Assembly (Montreal, Canada) in 2019.

1.4 Technology transfer and relevant applications in science and engineering

- High-resolution harmonic models of the gravitational and topographic potential fields of the Earth and other celestial bodies are made available via the website of the International Centre for Global Earth Models (ICGEM) (http://icgem.gfz-potsdam.de/tom_reltopo).
- Software for high-degree harmonic analysis and synthesis has been developed and made available. This includes updates to the MATLAB-based GrafLab and isGrafLab software for spherical harmonic synthesis, new MATLAB-based code for ultra-high degree surface spherical harmonic analysis (http://edisk.cvt.stuba.sk/~xbuchab/) [6], an extension to the open-source SHTools software for use to ultra-high degree (https://www.researchgate.net/publication/291102839_ultra_high_degree_extension_v1_SHTOOLS) [29], development of routines for efficient computation of ultra-high degree associated Legendre functions [13 and 14].

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 2

- SC 2.2: Methodology for Geoid and Physical Height Systems – Chair J. Ågren (Sweden)

GGOS

- Focus Area Unified Height Systems – Chair: Laura Sánchez (Germany)

3. Future prospects

3.1 Research

Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis

- Study efficient methods for ultra-high degree and order harmonic analysis and synthesis for all potential quantities of interest on regular and irregular boundary surfaces.
- Comparison between least-squares and quadrature approaches to ultra-high d/o spherical and spheroidal harmonic analysis.
- Continued development of software for ultra-high degree surface harmonic analysis and synthesis, including inter-comparison between different software packages.

Convergence vs divergence in spherical and spheroidal harmonic series

- Comparison of traditional and Runge-Krarup-type spherical and spheroidal harmonic series on the surface of the Earth and other celestial bodies.

High-resolution spherical and spheroidal models and degree variance models.

- Continued algorithm improvement for computation of high-resolution harmonic models of topography and its constituents, topographic or topographic-isostatic potential fields, and gravitational potential fields based on the latest input data.

3.2 Technology transfer and relevant applications in science and engineering

- Aim to have all ultra-high degree harmonic models made available in one location.
- Provide a repository for freely accessible software for high-degree harmonic analysis and synthesis.

4. Publications

1. Abd-Elmotaal H, Kühtreiber N (2015) On the computation of the ultra-high harmonic coefficients of the topographic-isostatic masses within the data window. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 12-17
2. Abd-Elmotaal H, Kühtreiber N (2019) Alternative approach for the determination of the austrian gravimetric geoid. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 7-12
3. Abd-Elmotaal H, Kühtreiber N (2019) One-step rigorous algorithm for the harmonic analysis of topographic-isostatic masses on the ellipsoid with bench-marking approach. *Survey Review* (in press).
4. Bucha B, Janák J, Papčo J, Bezděk A (2016) High-resolution regional gravity field modelling in a mountainous area from terrestrial gravity data. *Geophysical Journal International* 207: 949-966
5. 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
6. Bucha B, Hirt C, Kuhn M (2019) Cap integration in spectral gravity forward modelling: near- and far-zone gravity effects via Molodensky's truncation coefficients. *Journal of Geodesy,* 93: 65-83
7. Bucha B, Hirt C, Kuhn M (submitted) Cap integration in spectral gravity forward modelling up to the full gravity tensor. *Journal of Geodesy*.
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9. Claessens SJ, (2016) Spherical harmonic analysis of a harmonic function given on a spheroid. *Geophysical Journal International* 2016(1): 142-151

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13. Fukushima T (2018) Transformation from surface spherical harmonic expansion of arbitrary high degree and order to double Fourier series on sphere. *Journal of Geodesy* 92(2): 123-130
14. Fukushima T (2018) Fast computation of sine/cosine series coefficients of associated Legendre function of arbitrary high degree and order. *Journal of Geodetic Science* 8(1): 162-173.
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16. Grombein T, Seitz K, Heck B (2017) On high-frequency topography-implied gravity signals for height system unification using GOCE-based global geopotential models. *Surveys in Geophysics* 38(2): 443-477
17. Grombein T (2017) Gravity forward modelling with a tesseroid-based Rock-Water-Ice approach – theory and applications in the context of the GOCE mission and height system unification. PhD thesis, Schriftenreihe des Studiengangs Geodäsie und Geoinformatik, Karlsruhe Institute of Technology (KIT), KIT Scientific Publishing, Karlsruhe, Germany
18. Gruber C, Abrykosov O (2016) On computation and use of Fourier coefficients for associated Legendre Functions. *Journal of Geodesy* 90: 525-535
19. Hamáčková E, Šprlák M, Pitoňák M, Novák P (2016) Non-singular expressions for the spherical harmonic synthesis of gravitational curvatures in a local north-oriented reference frame. *Computers and Geosciences* 88: 152-162
20. Hirt C, Rexer M (2015) Earth2014: 1 arc-min shape, topography, bedrock and ice-sheet models – available as gridded data and degree-10,800 spherical harmonics. *International Journal of Applied Earth Observation and Geoinformation* 39: 103-112
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Joint Study Group JSG 0.19: Time series analysis in geodesy

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1. Activities

1.1 Summary

Different deterministic and stochastic time series analysis methods were used to analyze geodetic time series such as Earth Orientation Parameters (EOP) and their fluid excitation functions, permanent station positions, geocenter coordinates, altimetric sea level anomaly (SLA) data and troposhperic parameters. Special emphasis has been placed on detection of non-linear motion and noise character in GNSS station positions time series in order to determine of their reliable velocities. In some papers the spatio-temporal filtering of GNSS station position time series has been proposed to examined common seasonal time-varying signals as well as the impact of environmental loadings on these station position time series has been taken into account. In same papers different EOP forecast methods are discussed.

1.2 Research

The combination of the Fourier Transform Band Pass Filter with the Hilbert transform (FTBPF+HT) was applied to compute variable amplitudes and phases of seasonal and subseasonal oscillations in altimetric SLA data (Kosek et al. 2015a). Normalized Morlet wavelet transform (NMWT) of the differences between pole coordinates data and their predictions computed by combination of the least-squares and autoregressive (AR) forecasts revealed residual prograde Chandler and annual oscillations (Brzezinski et al. 2016). The wavelet based semblance filtering (Kosek et al. 2015b) and the FTBPF+HT methods were used to detect systematic errors in geocenter coordinates determined from GNSS, SLR, DORIS, and GRACE (Kosek et al. 2019).

The problem of least squares function fitting using the orthogonal system of trigonometric functions for the observation model comprising complex-valued deterministic function observations in equidistant time moments was considered by Popiński (2016), where the observed function values are corrupted by multiplicative errors in amplitude and phase as well as additive noise. Theoretical and numerical aspects of adaptive decomposition of square integrable band-limited functions into a finite number of additive components using the FTBPF concept was investigated by Popiński (2018).

The Prognocean Plus system has been developed to predict altimetric SLA data in real time using three deterministic-stochastic data-based models and the results were compared with the MyOcean system and the previous version of Prognocean (Świerczyńska et al. 2016). To modelling long-term sea level variation due to changes of ocean floor the new method for reconstructing the ocean depth-age curve has been proposed with comparable accuracy to already existing models (Niedzielski et al. 2016) and the novel approach to estimate the reference ocean depth has been developed (Jurecka et al. 2016). The overview of different prediction methods in marine studies has been published by Niedzielski (2017).

The short-term 5-hour forecasts of Zenith Total Delay (ZTD) time series were computed by the AR and autoregressive moving average (ARMA) models to provide fully operational service for real-time PPP (Precise Point Positioning) (Wilgan 2015).

Analyses of seasonal signals in the GNSS coordinate time series using the iterative Least Squares Estimation approach (iLSE) together with estimation of correlation between these coordinates and deformations of the Earth's crust have been presented by Kaczmarek and Kontny (2018a). The methods of identifying the noise model in the GNSS station coordinates time series using Continuous Wavelet Transform (CWT) coefficients for signal reconstruction and the least squares estimation signal for annual and semi-annual period revealed flicker noise in these series (Kaczmarek and Kontny 2018b).

A non-parametric wavelet decomposition was employed to investigate the non-linear motion of GNSS stations (Bogusz 2015). The velocities with associated uncertainties of GPS position time series of 115 European stations were estimated by noise analysis to include the power-law dependencies in uncertainties' estimates and it showed that these time series are characterized by the power-law noise close to flicker noise with amplitudes reaching 20 mm/yr-κ/4 at maximum (Klos and Bogusz 2017). Rescaled-range method with Hurst exponent and detrended fluctuation analysis were used to analyze 130 Polish GPS position time series and results proved that there is a clear dependence between consecutive values of GPS residuals, indicating a power-law noise presence (Bogusz et al. 2016a). Similarly, to the daily GPS position time series (Klos et al. 2016a), the weekly-sampled data are characterized by power-law noise, shown by Klos et al. (2015); however, due to their sparser sampling, the amplitudes of weekly observations are smaller than for the daily time series. The impact that the pre-analysis has on the noise estimates, has been demonstrated by Klos et al. (2016b) for the outliers. The authors focused on various methods to identify and remove values outlying from others, followed by noise analysis and they concluded that the outliers have to be identified and removed to provide the best estimates of noise character. Bogusz et al. (2016b) described the methodology of reliable determination of the velocities of permanent GNSS stations. They showed, that proper treatment of either deterministic or stochastic part of the position time series will lead to the most reliable velocities along with their uncertainties. Klos et al. (2018e) provided a General Dilution of Precision (GDP) estimates, being the ratio of two uncertainties of velocities. Both uncertainties are determined from two different deterministic models while accounting for stochastic noise at the same time. The authors proved that adding more and more seasonal terms to the series, we increase the bias of the velocity uncertainties. They estimated that 9 and 17 years of continuous daily observations is needed for, respectively, flicker and random-walk noise to make the GDP decrease below 5%. Klos et al. (2018a) focused on the estimates of noise character in DORIS position time series and it was noticed, that this character changed thorough years from autoregressive process into pure power-law noise, with the quality of data significantly improved. Bogusz and Klos

(2016) analyzed another part of the functional model of the GNSS position time series. Seasonal signatures were modelled using tropical, Chandler, and draconitic periods, all from 1st to 9th harmonics. This approach was compared to the frequently employed assumptions that the tropical signal is modelled using annual and semi-annual-only curves. It was stated that the new approach helps to improve the velocity uncertainty of 56% at maximum. Bogusz et al. (2015a) applied the wavelet decomposition using Meyer's symmetric wavelet to reliably describe the changes in seasonal amplitudes in 3D GNSS position times series derived by the JPL. Gruszczynska et al. (2016, 2018) proposed to use the Singular Spectrum Analysis (SSA) with its multivariate variant (MSSA) to described this year-to-year variability. Gruszczynska et al. (2017) examined common seasonal time-varying signal for a set of European stations using Multichannel Singular Spectrum Analysis (MSSA) and proved that common seasonal curves are better-fitted to the original series than the Least-Squares estimates and the MSSA approach leads to no reduction in the time series power, which constitutes another advantage of this methodology. Klos et al. (2018c) proposed a two-stage method to subtract the impact of the environmental (atmosphere, non-tidal part of ocean changes and terrestrial hydrosphere) loadings on the GNSS position time series. They proved, that previous attempts to reliably remove loading impact failed by changing the stochastic part significantly along with uncertainties of the permanent station velocity. Application of the Improved SSA (ISSA) solved this problem, which was demonstrated on the vertical position changes of 376 permanent IGS stations, derived as the official contribution to International Terrestrial Reference Frame (ITRF2014). Klos et al. (2018b) noticed that wavelet decomposition, Chebyshev polynomials, SSA or Kalman filtering, do all influence the stochastic part of the GNSS position time series, once the seasonal part was modelled and removed, i.e. the stochastic part of seasonal signal is also removed. This will falsify the results of the noise analysis, and also, the velocity estimates and their uncertainties. Klos et al. (2019) introduced new methodology named as the Adaptive Wiener Filter (AWF) to estimate the time-varying seasonal signals including the character of the original time series. The AWF has been confronted with the commonly employed Kalman Filter, Singular Spectrum Analysis, Wavelet Decomposition and Least-Squares methods, demonstrating that it provides the accurate estimates for time-varying seasonalities, leaving the noise character intact. Bogusz et al. (2015b) used a 5-year daily GPS position time series time series (2008-2012) in the ITRF2008 processed at the Military University of Technology to evaluate the Common-Mode Error (CME), defined as the superposition of the technique-dependent and environmental systematic errors present in the them. Gruszczynski et al. (2016) proposed to use orthogonal transformation to subtract CME. They studied the Principal Component Analysis (PCA) with the existence of a non-uniform spatial response in the network to the CME being assumed. They found an improvement (by means of better credibility) of accuracy of the determined velocity being accompanied by the spatio-temporal filtering of position time series. Gruszczynski et al. (2018) introduced the probabilistic PCA (pPCA) which allows the spatio-temporal filtering to estimate and subtract the CME, with no need to interpolate the missing values. The efficiency of the proposed algorithm was firstly tested on the simulated incomplete time series, then the CME was estimated for a set of 25 permanent stations situated in central Europe. They found, that more than 36% of the total variance represented by the time series residuals can be explained by the 1st Principal Component (PC). Since the other PCs variances turned out to be less than 8%, they concluded that that common signals stored in the 1st PC are significant in GNSS residuals. The Zenith Wet Delay (ZWD) tropospheric series character examined by Klos et al. (2018d). showed that the first-order autoregressive noise process combined along with white noise is preferred over the widely employed white-noise-only approach and it was found that the ZWD trend uncertainty is largely underestimated (by 5–14 times) using the white-noise-only assumption.

A summary of research activities concerning theoretical geodesy performed during 2011-2014 and 2015-2019 in Poland were presented by Borkowski and Kosek (2015) and Borkowski et al. (2019), respectively.

Hourly time series of Earth rotation parameters from VLBI observations in a single-session strategy were determined. Then, the S1 (period of 24h) amplitudes for these time series were determined. First, the sine- and cosine-amplitudes were fitted with a classical least-squares approach, and, as an alternative approach, the so-called "stacked" day was generated, which was then used to derive the amplitudes (Girdiuk et al. 2016).

Estimation of the free core nutation (FCN) period is a challenging prospect, due to the non-stationary characteristics of celestial pole offsets (CPO). Instead of the direct Fourier Transform (FT) approach, the FCN period is estimated by another direct method, i.e, the sliding-window complex least-squares fit method (SCLF). The estimated uncertainty of the FCN period falls from several tens of days to several days from the FT to the SCLF method, which suggests that the SCLF method may serve as an independent direct way to estimate the FCN period (Zhou et al. 2016).

The study (Xu and Zhou 2015) firstly employs the calculation of base sequence with different length, in 1–90 day predictions of EOP, by the combined method of least squares and autoregressive model, and find the base sequence with best result for different prediction spans, which we call as "predictions over optimized data intervals". Compared to the EOP predictions with fixed base data intervals, the "predictions over optimized data intervals" performs better for the EOP prediction, and particularly promotes our competitive level in the international activity of EOP Combination of Prediction Pilot Project.

Artificial neural networks and fuzzy inference systems to predict the polar motion starting from daily to up to 1 year in future were applied. Such methods are capable to learn the nonlinear behaviour of the polar motion and use it successfully for prediction (Kucak et al. 2016).

Wu et al. (2015) used a Kalman filter to determine terrestrial reference frames from time series of the positions of stations in geodetic networks, the associated EOPs, and ground survey measurements.

Least-squares model of the deformation of the sea floor caused by an earthquake was fitted to the time series of GPS site displacement and oceanic tsunami measurements (Fu et al. 2017).

The period and Q of the Chandler wobble are estimated by finding those values that minimize the power in the Chandler frequency band of the difference between observed and modeled polar motion excitation functions. The observations of the polar motion excitation functions that we used are derived from both space-geodetic polar motion observations and from satellite laser ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations of the degree-2 coefficients of the Earth's time-varying gravitational field (Nastula and Gross 2015).

The problem of detecting discontinuities is fundamental for reliably estimating velocities from GNSS station position time series. Discontinuities may be related to equipment changes, earthquakes or ununderstood causes. In Gazeaux et al. (2015), GNSS position time series of a group of nearby stations are automatically assessed for discontinuity detection using an advanced mathematic method based on dynamic programming. It allows simultaneously estimating station-specific trends, seasonal signals and a common ground motion signal between all series as well as individual offsets in all time series. Bertin et al. (2017) have worked on a similar model but by investigating offsets at a station by station basis. A dictionary of function has been proposed to model station displacements as well as station discontinuities.

The time-variable Earth gravity field harmonics from the GRACE satellite mission are used to determine seasonal and nonseasonal scales of polar motion excitation functions from global geophysical fluids, and particularly from the portion from land-based hydrology. Hydrological excitation functions of polar motion from the mass of equivalent water thicknesses (EWT) derived gravimetrically from the solutions of three GRACE processing centers, the Center for Space Research (CSR), JPL and the GeoforschungsZentrum (GFZ), are intercompared. Additionally, we estimate the hydrological signal as well in a different manner, as a residual from geodetically observed polar motion, by subtracting atmospheric (pressure + wind) and oceanic (bottom pressure + currents) contributions (Nastula et al. 2016).

In the paper by Van Camp et al. (2016a) we revealed from continuous gravity measurements the evapotranspiration of a forested ecosystem at the mesoscale (~50 ha), by stacking hourly values. In the paper by Van Camp et al. (2016b) we showed that 7 calibrations of a superconducting gravimeter (SG) using an absolute gravimeter (each during a few day) are needed to ensure calibration of the SG at the 1 per mille level with 99% confidence. This was achieved through LSQ analysis and bootstrapping. The attenuation bias is discussed as well (case of noisy x and y time series in the LSQ process). Van Camp et al. (2016c) using Allan deviation analysed the signature of climate-induced interannual mass transfers on repeated absolute gravity measurements, everywhere in the world.

Meurers et al. (2016) revealed statistically significant temporal variations of M2 tidal parameters. This requires performing tidal analysis, which consist in LSQ adjustment of observed tides vs. predicted ones by ephemeris.

At JPL a sequential estimation approach to determining terrestrial and celestial reference frames using either a Kalman filter or a square-root information filter were developed (Abbondanza et al. 2017, 2019, Soja et al. 2018a,b, Wu et al. 2015). Three-corner hat method was applied to estimate uncertainties of station position measurements (Abbondanza et al. 2015). A Kalman filter was developed to smooth and predict celestial pole offsets (Nastula et al. 2019).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session Multi-sensor and time series data analysis (W. Kosek, K. Sosnica) at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.
- 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 2015, 2016, 2017, 2018 and 2019 in Vienna, Austria.

2. Cooperation/Interactions with IAG Commissions and GGOS (500 characters)

Commission 3

- SC 3.1: Earth Tides and Geodynamics – Chair: J. Bogusz (Poland),
- SC 3.3: Earth Rotation and Geophysical Fluids – Chair: J. Chen (USA)

Commission 4

- SC 4.3: Atmosphere Remote Sensing – Chair: Michael Schmidt (Germany)

3. Future prospects

3.1 Research

Permanent station position problems

- Detection of reliable station velocities and their uncertainties with taking into account their non-linear motion and environmental loadings.

- Application of different spatio-temporal methods to identify clusters with similar velocities of permanent station coordinates.

Earth Orientation Parameters
- Better short term prediction using the fluid excitation functions.

Sea level anomalies
- Optimal filtering and prediction for climate variability research.

Troposphere and Ionosphere parameters
- Deterministic and stochastic modelling and prediction for real time applications, e.g., precise GNSS positioning.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on time series analysis in geodesy at the *X Hotine-Marussi Symposium* in 2022.
- 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.

3.3 Editorial activity

- JSG publications: review papers on time series analysis in geodesy co-authored by the JSG 0.19 Members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography in time series analysis in geodesy.

4. Publications

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Joint Study Group 0.20: Space Weather and Ionosphere

Chair: *Klaus Börger (Germany)*
Affiliation: *Commissions 1, 4 and GGOS*

Members
Jens Agena (Germany)
Andreas Goss (Germany)
Johannes Hinrichs (Germany)
Anno Löcher (Germany)
Niclas Mrotzek (Germany)
Michael Schmidt (Germany)
Kristin Vielberg (Germany)

1. Activities

1.1 Summary

The principal goal of the Joint Study Group 0.20 was to investigate effects of an extreme and severe space weather event – referred to as Carrington event – on geodetic techniques or, in an extended view, on technical systems and applications such as navigation, satellites, communication and so on. In detail, we specified six tasks, i.e. to analyse (1) the impact of an extreme solar event on satellite motion, (2) the impact of an extreme solar event on GNSS (especially navigation), (3) the impact of an extreme solar event on signal propagation w.r.t. communication-techniques, (4) the impact of an extreme solar event on re-entry computations, (5) the impact of an extreme solar event on the life-time of space debris and (6) the impact of an extreme solar event on the International Space Station (ISS).

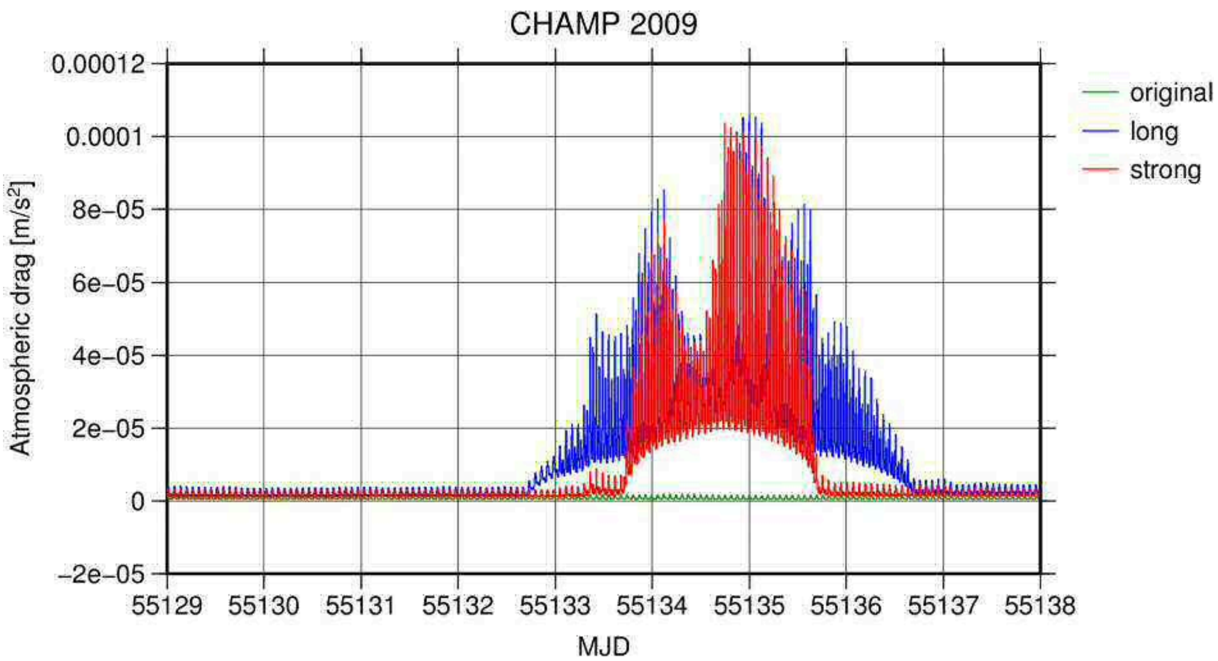

Figure 1: Simulated atmospheric drag for a LEO-satellite (called CHAMP) at 300 km altitude.

1.2 Achieved results

At the very beginning, the Joint Study Group designed and agreed upon a **work program**. This work program describes all necessary steps, the relations between the single work packages, a responsible person for the respective milestones and a time schedule. Afterwards, the program was to put into practice. We installed a **website** to provide information to interested people and – being more important – to serve as a platform for an internal exchange of news as well as of data and results.

Members of the Joint Study Group firstly worked on the **characterization of a superstorm**. At a first glance, this seems to be an easy matter, but it is far from trivial, since we had to consider very complex relationships. Therefore, a thorough analysis of previous (extreme) solar events was necessary to find regularities and to transfer a Carrington-event in our time. Eventually we took the Halloween-event of 2003 as a template and then we mainly introduced two changes. We amplified the storm and additionally we extended storm-duration. Further, we did not only consider the year 2003, but we moved the event also into the year 2009, being a period of low solar activity.

Finally, we had three different types of data for two different years, in each case denoted as ORIGINAL, STRONG and LONG. In terms of content, the simulation affects Kp-values, the F10.7 radio flux – both provided in standard formats, which is WDC for the Kp-value and which is FLUXTABLE.TXT for F10.7 – and the ionosphere. Concerning the latter, it is quite difficult to model an ionosphere that matches the situation described by the specified Kp-values and the specified values for the F10.7 radio flux. We put a lot of work into the principal component analysis (PCA) of the ionosphere, but in the end, the results were not satisfactory. For example, the correlations between the principal components and the time series of the physical parameters (Kp, F10.7 and others) were too weak, and in general, the percentages of the modes were too low.

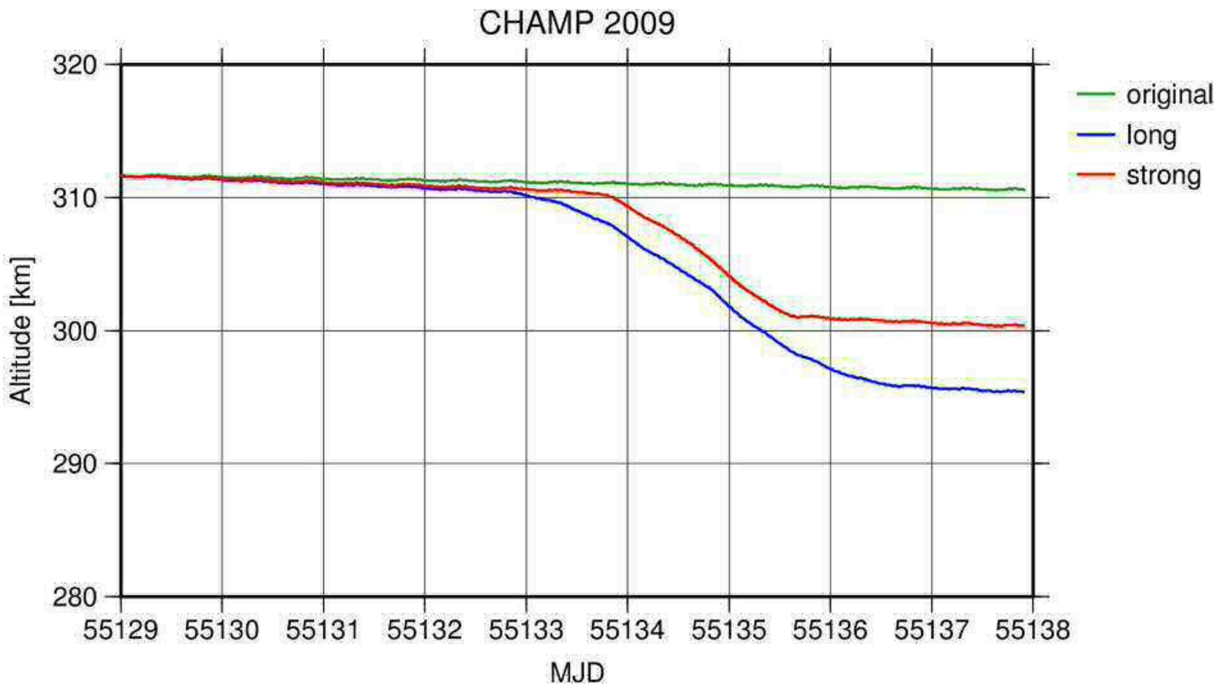

Figure 2: Loss of altitude of a LEO-satellite (called CHAMP).

As mentioned in the introduction, the Joint Study Group investigated different **effects of a solar superstorm**. The influence on satellite motion is particularly spectacular and shortly presented in the following for the year 2009. We used the corresponding simulation data and evaluated atmospheric drag, shown in Fig. 1, for a LEO-satellite (called CHAMP) at an altitude of about 300 km. The rising of the force is extraordinary, i.e. about two orders of magnitude, and it causes an enormous orbital decay, shown in Fig. 2. The decay is 12 km for the STRONG-variant and 17 km for the LONG-variant. The decay rate for both is 5 km per day. We made the same computations for the ISS, revealing a dramatic loss of altitude, which is about 30 km. Overall, the studies of the Joint Study Group 0.20 show in terms of amount, that a solar superstorm would have significant effects on space debris, the ISS, satellite motion and satellite orientation.

1.3 Final remarks

The Joint Study Group has done important and valuable work on space weather research. All findings were presented at the Hotine-Marussi Symposium 2018 in Rome. Concerning the ionosphere, further research has to be done to analyse spatial structures and the temporal behaviour. Then, the outcome can be used to model an ionospheric superstorm.

Joint Study Group 0.21: Geophysical modelling of time variations in deformation and gravity

Chair: *Yoshiyuki Tanaka (Japan)*
Affiliation: *Commissions 2 and 3*

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1. Activities

1.1 Summary

Improving observational accuracy of the GNSS and the GRACE has promoted our understanding of regional to global scale surface crustal deformations and mass redistributions associated with atmosphere, ocean, ice sheets, continental water and great earthqukes. In addition to those observations, InSAR and terrestrial gravity measurements have allowed us to elucidate local deformations due to earthquakes, volcanos, groundwater and landslides. The purpose of our group is to detect and model deformation and gravity change caused by such phenomena based on geodetic and geophysical data. Selected results during 2015-2019 are highlighted below.

Extensive studies were carried out to reconstruct regional glacial isostatic adjustment (GIA) and hydrological processes. It was discovered that the GIA, Greenland ice mass loss and mantle convection are the substantial three sources which drive the long-term polar drift since AD 1900. In those studies dealing with elastic and viscoelastic responses to surface loads, more and more theoretical models have been proposed which consider 3D heterogeneities and nonlinear rheologies. Benchmark tests between different codes have also been conducted for solving sea-level equations, indicating the validity of the adopted numerical approaches for modeling and understanding the GIA. Some studies incoporated thermal effects into the GIA models with use of geophysical data. Inversion methods were also developed which enable efficient computations.

A deep structure of the Earth was also studied. A large-scale density anomaly in the lowermost mantle was constrained from observations of body tides. A 6-year variation in the length-of-day was found, relating to the inner-core libration, which in turn creates a 6-year westward propagating wave. This wave is manifested in the GNSS, geomagnetic and global gravity data.

In the modeling of local deformations, new physical mechanisms were proposed in addition to elastic/viscoelastic deformaton, such as viscoplastic deformation, thermal pressurization, poroelastic deformation, erosion and detachment. Earthquake cycle mechanically driven by slab pull was presented, instead of kinematically imposed fault slip.

1.2 Research

Earthquake, volcano and landslide

- Earthquake-induced local crustal deformation [13, 14, 60, 81 and 82]
- Viscoelastic relaxation due to great earthquake
- GNSS and GRACE data analysis and interpretation [16, 26, 35, 50 and 101]
- Sea-level rise due to postseismic relaxation [53]
- Modeling of far-field deformation detected by GNSS [67 and 110]
- Modeling of lateral heterogeneity in viscosity [98]
- Forward and inverse modelling in a heterogeneous spherical Earth with nonlinear rheologies [27]
- Poroelastic deformation
    - Near-surface fluid injection [89]
    - Gravity change due to deep fluid flow triggered by slow slip [99]
- Earthquake cycle deformation, non-kinematically driven by slab pull [47]
- Volcano gravimetry and related theories [55, 80, 105, 106, 111 and 112]
- Volcanic crustal deformation modeling [10, 15, 21, 29, 37, 38, 44 and 104],
- including thermochemical effects [36] and hydrothermal pressurization [45]
- Landslide modeling based on GNSS and InSAR data [11, 17 and 40]
- 3D viscoplastic finite element method [18]
- Data analysis techniques by InSAR and GNSS [8 and 71]
- Review for modeling and data analysis [46]

Plate tectonics

- Relative plate motion of Iberian Peninsula [79]
- Seismotectonics in Himalaya [33]
- Recent surface vertical displacements of the European Alps and the possible mechanisms including geological effects [93]
- Regional GNSS observation network [39]
- Moho depth determination using gravity data [9]

Surface mass variations

- Reviews on theory and applications of satellite missions [59, 92, 77 and 103]
- Atmospheric and hydrological mass variations
    - Surface mass variations and crustal deformations from GNSS and GRACE data [42, 43, 51, 52, 75 and 102]
    - Effects of Lateral heterogeneity on the elastic response [30 and 100]
    - A numerical global deformational model for use with elastic responses [1]
- Glacial Isostatic Adjustment (GIA)
    - Regional models [3, 34, 54, 57, 58, 62, 83, 84, 86, 88, 90, 91, 97, 107 and 109]
    - Vertical motion and sea level change [5, 49, 61, 65, 66 and 85]

- Deformation due to sediment transport [108]
- Mantle-plume driven thermomechanical ice sheet model [87]
- Effects of viscous heating on surface heat flow [56]
- Inversion methods and sensitivity analyses for 1D and 3D earth parameters [22, 28, 48, 68 and 76]
- Benchmark tests for sea-level equations [69]

Tides and Earth rotation

- The 20th Century polar motion and its sources [2, 4 and 23]
- Effects of earthquakes on polar motion [20 and 25]
- Estimation and interpretation of low-degree coefficients [73, 94, 95 and 96]
- A generalized normal mode theory for the tidal response [63]
- Body tide observations to constrain lateral variations in density in the lowermost mantle [64]
- Lower mantle viscosity and anelasticity inferred from geodetic data [31 and 74]
- 6-year variation in the length-of-day relating to the inner-core libration, consistent with geodetic and geomagnetic data [32]
- Effects of boundary topography on free oscillation seismology, body tides, and rotational dynamics [7]
- Importance of proper implementation of rotation variations in GIA modelling derived from the energy balance approach [78]

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of "Interrelation between seismicity and gravity field anomalies – New insights into earthquake rupture processes" at *the AGU fall meeting* in 2016.
- Organization of IAG Workshop on GIA and Elastic Deformation (Reykjavik, Iceland) in 2017 (http://www.polar.dtu.dk/english/Workshop-on-Glacial-isostatic-adjustment-and-elastic-deformation-2017).
- Organization of the sessions on GIA at *the EGU General Assemblies* in 2017 and 2018 and *the AGU Fall Meeting* in 2017.
- Field work on Etna in 2018 (http://www.geo.sav.sk/en/slovak-italian-volcano-gravimetric-campaign-etna-2018/).
- Co-organization of the session "Deformation and gravity field modelling at regional scales" at *the IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.

1.4 Editorial activity

- Fernández J, Pepe A, Sigmundsson F, Poland M (2017) *Journal of Volcanology and Geothermal Research*. Special Issue: "Measuring Changes at Volcanoes using Geodesy: an update of Methods and Results", 344, 1-288.

1.5 Technology transfer and relevant applications in science and engineering

- Melini et al. (2015) developed a new tool for the computation of the Earth's response to surface loads (REAR).
- Bevis et al. (2016) reviewed methods to compute the geoelastic response to a disk load and provided a MATLAB function to implement this alhgorithm.
- Gao et al. (2017) opened a code for calculating viscoelastic postseismic deformation in a spherically symmetric, self-gravitating layered Earth.
- Camacho et al. (2018) presented a software package to carry out inversions of surface deformation data (any combination of InSAR, GPS, and terrestrial data, e.g., EDM, levelling) as produced by 3D free-geometry extended bodies with anomalous pressure changes.

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 2

- SC 2.3: Satellite Gravity Missions – Chair: Adrian Jäggi (Switzerland)
- SC 2.6: Gravity and Mass Transport in Earth System – Chair: Jürgen Kusche (Germany)

Commission 3

- SC 3.1: Earth Tides and Geodynamics – Chair: J. Bogusz (Poland)
- SC 3.2: Crustal Deformation – Chair: Z.-K. Shen (China)
- SC 3.3: Earth Rotation and Geophysical Fluids – Chair: J. Chen (USA)
- SC 3.4: Cryospheric Deformation – Chair: S. Abbas Khan (Denmark)
- SC 3.5: Tectonics and Earthquake Geodesy – Chair: H. Ozener (Turkey)

3. Future prospects

3.1 Research

Constraint of 3D heterogeneities in density and viscoelastic structure

- Model developments which consider 3D heterogeneities and nonlinear rheology.
- Sensitivity analyses and inversion methods to make use of observation data.
- Integration of geophysical data such as seismic tomography, heat flow, high-temperature/high-pressure experiments and geomagnetic data.
- Elucidation of the cause of the 6-year variation in the LOD.

Exploration and application of new model factors to local deformations

- Thermochemical structure, hydrothermal pressurization, plastic deformation and poroelastic deformation due to crustal fluid flow.
- Dynamic plate subduction model for understanding earthquake cycles where slip is not imposed in advance.
- Benchmark tests for postseismic viscoelastic deformation in a self-gravitating/non-gravitating, flat/spherical, 3D/1D Earth models.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on deformation and gravity variation at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of sessions on GIA at *EGU General Assembly/AGU fall meeting.*
- Proposal for a theoretical session on deformation and gravity variation at those meetings.

3.3 Technology transfer and relevant applications in science and engineering

- Reference bibliography for deformation and gravity variation.
- Distribution code which computes postseismic viscoelastic deformation in a 3D heterogeneous, self-gravitating spherical Earth.

4. Publications

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2. Adhikari S, Ivins ER (2016) Climate-driven polar motion: 2003–2015. *Science Adv*. 2 (4): e1501693; doi: 10.1126/sciadv.1501693.
3. Adhikari S, Ivins ER, Larour E (2017) Mass transport waves amplified by intense Greenland melt and detected in solid Earth deformation. *Geophysical Research Letters* 44; doi: 10.1002/2017GL073478.

4. Adhikari S, Caron L, Steinberger B, Reager JT, Kjeldsen KK, Marzeion B, Larour L, Ivins ER (2018) What drives 20th Century polar motion? *Earth Planet Sci. Lett.* 502: 126-132, https://doi.org/10.1016/j.epsl.2018.08.059.
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Global Geodetic Observing System

http://www.ggos.org

Chair 2015–2017: Hansjörg Kutterer (Germany)
Chair 2017–2019: Richard Gross (USA)
Vice Chair: Ruth Neilan (USA))

As the observing system of the IAG, GGOS facilitates a unique and essential combination of roles centering upon advocacy, integration, and international relations. GGOS also promotes high-level outcomes, such as the realization of the International Terrestrial Reference Frame through developing and maintaining 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 and outreach and is responsible for the GGOS website and maintaining a presence on social media. The new position of Manager of External Relations resides within the Coordinating Office.

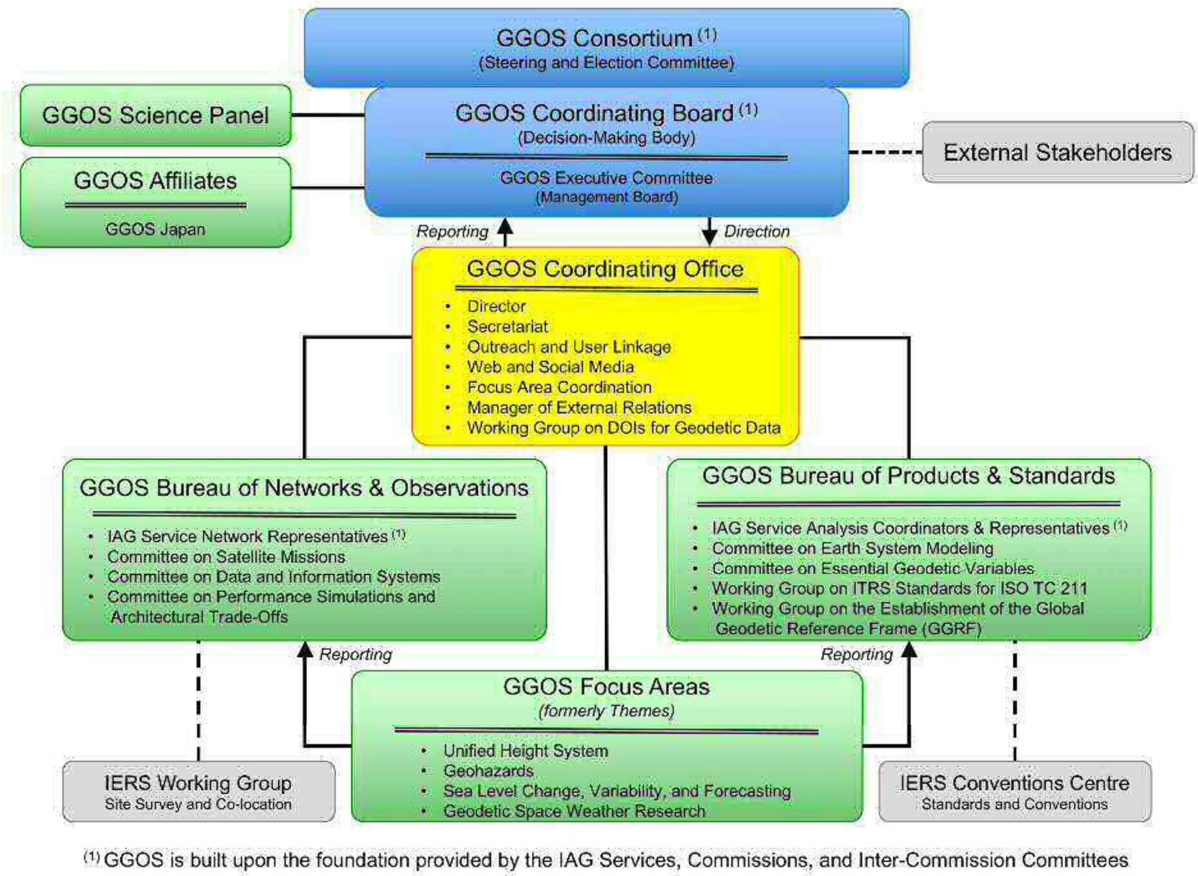

Figure 1. Organization chart of GGOS.

Overview

The 2015–2019 period was an active time of growth and organization within GGOS. A summary of the new activities that began during this time period is given below. A key activity touching on all elements of this overview was the revision and update of the GGOS Terms of Reference (ToR) in 2018 to reflect recent developments and strategic direction.

A new GGOS Focus Area on "Geodetic Space Weather Research" was established in 2017. The main objectives of the new Focus Area are to: (1) improve positioning and navigation by developing high-precision and high-resolution models of the electron density of the ionosphere, and to (2) improve satellite orbit determination by developing high-precision and high-resolution models of thermospheric drag.

As a mechanism to increase participation in GGOS, especially in the under-represented areas of Africa, Asia-Pacific, and South and Central America, a new component of GGOS, known as GGOS Affiliates, has been created. A GGOS Affiliate is a national or regional organization that coordinates geodetic activities in that nation or region. Once established, each GGOS Affiliate will have a representative to the GGOS Consortium and collectively they will have two representatives to the GGOS Coordinating Board. GGOS Japan, formerly known as the GGOS Working Group of Japan, became the first GGOS Affiliate in November 2017. GGOS Japan was established in 2013 and its current Chair is Prof. Toshi Otsubo of Hitotsubashi University. It provides a forum for multi-technique, space-geodetic discussions within Japan and works to improve the quality of its space-geodetic observations. GGOS Japan also encourages the different agencies in Japan that own, operate, and maintain the space-geodetic infrastructure there to collaborate with each other.

GGOS represents the IAG within the Group on Earth Observations (GEO) where it has been appointed to the GEO Programme Board for 2018–2020, GGOS participates in the Committee on Earth Observation Satellites (CEOS), and GGOS has a stake in the United Nations Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy. Given the fundamental importance of GGOS participation in these external organizations and to better manage GGOS' involvement in them, the position of Manager of External Relations was created. Since the Manager of External Relations will coordinate GGOS engagement with external organizations, the position of Manager of External Relations resides within the Coordinating Office. The Manager of External Relations is a voting member of both the GGOS Coordinating Board and the GGOS Executive Committee. Allison Craddock became the first Manager of External Relations in January 2018.

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 systems that are used to observe the EGVs. A Committee within the Bureau of Products and Standards was established in order to define the list of Essential Geodetic Variables and to assign requirements to them. The Committee consists of representatives of the IAG Services, Commissions, Inter-Commission Committees, and GGOS Focus Areas. Richard Gross is the Chair of the Committee.

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 ToR, the Consortium membership is reviewed and refreshed every four years, which last took place coincident to the 2015 IUGG General Assembly. The members of the GGOS Consortium during 2015–2019 are given in Table 1.

The presiding chair of GGOS is also the chair of the GGOS Consortium. The GGOS Consortium meets annually, which during 2015–2019 took place during GGOS Days:

1. GGOS Days 2015, Frankfurt am Main, Germany, 21–23 October 2015
2. GGOS Days 2016, Boston, Massachusetts, USA, 24–27 October 2016
3. GGOS Days 2017, Vienna, Austria, 31 October to 02 November, 2017
4. GGOS Days 2018, Tsukuba, Japan, 02–05 October 2018

Table 1. Members of the GGOS Consortium During 2015–2019

Organization	**Name**	**Title**
GGOS	Hansjörg Kutterer Richard Gross	Chair (2015–2017) Chair (2017–2019)
GGOS Affiliate of Japan	Basara Miyahara	Designated GGOS Representative
International Gravimetric Bureau (BGI)	Sylvain Bonvalot	Director
International Gravimetric Bureau (BGI)	Sean Bruinsma	Designated GGOS Representative
Bureau international des poids et mesures, BIPM	Felicitas Arias	Director, BIPM Time Department
Bureau international des poids et mesures, BIPM	Gérard Petit	Principal Physicist, BIPM Time Department
International Centre for Global Earth Models (ICGEM)	Franz Barthelmes	Director
International DORIS Service (IDS)	Laurent Soudarin	Director, Central Bureau
International DORIS Service (IDS)	Pascal Willis	Chair, Governing Board
International Earth Rotation and Reference Systems Service (IERS)	Daniela Thaller	Director, Central Bureau
International Geoid Service (IGeS)	Mirko Reguzzoni	President
International Geoid Service (IGeS)	Giovanna Sona	Director
International Geoid Service (IGeS)	Urs Marti	Designated GGOS Representative
International Geoid Service (IGeS)	Jianliang Huang	Designated GGOS Representative
International Gravity Field Service (IGFS)	Riccardo Barzaghi	Chair
International Gravity Field Service (IGFS)	Georgios Vergos	Director, Central Bureau
International GNSS Service (IGS)	Ruth Neilan	Director, Central Bureau
International GNSS Service (IGS)	Gary Johnston	Chair, Governing Board
The International Laser Ranging Service (ILRS)	Giuseppe Bianco	Chair, Governing Board
The International Laser Ranging Service (ILRS)	Erricos Pavlis	Analysis Coordinator
International VLBI Service for Geodesy and Astrometry (IVS)	Axel Nothnagel	Chair, Directing Board

International VLBI Service for Geodesy and Astrometry (IVS)	Dirk Behrend	Director, Coordinating Center
Permanent Service for Mean Sea Level (PSMSL)	Lesley J. Rickards	Director
Permanent Service for Mean Sea Level (PSMSL)	Mark Tamisiea	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Jean-Paul Boy	Director, Central Bureau
International Geodynamics and Earth Tides Service (IGETS)	Christoph Foerste	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Alexander Kopaev	Designated GGOS Representative
Commission 1: Reference Frames	Geoff Blewitt	President
Commission 1: Reference Frames	Johannes Böhm	Vice President
Commission 1: Reference Frames	Tonie van Dam	Designated GGOS Representative
Commission 2: Gravity Field	Roland Pail	President
Commission 2: Gravity Field	Shuanggen Jin	Vice President
Commission 3: Earth Rotation and Geodynamics	Manabu Hashimoto	President
Commission 3: Earth Rotation and Geodynamics	Chengli Huang	Vice President
Commission 4: Positioning and Applications	Marcelo Santos	President
Commission 4: Positioning and Applications	Allison Kealy	Vice President
Inter-Commission Committee on Theory (ICCT)	Pavel Novák	President
Inter-Commission Committee on Theory (ICCT)	Mattia Crespi	Vice President
Inter-Commission Committee on Theory (ICCT)	Dimitrious Tsoulis	Designated GGOS Representative

Coordinating Board

The Coordinating Board is the decision-making body of GGOS. The members of the GGOS Coordinating Board during 2015–2019 are given in Table 2.

The Chair of GGOS is the Chair of the Coordinating Board. The Coordinating Board meets twice-per-year, which during 2015–2019 took place during GGOS Days and the Saturday before EGU:

1. GGOS Days 2015; Frankfurt am Main, Germany; 21–23 October 2015
2. EGU; Vienna, Austria; 16 April 2016
3. GGOS Days 2016; Boston, Massachusetts, USA; 24–27 October 2016
4. EGU; Vienna, Austria; 22 April 2017
5. GGOS Days 2017; Vienna, Austria; 31 October to 02 November, 2017
6. EGU; Vienna, Austria; 07 April 2018
7. GGOS Days 2018; Tsukuba, Japan; 02–05 October 2018
8. EGU; Vienna, Austria; 06 April 2019

Table 2. Members of the GGOS Coordinating Board During 2015–2019

Position	**Voting**	**Name**
Chair	Yes	Hansjörg Kutterer (2015–2017) Richard Gross (2017–2019)
Vice Chair	Yes	Ruth Neilan
Chair, Science Panel	Yes	Richard Gross (2015–2017) Kosuke Heki (2017–2019)
Director, Coordinating Office	Yes	Allison Craddock (2015–2016) Günter Stangl (2016–2017) Matthias Madzak (2017–2018) Helmut Titz (2018–2019)
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	Toshi Otsubo
Representative, IAG President	Yes	Richard Gross (2015–2017) Zuheir Altamimi (2017–2019)
Representative, IAG Services	Yes	Riccardo Barzaghi
Representative, IAG Services	Yes	Ruth Neilan
Representative, IAG Services	Yes	Christoph Foerste
Representative, IAG Services	Yes	Urs Marti
Representative, IAG Commissions and ICCT	Yes	Pavel Novák
Representative, IAG Commissions and ICCT	Yes	Roland Pail
Member-at-Large	Yes	Ludwig Combrinck
Member-at-Large	Yes	Luiz Paulo Fortes
Member-at-Large	Yes	Gary Johnston
Chair, Standing Committee on Satellite and Space Missions	No	Roland Pail
Chair, Standing Committee on Data and Information Systems	No	Allison Craddock (2015–2016) Günter Stangl (2016–2017) Matthias Madzak (2017–2018) Helmut Titz (2018–2019)
Chair, Standing Committee on Contribution to Earth System Modelling	No	Maik Thomas
Chair, GGOS Committee/IAG WG on PLATO	No	Daniela Thaller
Chair, JWG on Establishment of the GGRF	No	Urs Marti
Chair, WG on ITRS Standards	No	Claude Boucher
Lead, Focus Area on Unified Height System	No	Laura Sanchez
Lead, Focus Area on Geohazards	No	John LaBrecque
Lead, Focus Area on Sea Level	No	Tilo Schöne (2015–2018)
Lead, Focus Area on Geodetic Space Weather Research	No	Michael Schmidt
Manager, GGOS Web and Social Media	No	Allison Craddock (2015–2016) Günter Stangl (2016–2017) Matthias Madzak (2017–2018) Helmut Titz (2018–2019)
Immediate Past Chair of GGOS	No	Markus Rothacher (2015–2017) Hansjörg Kutterer (2017–2019)
Representative, GIAC/GIC*	No	Per Erik Opseth (2015–2016)

* Please note that GIAC was terminated at the end of 2016, so all references to GIAC or GIC are purely for historical purposes.

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 2015–2019 are given in Table 3.

The Chair of GGOS is the Chair of the Executive Committee. The Executive Committee holds monthly conference calls and meets face-to-face during the meetings of the Coordinating Board (see above).

Table 3. Members of the GGOS Executive Committee During 2015–2019

Position	**Status**	**Name**
Chair	Member	Hansjörg Kutterer (2015–2017) Richard Gross (2017–2019)
Vice Chair	Member	Ruth Neilan
Director, Coordinating Office	Member	Allison Craddock (2015–2016) Günter Stangl (2016–2017) Matthias Madzak (2017–2018) Helmut Titz (2018–2019)
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	Pavel Novák
Immediate Past Chair of GGOS	Guest	Markus Rothacher (2015–2017) Hansjörg Kutterer (2017–2019)
Chair, Science Panel	Guest	Richard Gross (2015–2017) Kosuke Heki (2017–2019)
Representative, IAG President	Guest	Richard Gross (2015–2017) Zuheir Altamimi (2017–2019)
Representative, GIAC/GIC*	Guest	Per Erik Opseth (2015–2016)

* Please note that GIAC was terminated at the end of 2016, so all references to GIAC or GIC are purely for historical purposes.

GGOS Coordinating Office

Director:	*Helmut Titz (Austria)*
Manager of External Relations:	*Allison Craddock (USA)*
Members:	*Martin Sehnal (Austria)*

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.

History

The GGOS Coordinating Office has been transitioned twice in the period of 2015 – 2019 and there have been 5 directors of the CO.

- Until 04/2015: Giuseppe Bianco (ASI, Italy)
- 05/2015 – 04/2016: Allison Craddock (BKG, Germany)
- 05/2016 – 08/2017: Günter Stangl (BEV, Austria)
- 09/2017 – 11/2018: Matthias Madzak (BEV, Austria)
- 12/2018 onwards: Helmut Titz (BEV, Austria)

ASI: Agenzia Spaziale Italiana
BKG: Bundesamt für Kartographie und Geodäsie
BEV: Bundesamt für Eich- und Vermessungswesen

The position of the GGOS Manager of External Relations was officially approved at the Vienna GGOS Days in October 2017. Allison Craddock of the NASA Jet Propulsion Laboratory was elected to serve as the Manager of External Relations in January 2018.

Activities and Actions

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

GGOS website / GGOS.ORG Domain-Transfer

In September 2016 the BEV installed a server system for the implementation and operation of the new GGOS website. In Mai 2017 the official GGOS website www.ggos.org was shifted from ASI to BEV. Nevertheless it took another 2 years to finally complete the transfer of the ggos.org domain successfully to the BEV in February 2019. The new GGOS website was built from scratch while maintaining key items and historical resources. The webpages are maintained decentral by the different GGOS components using the DJANGO content management system. The CO is responsible for assigning usernames and access permissions for specific pages to the responsible persons and helps to set up the webpages and subpages. Links to the IAG Services, to metadata, datacentres and products have been established.

GGOS cloud server

An online cloud storage on the GGOS server has been installed and set operational on September 2017 temporary using the ggosdays.com domain name, as the official ggos.org domain was not accessible at that time. This cloud storage is based on the OwnCloud software. It is used for external (public) file distribution as well as internal file sharing. 28 personal user logins and 6 groups have been created and activated. Nevertheless the cloud storage has been rarely used.

Online Meetings Calendar

A Google Calendar was created to be able to view a timeline of the major internal and external meetings that may be interesting for GGOS. The calendar can be viewed on the GGOS website or be imported to other applications using iCal.

GGOS social media presence via Twitter

A GGOS Twitter account named @IAG_GGOS was created to be present in the social media and to speed up dissemination of GGOS-related information to the customers.

Online-Voting Tool

In order to use online voting possibilities more professionally, an account on surveymonkey.com was created and several GGOS internal elections were already performed online.

Conference attendance

- European Geosciences Union (EGU) (2015, 2016, 2017, 2018, 2019)
- American Geophysical Union (AGU) (2016, 2017)
- GGOS Days (2016, 2017, 2018)
- International Association for Geodesy (IAG/IASPEI) (2017)
- Group on Earth Observations (GEO) (2016, 2017)

GGOS External Relations

The position of GGOS Manager of External Relations was officially approved at the Vienna GGOS Days in October 2017.

Group on Earth Observations (GEO)

GROUP ON EARTH OBSERVATIONS

GGOS represents the IAG in the Group on Earth Observations (GEO), contributing to the GEO Foundational Task **GEOSS In-Situ Earth Observation Resources.** This task conducted a survey of existing in-situ Earth observing systems as a first step towards identifying gaps in the available observations. Gross participated in this survey by describing IAG's geodetic observing networks. In addition, IAG/GGOS has been selected to be a member of the **GEO Programme Board during 2018-2020**, with Gross being the Principal Representative and Craddock as Alternate Representative of IAG/GGOS to the Programme Board. IAG/GGOS is now one of 32 members of the Programme Board for the next 3 years and will have a voice in steering the activities of GEO.

Within the Programme Board, Gross has participated on behalf of IAG/GGOS in the **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.

Also under the auspices of the Programme Board, Craddock has participated on behalf of IAG/GGOS in the **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)**.

GGOS also participates in the **GEO Communicators Network**, which was established in November 2017 as a means to connect communications professionals supporting earth observations, open data, and other initiatives such as UN SDGs. As a collaborative function of the Coordinating Office Director and Manager of External Relations, GGOS social media has interacted with GEO and other stakeholders through twitter posting, "liking" and re-posting. Through the GEO Communicators Network, GGOS supports relevant messages on social media with the GEO-led or supported hashtag campaigns

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.

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 renewed its engagement with CEOS by appointing the Manager of External Relations as the GGOS representative to their **Ad Hoc Team on the Sustainable Development Goals** (AHT SDG), which highlights the potential role for Earth observations in supporting the global indicator framework of the United Nations Sustainable Development Goals. AHT SDG works closely with GEO (through the collaborative EO4SDG campaign) to highlight the numerous applications of Earth observations that provide data critical to monitoring progress toward the SDGs, and thereby further illustrate the immediate and secondary values of Earth observation data.

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). Harald Schuh, Mike Pearlman represented the IAG at the most recent session of the GGIM in New York (August 2018), and the meetings 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.

For more information, please visit the UN-GGIM website:
http://ggim.un.org/UN_GGIM_wg1.html.

Numerous GGOS Consortium 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

GGOS Consortium 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
- Gary Johnston, Australia; SCoG Co-chair

Pilot External Relations Project: 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.

Connecting United Nations Initiatives with the GGOS Geohazards Focus Area through the GAR19 Report

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 [2019] GAR will provide: a) an update on global progress made in implementing the outcome, goal, targets and priorities of the Sendai Framework and disaster-related Sustainable Development Goals (SDGs), b) current and future risk trends introducing systemic risk perspectives as represented in the forthcoming Global Risk Assessment Framework (GRAF), c) cutting edge, innovative research and practice in disaster risk management and good practice on how to manage and reduce disaster risks, and d) an introduction to the wider scope and systemic nature of hazards to be considered in implementing the Sendai Framework.*
>
> *Developed through an extensive set of partnerships with international organizations, governments, businesses, academic and research institutions, the GAR is both an ongoing process of evidence generation and policy engagement, and a product – in the form of a biennial report published by the UNISDR. The process contributes directly to greater access to risk information for decision-making, and identifies feasible practices that can be employed at the local, national, regional and international levels.*

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

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 Affiliate
GGOS Japan

Chair: *Toshimichi Otsubo (Japan)*
Secretary: *Basara Miyahara (Japan)*

Background

The GGOS Working Group of Japan was established in 2013 under IAG Subcommittee of Science Council of Japan to strengthen the collaboration among space geodesy agencies in Japan and to get connected to international organizations. It was approved to become the first "GGOS Affiliate" in 2017 and renamed as "GGOS Japan" in 2019.

Activities 2015-2019

GGOS Japan has proposed or been involved in a number of science sessions on global geodesy in domestic meetings (Meetings of Geodetic Society of Japan, JpGU) and international meetings (IAG, AGU, IUGG etc). It regularly hosted its own meetings in Japan. In addition, here is the list of what it has achieved in the 2015-2019 period.

2014-2016: GSI's VLBI station modernization and relocation from Tsukuba to Ishioka.
May 2016: New Chair: T Otsubo (was S Matsuzaka), Secretary: B Miyahara (was T Otsubo).
August 2017: Updated the GGOS station list (7 stations of 6 institutes) of Japan whose first version was submitted in 2014.
October 2017: Became the first GGOS Affiliate. T Otsubo appointed as GGOS CB Member and B Miyahara as Consortium Member.
March-April 2018: Published the GGOS special issue in Journal of the Geodetic Society of Japan (written in Japanese); 14 papers in Issues 2 and 3, Volume 63.
May-July 2018: Issued and printed its leaflet.
June 2018: K Heki appointed as Science Panel Chair of GGOS.
October 2018: Cohosted GGOS Days 2018.
Summer-Autumn 2019 (planned): Set up its website under ggos.org.
May 2020 (planned): Propose a GGOS-related session in JpGU+AGU joint meeting.

Publications and presentations

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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 2015-2019 quadrennium 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 2015-2019 quadrennium, GGOS sessions have been organized at:

- 2015 American Geophysical Union Fall Meeting in San Francisco
- 2016 American Geophysical Union Fall Meeting in San Francisco
- 2017 American Geophysical Union Fall Meeting in New Orleans
- 2018 American Geophysical Union Fall Meeting in Washington DC
- 2015 Asia Oceania Geosciences Society Annual Meeting in Singapore
- 2016 European Geosciences Union General Assembly in Vienna
- 2017 European Geosciences Union General Assembly in Vienna
- 2018 European Geosciences Union General Assembly in Vienna
- 2019 European Geosciences Union General Assembly in Vienna

- 2017 Japan Geophysical Union – American Geophysical Union Joint Meeting in Chiba, Japan
- 2018 Japan Geoscience Union Meeting in Chiba, Japan
- 2017 International Association of Geodesy – International Association of Seismology and Physics of the Earth's Interior Joint Scientific Assembly in Kobe, Japan

In addition to helping organize sessions at scientific conferences, the GGOS Science Panel also organizes topical science workshops in order to foster discussion about the geodetic observations and infrastructure required by different scientific disciplines. One such workshop was organized during 2015-2019 as the *IAU/IAG/IERS Joint Symposium on Geodesy, Astronomy, & Geophysics in Earth Rotation* held in Wuhan, China during 18-23 July 2016.:

International Symposium on Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016), Wuhan, China; 19-23 July 2016

The rotation of the Earth varies continuously, in both its rate of rotation and in the orientation of its axis with respect to either crust-fixed or space-fixed reference frames. Its study links together the fields of Geodesy, Astronomy and Geophysics. In this Symposium, over 50 participants from Asia, Europe, and the Americas met in Wuhan, China to assess our current ability to observe the Earth's time varying rotation, to assess our current understanding of the causes of the observed variations, to assess the consistency of Earth rotation observations with global gravity and shape observations, to explore methods of combining Earth rotation, gravity, and shape observations, and to identify improvements in the global geodetic observing system needed to further our understanding of the Earth's variable rotation. Peer-reviewed proceedings of the Symposium will be published as a special issue of *Geodesy and Geodynamics*.

Unified Analysis Workshops are co-organized by the International Association of Geodesy's Global Geodetic Observing System (GGOS) and International Earth Rotation and Reference Systems Service (IERS). The 2017 Workshop was the 5th in a series of workshops that are held every two years for the purpose of discussing issues that are common to all the space-geodetic measurement techniques. Attendance at the Workshops are by invitation only with each IAG Service nominating 5-6 experts to attend and participate in the discussion.

Unified Analysis Workshop, Paris, France; 10-12 July 2017

At the 2017 Workshop the discussion focused on (1) Systematic errors and biases in GNSS observations, (2) Systematic errors and biases in VLBI observations, (3) Systematic errors and biases in SLR observations, (4) Systematic errors and biases in DORIS observations, (5) Site survey and co-location, (6) Reference systems and frames, (7) Conventional mean pole, (8) Standards, conventions, and formats, and (9) Interoperability of portals and metadata.

Objectives and Planned Efforts for 2019-2023 and Beyond

During the next quadrennium 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

A GGOS session is also planned in the 2020 JPGU-AGU joint meeting in Chiba, Japan, as we did in 2017. The next Unified Analysis Workshop will be held in Paris, France during 02-04 October, 2019 (also planned in 2021, detail to be determined).
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. The Science Panel convened sessions on EGV in the 2018 AGU Fall Meeting and the 2019 EGU General Assembly. Activities related to EGV will continue in the newly established committee on EGV, which includes the whole Science Panel members.

GGOS Bureau of Networks and Observations

Prepared by Michael Pearlman, Carey Noll, Erricos C. Pavlis, Frank Lemoine, Daniela Thaller, Guenter Stangl, Jürgen Müller, Benjamin Männel, and Sten Bergstrand

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 (Carey Noll/NASA USA)
- Analysis Specialist (Erricos Pavlis/UMBC USA)
- IERS Representative (Sten Bergstrand/BIPM France)
- Representatives from each of the member Services:
  - IGS (Allison Craddock/JPL USA, Gary Johnston/GA/Australia)
  - ILRS (Toshi Otsubo/Hitotsubashi U. Japan, Wu Bin/SHAO China)
  - 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 (Lesley Rickards/BODC UK, Tilo Schone/GFZ Germany)
- Representatives from each of the member Standing Committees:
  - PLATO (Daniela Thaller/BKG Germany, Benjamin Maennel/GFZ Germany)
  - Data and Information Systems (Guenter Stangl, Matthias Madzak/BEV Austria, Carey Noll/NASA USA)
  - Satellite Missions (Jürgen Müller/IfE Germany, Roland Pail/TUM Germany)
  - IERS Working Group on Survey Ties and Co-location (Sten Bergstrand/BIPM France)

Activities, Actions, and Publications during 2015-2019

Activities

The Bureau:

- Continued to provide a forum for the Services and Standing Committees/Working Groups to share and discuss plans, progress, and issues, and to develop and monitor multi-entity efforts to address GGOS requirements; meetings are held in conjunction with AGU and EGU each year; material from the meetings are posted on the GGOS website.
- Continued the Bureau's "Call for Participation in the Global Geodetic Core Network: Foundation for Monitoring the Earth System" and work with new potential groups interested in participating; a total of 19 submissions have been received covering 114 sites that included legacy core sites, legacy/new technology co-location sites, core and co-location sites under development, and sites offered for future participation; a summary of the CfP responses is available on the Bureau's website. A number of other new stations will join once they are operational.

Several new stations have joined or are in the process of joining the network during this period. Correspondence has been underway with ROSCOSMOS regarding their formal joining in the network, but their stations have been regular participants. Certificates of participation have been sent out to network sites.

- Continued to advocate for new and increased network participation, encouraging formation of new partnerships to develop new sites, monitored the status of the networks; held meetings and communications with representatives from Russia, Italy, Brazil, Japan, Spain, France, and Saudi Arabia to discuss implementation of new stations and upgrade of legacy stations.

  The BN&O has been advocating for enhanced network infrastructure for Latin America; participated in the UNGGIM Meeting on the Americas at the UN in August 2018; plans to participate in the SIRGAS meeting in Rio de Janeiro in November.

- Supported efforts for the integration of various ground observation networks within the GGOS affiliated Network; continued to maintain and update the "Site Requirements for GGOS Core Sites" document (with the IAG Services); the next major step will be to include the requirements for the gravity field once it is fully documented by the IGFS and the IGRF working group; work with the IGFS in the definition of its requirements.
- Continued to promote and advocate for GGOS and the GGOS integrated global geodetic ground-based infrastructure through talks and posters at AGU, EGU, AOGS, APSG (China), JpGU-AGU, IAG, etc. and meetings and special presentations at GSI (Japan), IMPE (Brazil), IAP (Russia), etc.; supported efforts to integrate relevant parameters from other ground networks (gravity field, tide gauges, etc.) into the GGOS network to support GGOS requirements.
- Continued to maintain and update the inventory/repository of current and near-future satellite missions, highlighting those of most interest to GGOS; continued advocating for new advocating new missions; wrote letters of support for the E-GRASP/Eratosthenes proposals; need to stress greater cooperation between the PLATO and Missions Standing Committees. More details are provided in the Missions Standing Committee section below .
- Provided simulations and analyses to estimate how the data products will improve over time as the infrastructure improves. The results from the periodic network surveys will be used to project network data quality capability 5 and 10 years ahead. Simulations on the e-GRASP/Eratosthenes mission and other co-location missions to strengthen the case for support and for network planning. More detail is provided in the Standing Committee on Performance Simulations & Architectural Trade-Offs (PLATO) section below.
- Continued development and implementation of a GGOS metadata system in two stages: a stage-one scheme (hosted by CDDIS) for GGOS and GGOS-relevant data and a longer term, stage-two implementation, for the full GGOS requirements including site and instrument information, based on an XML metadata scheme under development by the Geoscience Australia, UNAVCO, and the IAG. Additional details are provided in the Data and Information Standing Committee section below.
- Continued working on the establishment of a common terminology for all space geodesy techniques, a terminology which is also valid outside the space geodetic community; the DORIS community has adapted a common terminology, and improved its surveying procedures as well as communication of the results. The IGS terminology has done the same, but there are differences among the techniques; continued working on outreach to increase local survey participation and standardization. More details are provided in

the IERS Working Group on Survey Ties and Co-Location (see IERS Section of the Travaux Report).

Related Bureau Documentation:

As part of the network activity, the Bureau has facilitated the creation of several key documents; these documents will be made available on the GGOS website in the near future.

- "GGOS Site Requirements for Fundamental Stations" document.
- A guidelines document for site characterization of the GGOS network sites was developed, "The Global Geodetic Core Network: Foundation for Monitoring the Earth System".
- A plan to define the process by which GGOS determines the extent of the needed infrastructure, including the scope and specification of the network, conditioned on the existing or plausible technology available, "GGOS Infrastructure Implementation Plan".
- A plan to assess the current and future plans for a GGOS core network, including projections five to ten years in the future, "Space Geodesy Network Model".
- Documents developed within the context of NASA's Space Geodesy Project, evaluating several sites as potential core sites; these documents are available from the SGP website at:
  https://space-geodesy.nasa.gov/documentation/Project_Documentation.html
- A summary report issued from the TLS (Terrestrial Laser Scanner) Workshop that was held at NASA GSFC, September 08-10, 2008.

Websites: http://www.ggos.org/en/bureaus/bno/

Publications and Presentations

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M. Pearlman, E. Pavlis, C. Ma, C. Noll, D. Thaller, B. Richter, R. Gross, R. Neilan, J. Mueller, R. Barzaghi, S. Bergstrand, J. Saunier, M. Tamisiea, "Update on the Activities of the GGOS Bureau of Networks and Observations", Abstract No. 10095. Presented at European Geosciences Union General Assembly, April 17-22, 2016.

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G. Stangl, C. Noll, "GGOS: The Global Geodetic Observing System" (poster), presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016.

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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 April 2019):

- R. Dach, F. Andritsch (AIUB, Switzerland)
- D. Thaller, D. König (BKG, Germany)
- R. Biancale (CNES/IGN, France)
- M. Bloßfeld A. Kehm (DGFI-TU Munich, Germany)
- M. Rothacher, I. Herrera Pinzon (ETH Zürich, Switzerland)
- B. Männel, S. Glaser (GFZ/TU Berlin, Germany)
- J. Müller, F. Hofmann (IfE University Hannover, Germany))
- D. Coulot, A. Pollet (IGN, France)
- R. Gross (JPL, USA)
- E.C. 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.)

Achievements over the past four years:

- Several projects related to simulation studies became funded and even extended to a second phase, like DIGERATI at DGFI-TUM, SORTS at TU Vienna, GGOS-SIM at GFZ, or KoKoRef at BKG
- Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn)
- Simulations for the planned E-GRASP/Eratosthenes which was a proposal for a dedicated co-location in space satellite mission within ESA Earth-Explorer-9 call. The proposal was submitted by a science team led by Richard Biancale (Biancale e al., 2017).
- Simulations for improved global SLR and VLBI station networks were carried out (Glaser e., 2017, Kehm et al., 2018, Anderson et al., 2018, Glaser et al. 2019).
- Simulations for improved SLR tracking of GNSS satellites were performed by AIUB (Andritsch et al., 2018).

- Simulations and analysis of VLBI tracking data of GNSS satellites and the Chinese APOD cube-satellite were carried out to assess the possibilities of VLBI satellite tracking (Hellerschmied e al., 2018).
- 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).
- Local baselines were analyzed to identify technique-specific systematic error sources (Herrera Pinzón and Rothacher, 2018).
- The combined processing ground- and space-based GNSS observations was studied (Männel and Rothacher, 2017).
- Simulation for new laser ranging on the lunar surface were carried out by IfE, Uni Hannover (Hofmann, 2017, Hofmann et al, 2018).
- A PLATO status report was published in the International Symposium on Advancing Geodesy in a Changing World (Männel et al., 2018).
- Presentations were given at IAG Assembly (July 2017), COSPAR/REFAG (July 2018), annual conferences of EGU and AGU as well as meetings of IAG Services.

Outcomes and Future Plans

- A coordinated increase of ETALON observations should be further considered at the expense of LAGEOS observations, and specific studies based on the dedicated ETALON tracking campaigns by the ILRS will be carried out.
- In addition to building new SLR stations, existing laser telescopes should be encouraged and supported to increase their performance, if possible, to the proposed level of 20%.
- In terms of LLR additional stations capable to perform measurements to (new) lunar reflectors are highly important to achieve highest accuracy.
- 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 co-location in space satellite mission. 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 launched in 2018 and is still ongoing
- Status reports will be given at IUGG General Assembly (July 2019) and IAG Symposia (2021)
- Annual meetings are foreseen in conjunction with EGU General Assembly

Publications

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Biancale R, Pollet A, Coulot D, Mandea M (2017) E-GRASP/ Eratosthenes: a mission proposal for millimetric TRF realization. In: EGU general assembly, geophysical research abstracts, vol 19. EGU2017-8752

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Pavlis, E. C., S. M. Merkowitz, C. J. Beaudoin, M. Kuzmicz-Cieslak, D. D. Rowlands, and F. G. Lemoine (2019) GEOCON: Geodetic System Ties Using a CubeSat Constellation, EGU General Assembly 2019, Geophysical Research Abstracts, Vol. 21, EGU2019-6158-1

GGOS Standing Committee on Satellite Missions (CSM)

Chair: Jürgen Müller (Germany)
Co-Chair: Roland Pail (Germany)

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 has about one meeting per year. The main work, however, is done via email exchange.

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. CSM - formerly GGOS Satellite Mission Working Group - was established in December 2008, under the lead of C.K. Shum. In December 2010, Isabelle Panet became Chair, in December 2013 Roland Pail followed. Since December 2015, Jürgen Müller is the new Chair.

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

- An inventory/repository of the GGOS satellite infrastructure has been prepared.
- A list of satellite contributions to fulfill the GGOS 2020 goals has been prepared.
- Both lists have been published at the CSM section of the GGOS website.
- In 2018 (as in the years before), individual members of CSM have contributed to ESA's Earth Explorer 10 call by actively acting in the proposers' team of the planned future gravity satellite mission MOBILE – which finally has not been selected.
- Close cooperation exists with the Bureau of Products and Standards, and the Sub-Commissions 2.3 and 2.6 of IAG. Additionally, there are strong interfaces to national and international space agencies.
- Exchange with PLATO has been initiated by identifying joint interests and possible collaborations.

Objectives and Planned Efforts for 2019 and Beyond

1. The new CSM website will continuously be updated collaborating with the GGOS Coordinating Office.
2. The inventory/repository of current and near-future satellite missions will regularly be updated.

3. The list of satellite contributions to the GGOS 2020 goals will regularly be updated.
4. CSM will further support advocating new satellite missions.
5. The exchange with PLATO shall be expanded, e.g., to stimulate dedicated simulations to better understand and overcome shortcomings with respect to the GGOS 2020 goals.
6. CSM will continue to support GGOS positions in preparation to CEOS/GEO meetings.
7. CSM will further support the Executive Committee and the GGOS Science Panel in the GGOS Interface with space agencies.

Most of the CSM tasks are ongoing activities. These tasks require interfacing with other components of GGOS, especially with the ground networks component, the simulation activity (PLATO) as well as the Bureau of Products and Standards.

Website: http://www.ggos.org/en/bureaus/bno/committee-satellite-missions/

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: Guenter Stangl/Matthias Madzak (Austria)
Co-Chair: Carey Noll (USA)

Purpose and Scope

Develop a metadata strategy for all ground-based measurement techniques and data products that provides discoverability and interoperability, is easily transferable via web services, and is based on internationally recognized data exchange methods; the plan is to implement a metadata scheme in two stages: a stage-one scheme for GGOS and GGOS relevant data products and a longer term, stage-two scheme for the full GGOS requirements.

The current focus of the WG is on developing standards for metadata that can be utilized by the space geodesy community. Metadata typically encompass critical information about the measurements that are required to turn these measurements into usable scientific data. Metadata also includes information that supports data management and provides a foundation for data discovery. Data centers extract metadata from incoming data sources and also augment that metadata with information from other sources. It is typical for data centers to store the metadata in databases in order to manage the data in their archives and to distribute both data and metadata to data users. Metadata can further be utilized by data discovery applications to allow users to find datasets of interest. In order to be effective, metadata need to be simple to generate and maintain. They must be consistent and informative for the archivist and the user.

GGOS is seeking a metadata schema that can be used by all of its elements for standardized metadata communication, archiving, and retrieval. First applications would be automated distribution of up-to-date stations configuration and operational information, data archives and catalogues, and procedures and central bureau communication. Several schemas that show promise have been under development by SOPAC (Scripps), GML (Australia/NZ), etc. The intent is that data need be entered only from an initial source (a station, a Data Center, an Operations Center, data products, etc.) and would then flow to and be integrated into those metadata files where users would have access. The plan is to organize a meeting, probably in early August at UNAVCO in Boulder, for representatives from the Services, the Data Centers, the Science Community, etc. to give each of the schema developers an opportunity to preach his wears and allow discussion on the pros and cons of each.

The objective is to try to come to closure on a schema that we could as a community adopt for general implementation. Groups would not be obligated to a rapid implementation schedule, but would commit to the agreed schema when they are ready to begin the process.

Activities and Actions

- CDDIS continues to construct collection-level metadata records for implementation in NASA EOSDIS (CMR)
- Concepts and plans for implementation of a GGOS metadata scheme have been presented at Bureau meetings; status of the activities have also been presented
- IGS continues development of Site Log XML metadata (lead: UNAVCO)
  - Several IGS data centers and groups have worked with this schema and are implementing/refining
  - Use Cases are slowly being assembled
  - Software tools for text site log to XML site log conversion are being developed and will be available to all
- Geosciences Australia (GA) has released GeodesyML

  - The GeodesyML project (http://www.geodesyml.org) has been created to facilitate the discoverability and availability of geodetic data and metadata to new (and existing) user communities in a standardized, discoverable, and interoperable way;
  - Machine-to-machine communications are required to improve efficiency, robustness, and accuracy for sharing geodetic data and their metadata.
  - Implements an application schema for the Site Log XML metadata;
  - Nick Brown (GA) has been funded to do a scoping study that will build upon GeodesyML, SensorML, OGC and ISO and other international standards when possible to enabling machine-to-machine communication. International participation in the scoping study is invited. Results from the study are due at the end of 2019. Although the study is being carried out for GNSS, the efforts will benefit the IGS and GGOS.

Objectives and Planned Efforts for 2019 and Beyond

- Adopt and implement a metadata system to provide access to GGOS relevant data products.
- GA and groups participating in the GeodesyML activity are creating a scoping study to investigate and document the critical gaps in standards which restrict how to make geodetic data, in particular precise positioning data, accessible to user communities. Some activities to be covered by the study:
  - Improve and expand data standards for accessing geodetic data and enabling their combination with other data sets;
  - Review and document current standards and identify critical gaps in the proposed standards;
  - Review community use cases and document how they can be met by GeodesyML and international standards.
- Adopt and implement a full metadata system including site information and relevant tools and capability (e.g., the GeodesyML scheme)
  - Definition of the requirements; definition of Phase 1 (March 2020)
  - Resolve issues and applicability of the Australian GL scheme and recommend schema (EGU 2020)
  - Metadata implementation plan including definition of tasks, roles, and distribution of tasks, and plans for integration of components (June 2020)
  - Demonstration of Phase 1 prototype (December 2020)
  - Demonstration of Phase 1 first operational system (December 2021)

IERS Working Group on Site Survey and Co-location

Chair: Sten Bergstrand (France)
Co-Chair: John Dawson (Australia)

Members:

https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

Purpose and Scope

The working group was established in 2004 as part of the IERS to homogenize local surveying activities at different space geodetic sites. In 2014, it was agreed that the working group would act also for GGOS under the IERS name. The overall goal is to provide a base necessary for rigorous terrestrial reference frame realizations, and to highlight the presence of technique- and/or site-specific biases. The main effort aspires to provide the means of an uncertainty assessment that can be included in the next ITRF.

Activities and Actions

- Recent work has first been to establish a general and common terminology to all techniques, which is also valid outside the space geodetic community, and to fulfill the local tie requirements set out in the GGOS book. The DORIS community has adapted the common terminology, and improved its surveying procedure as well as communication of results.
- IGS terminology has been adapted without alterations; the concepts are there, but the technique specific terminologies vary. The main focus of the IGS component has been a reassessment of existing sites rather than surveying as such.
- The ILRS maintains a list of current and historical sites. A combined effort from several institutes involved a common application to the European EMPIR program. The application fulfilled the acceptance criteria, but was not granted funding due to limited resources.
- The VLBI terminology concerning site surveys has been consolidated, and an automated terrestrial monitoring system for telescopes called Heimdall has been developed, as well as a complete model for telescope deformation.
- A campaign to examine the short-term combination of VLBI, GNSS and automated terrestrial monitoring at two baseline ends has been performed, with some processing left to be finished.

Objectives and Planned Efforts for 2017-2019 and Beyond

- Assess the ground truth uncertainty of different techniques to include in the next ITRF;
- Evaluate the VLBI-GNSS-terrestrial campaign of the Onsala-Metsähovi baseline; additionally, more sites should be surveyed. However, this is an activity that the respective station managers need to allocate funding for. The working group does not have the means to do this, and would appreciate any help to create a pull in this direction.

Website

https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html

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, Chair: Richard Gross (USA), (Remark: This component has been newly established, the TOR are under development)*
- *WG1 ITRS Standards for ISO TC211, Chair: C. Boucher (France)*
- *WG2 Establishment of the Global Geodetic Reference Frame (GGRF), Chair: Urs Marti (Switzerland)*

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 2019)

Position (IAG Service, other entity)	Representatives	Affiliation, Country
IERS Conventions Center	Gérard Petit (until 2016)	BIPM (France)
	Nick Stamatakos (since 2017)	USNO (USA)
IERS Analysis Coordinator	Thomas Herring	MIT (USA)
	R. Heinkelmann (since 2019, BPS)	GFZ (Germany)
IGS Representative	Urs Hugentobler (BPS staff)	TUM (Germany)
ILRS Analysis Coordinator	Erricos Pavlis	UMBC/NASA (USA)
IVS Analysis Coordinator	John Gipson	GSFC/NASA (USA)
IDS Representatives	Frank Lemoine, John Ries,	GSFC/CSR (USA)
	Jean-M. Lemoine, H. Capdeville	CNES/GRGS (France)
IGFS Chair	Riccardo Barzaghi	Politec. Milano (Italy)
BGI Chair	Sylvain Bonvalot	IRD (France)
ISG President	Mirko Reguzzoni	Politec. Milano (Italy)
ICGEM Chair	Franz Barthelmes (until 2017)	GFZ (Germany)
	E. Sinem Ince (since 2018)	GFZ (Germany)
IDEMS Director	Kevin M. Kelly	ESRI (USA)
IGETS Chair	Hartmut Wziontek	BKG (Germany)
Gravity Comm. (corresp. Member)	Jürgen Kusche	Univ. Bonn (Germany)
IAG Representative to ISO	Johannes Ihde (until 2017)	BKG, GFZ (Germany)
	Detlef Angermann (since 2018)	TUM (Germany)
IAG Communication and Outreach	Josef Ádám	Univ. Budapest (Hungary)
IAU Commission A3 Representative	Catherine Hohenkerk (until 2018)	United Kingdom
	James L. Hilton (since 2018)	USNO (USA)
IAU Representative	Robert Heinkelmann (BPS staff)	GFZ (Germany)
Control Body for ISO Geodetic	Michael Craymer (Chair)	NRCan (Canada)
Registry	Larry Hothem (Vice Chair)	USA

Overview

The Bureau of Products and Standards (BPS) is a key component of IAG's Global Geodetic Observing System (GGOS). It supports IAG in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth, along with its temporal variations. The BPS is built upon existing observing and processing systems of IAG.

Mission and overall objectives of the BPS:

- to serve as contact and coordinating point for the homogenization of IAG/GGOS standards and products;
- to keep track of the adopted geodetic standards and conventions across all IAG components, and to initiate steps to close gaps and deficiencies;
- to focus on the integration of geometric and gravimetric parameters and to develop new products needed for Earth sciences and society.

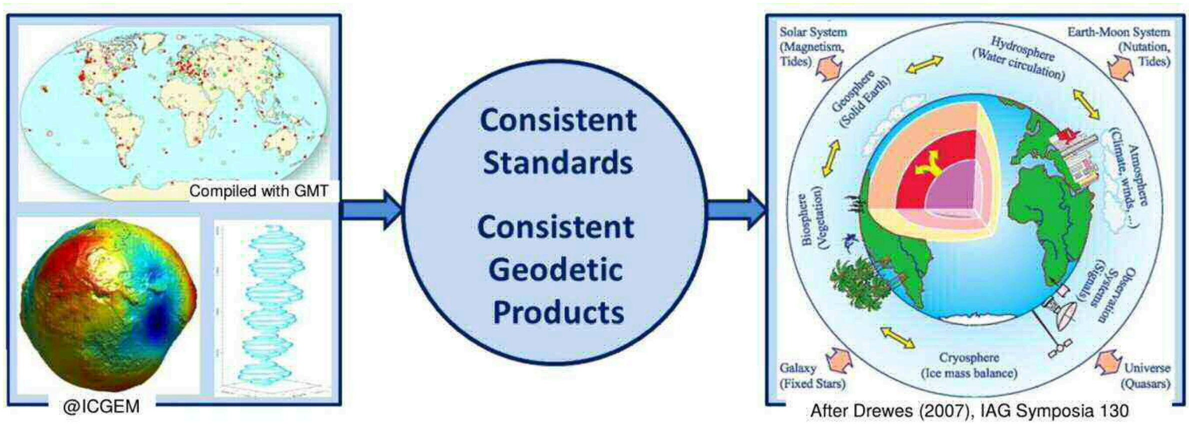

***Fig. X.1**: The integration of the "three pillars" geometry, Earth rotation and gravity field requires consistent standards to obtain consistent geodetic products as the basis for Earth system research and for precisely quantifying global change phenomena.*

As regards the development of standards, there is a link with the IERS Conventions Center, the IAU Commission A3 "Fundamental Standards", the IAU Working Group "Numerical Standards for Fundamental Astronomy", the Bureau International des Poids et Mesures (BIPM), the Committee on Data for Science and Technology (CODATA), and the International Organization for Standardization (ISO) with its Technical Committee ISO/TC211.

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 (see Angermann et al., 2016 and 2018).

Summary and recommendations on numerical standards

As shown in Table **X.2**, different numerical standards are in use within the geodetic community. The values of the Geodetic Reference System 1980 (GRS80) are still used as official ellipsoid parameters, although it represents the scientific status of the 1970s. In the concept of GRS80, the tidal systems and relativistic theories are not considered (Ihde et al., 2017). The numerical standards of the IERS Conventions 2010 are commonly used for the processing of the geometric observations and for the generation of IERS products. The fact that the semi-major axis between GRS80 and IERS Conventions 2010 differs by 0.4 m is critical and has to be considered correctly for users of geodetic products. Table **X.2** also shows the numerical standards of the Earth Gravitational Model 2008 (EGM2008; Pavlis et al., 2012), which are partly different from the numerical standards given in the IERS Conventions. In cooperation between the IERS Conventions Center and the BPS, the conventional value W_0 = 62 636 853.4 m^2s^{-2} for the geopotential at mean sea level issued in the IAG (2015) Resolution No. 1 (Ihde et al., 2017; Sánchez and Sideris, 2017) has been updated in Chapter 1 of the IERS Conventions in 2017. Thus, the former difference between the IERS Conventions 2010 value and the IAG 2015 value of about -2.6 m^2s^{-2} (equivalent to a level difference of about 27 cm) has been resolved.

The current situation concerning numerical standards and the different use of time and tide systems is a potential source for inconsistencies and even errors of geodetic products. Thus, it is essential for a correct interpretation and application of geodetic results and products that the underlying numerical standards are clearly documented. Moreover, the combination of geodetic results referring to different time or tide systems, transformations have to be performed to get consistent results.

Tab. X.2: *Numerical standards of conventional parameters presently in use within IAG. The defining parameters of the GRS80 are **a**, **GM**, **J_2** and **ω**. The IAG Resolution No. 1 (2015) recommends a conventional **W_0** value of 62 636 853.4m^2s^{-2}. Note the consequential decoupling of **W_0** and **L_G**. This **W_0** value could be used as a defining parameter for a new GRS20XX, the semi-major axis **a** would then become a derived quantity. The advantage of **W_0** is that it does not depend on the tide system, which is not the case of the semi major axis **a**.*

	semi-major axis a [m]	Geocentric Grav. Constant GM [$10^{12}m^3s^{-2}$]	Dyn. form factor J_2 [10^{-6}]	Earth's rotation ω [rad s^{-1}]	Normal potential U_0 or W_0 [m^2s^{-2}]
GRS80 (1979)	6 378 137	398.600 5	1 082.63	7.292 115	62 636 860.850
EGM2008	6 378 136.3	398.600 4415$^{(1)}$	1 082.635 9	7.292 115	62 636 856.0 (1998)
IERS Conv. (2010)	6 378 136.6$^{(2)}$	398.600 4418$^{(3)}$	1 082.635 9	7.292 115	62 636 856.0 (1998)
IERS Conv. (update 2017)	6 378 136.6$^{(2)}$	398.600 4418$^{(3)}$	1 082.635 9	7.292 115	62 636 853.4 (2015)
IAG Resol. No. 1 (2015)					62 636 853.4 (2015)

$^{(1)}$TT-compatible value; $^{(2)}$value given in zero-tide system; $^{(3)}$TCG-compatible value

The following recommendations on numerical standards have been specified in the BPS inventory, also endorsed as recommendations of the Unified Analysis Workshop held in Paris 2017, which was co-organized by GGOS and the IERS:

- **Recommendation 1**: The used numerical standards including time and tide systems must be clearly documented for all geodetic products.
- **Recommendation 2**: The geopotential value W_0 = 62 636 853.4 m^2s^{-2} issued by the IAG resolution No. 1 (2015) should be used as the conventional reference value for geodetic work.
- **Recommendation 3**: The development of a new Geodetic Reference System GRS20XX based on best estimates of the major parameters related to a geocentric level ellipsoid is desired.

Product-based review of standards and conventions

The following major topics were addressed in the product-based evaluation of standards and conventions (see chapter 4 in the BPS inventory, Angermann et al., 2016):

- Celestial reference systems and frames
- Terrestrial reference systems and frames
- Earth orientation parameters
- GNSS satellite orbits
- Gravity and geoid
- Height systems and their realizations

IAG products exist for the celestial and terrestrial reference frames as well as for the EOP which are provided by the responsible Product Centers of the IERS (see www.iers.org). These products are derived from a combination of the contributing VLBI, SLR, GNSS and DORIS data. The IERS Conventions provide the basis for the work of the geometric IAG Services (IGS, ILRS, IVS and IDS), as well as for the definition and realization of geodetic reference systems and for the generation of IERS products. In addition to the IERS Conventions, several technique-specific standards are defined for the analysis of the individual geometric observations and technique-specific products (e.g., GNSS satellite orbits). The BPS inventory gives an overview about the present status concerning the IERS products, it identifies gaps and deficiencies and provides recommendations for future improvements for each product (Angermann et al., 2016). The work of the BPS should be considered as a supplement to the extensive activities performed within the IAG Services and the IERS. The present issues concerning the analysis and combination of the geometric space-techniques were discussed during the Unified Analysis Workshop 2017, which was co-organized by GGOS and the IERS.

Some general recommendations of the BPS inventory concerning the IERS products are given below:

- At present, the celestial and the terrestrial reference frames and their integral EOP solutions are not fully consistent with each other as they are computed independently by separate IERS Product Centers. The Resolution No.3 (2011) of the IUGG) recommends, that the highest consistency between the ICRF, the ITRF and the EOP as observed and realized by IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS.
- The processing standards and models should be consistently applied by all the analysis centers of the IAG Services providing data for the generation of the IERS products.
- The station networks and the spatial distribution of high quality co-location sites should be improved as a fundamental requirement to achieve the GGOS accuracy requirements as specified in the GGOS 2020 book.

The IGFS is responsible to coordinate the gravity-related IAG Services and its overall goal is to provide gravity field related data, software and information for the scientific community. In 2016, the new IGFS Central Bureau, hosted at the Aristotle University of Thessaloniki (Greece), started its activity, providing an updated IGFS website (igfs.topo.auth.gr), including a dedicated product portal for the download of data and results generated by the IGFS Services. As an example, about 170 models of the global gravity field of the Earth are made available to the public via the ICGEM website (icgem.gfz-potsdam.de). A recommendation is that a conventional global gravity field model might be useful as a reference model to be used for the generation of official IAG products, whereas scientific users should be free to use any preferred model for their particular purposes. The last topic of the product-based inventory focuses on height systems and their realizations (see Report of the GGOS Focus Area "Unified Height System"). More detailed information on the product-based evaluation are found in the BPS inventory (Angermann et al., 2016).

Summary of further BPS activities:

- The BPS is working on the update and revision of the inventory on standards and conventions. The 2nd version of this inventory will be published online on the GGOS website. The planned release date is June 30, 2019. The major changes are summarized as Document Change Record. These changes include updates on the organizational structure of GGOS and on numerical standards, as well as the replacement of the previous realizations (i.e., ICRF2, ITRF2008, EOP 08 C04) by the latest versions ICRF3, ITRF2014 and EOP 14 C04. Furthermore, the section on GNSS orbits, the activities of the IGFS and the developments towards the realization of the International Height Reference System have been updated and revised.
- In the field of standards and conventions the BPS closely interacts with the IERS Conventions Centers and IAU Commission A3 "Fundamental Standards". A topic of discussion during the GGOS Days 2018 in Tsukuba (Japan) was the interaction of the BPS and the IERS Conventions Center regarding the re-writing/revising of the IERS Conventions. As a result, the director of the BPS has been nominated as the Chapter Expert for the "General Definitions and Numerical Standards".
- The BPS also supports the development of new products derived from a combination of geometric and gravimetric observations. Towards this aim various activities have been initiated and dedicated GGOS entities have been established to focus on the development of integrated products, such as the Focus Area "Unified Height System", the Focus Area "Geodetic Space Weather Research" and the Joint IAG Working Group "Establishment of the Global Geodetic Reference Frame (GGRF)".
- The director of the BPS has been nominated by the IAG Executive Committee as the IAG Representative to the UN Global Geospatial Information Management (UN-GGIM) Subcommittee "Geodesy" (the former GGRF Working Group) for the Focus Group "Data Sharing and Development of Geodetic Standards". The BPS contributed to the GGRF Roadmap Implementation Plan to the UN-GGIM Committee of Experts, provided for the 8th session in New York (August, 2018). This Focus Group (which has been renamed in a UN GGIM Working Group) has formulated three main recommendations on data sharing and common standards along with a number of actions to be accomplished in these two fields.
- In 2018, the Committee on the definition of Essential Geodetic Variables (EGVs) has been established as a new GGOS component associated to the BPS. The members of the Committee on EGVs comprise the GGOS Science Panel, representing the IAG Commissions, the Inter-Commission Committee on Theory, and the four GGOS Focus Areas, as well as representatives of the IAG Services. The Committee on EGVs is chaired by R. Gross. It consists of 34 members in total. Examples of EGVs might be the position of reference objects (ground stations, radio sources), EOPs, ground- and space-based gravity measurements, etc. Such EGVs could then serve as a basis for a gap analysis to identify requirements concerning observational properties and networks, accuracy, spatial and temporal resolution and latency.

BPS board meetings during the period 2015-2019:

- IUGG General Assembly 2015, Prague, Czech Republic, June 27, 2015
- GGOS Days 2016, Frankfurt am Main, Germany, October 22, 2015
- EGU 2016, Vienna, Austria, April 19, 2016
- GGOS Days 2016, Cambridge, USA, October 26, 2016
- EGU 2017, Vienna, Austria, April 25, 2017
- GGOS Days 2017, Vienna, Austria, November 1, 2017
- EGU 2018, Vienna, Austria, April 10, 2018
- GGOS Days 2018, Tsukuba, Japan, October 3, 2018

Selected Publications:

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler, U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG Products. The IAG Geodesist's Handbook 2016, J Geod 90(10): 1095-1156, doi: 10.1007/s00190-016-0948-z, 2016

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler, U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG Products. In: Rizos C. Willis P. (Eds.) IAG 150 Years, IAG Symposia 143, 571-577, doi: 10.1007/1345_2015_165, 2016

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Recent Activities and Future Plans. International Association of Geodesy Symposia, doi: 10.1007/1345_2018_28, 2018

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., GruberT., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics 38(3), 549-570, doi: 10.1007/s10712-017-9409-3, 2017

Sánchez L., Čunderlík R., Dayoub N., Mikula K., Minarechová Z., Šíma Z., Vatrt V., Vojtíšková M.: A conventional value for the geoid reference potential W0. Journal of Geodesy 90(9), 815-835, doi: 10.1007/s00190-016-0913-x, 2016

Sánchez L., Sideris M. G.: Vertical datum unification for the International Height Reference System (IHRS). Geophys J Int 209(2), 570-586, doi: 10.1093/gji/ggx025, 2017

GGOS Committee on Earth System Modeling

Chair: Maik Thomas (Germany)

Activities

Recent 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. In particular, the following progress could be achieved:

- A module for a realistic representation of the elastic response of the lithosphere to short-term variations of surface mass loading has been developed and implemented into various model approaches. Sensitivity of results to different numerical approaches (local, regional, global) for load-induced surface deformation as well as effects due to mantle inelasticity have been estimated.
- Several time series from system model simulations are operationally provided to the community via the GGFC/IERS Combination Center, e.g., time series of site displacements due to hydrological loading derived from model simulations applying the new loading module or effective angular momentum functions based on atmosphere-hydrosphere models.
- Kalman-based algorithms for the assimilation of (integral) geodetic observations have been generalized and implemented into stand-alone model components in order to improve numerical predictions of variations of surface deformation and Earth rotation parameters. Alternative techniques for the introduction of observational data into dynamically coupled models (e.g., particle filtering) have been intensively discussed; however, no generalized approach to constrain dynamically coupled models can be provided, so far.
- Feasibility studies for the provision of error estimates and uncertainties based on single- and multi-model ensembles have been performed.

Selected Publications

Dill, R., Klemann, V., Martinec, Z., Tesauro, M.: Applying local Green's functions to study the influence of the crustal structure on hydrological loading displacements. Journal of Geodynamics, 88, p. 14-22, 2015.

Dobslaw, H., Bergmann, I., Dill, R., Forootan, E., Klemann, V., Kusche, J., Sasgen, I.: The updated ESA Earth System Model for future gravity mission simulation studies. Journal of Geodesy, 89, 5, p. 505-513, 2015.

Irrgang, C., Saynisch, J., Thomas, M.: Ensemble simulations of the magnetic field induced by global ocean circulation: Estimating the uncertainty. Journal of Geophysical Research, 121, 3, p. 1866-1880, 2016.

Konrad, H., Sasgen, I., Klemann, V., Thoma, M., Grosfeld, K., Martinec, Z.: Sensitivity of Grounding-Line Dynamics to Viscoelastic Deformation of the Solid-Earth in an Idealized Scenario. Polarforschung, 85, 2, p. 89-99, 2016.

Martinec, Z., Klemann, V., van der Wal, W., Riva, R. E. M., Spada, G., Sun, Y., Melini, D., Kachuck, S. B., Barletta, V., Simon, K., James, T. S., G A.: A benchmark study of numerical implementations of the sea level equation in GIA modelling. Geophysical Journal International, 215, 1, pp. 389-414, 2018.

Saynisch, J., Bergmann, I., Thomas, M.: Assimilation of GRACE-derived oceanic mass distributions with a global ocean circulation model. Journal of Geodesy, 89, 2, p. 121-139, 2015.

Saynisch, J., Irrgang, C., Thomas, M.: Estimating ocean tide model uncertainties for electromagnetic inversion studies. - Annales Geophysicae, 36, pp. 1009-1014, 2018.

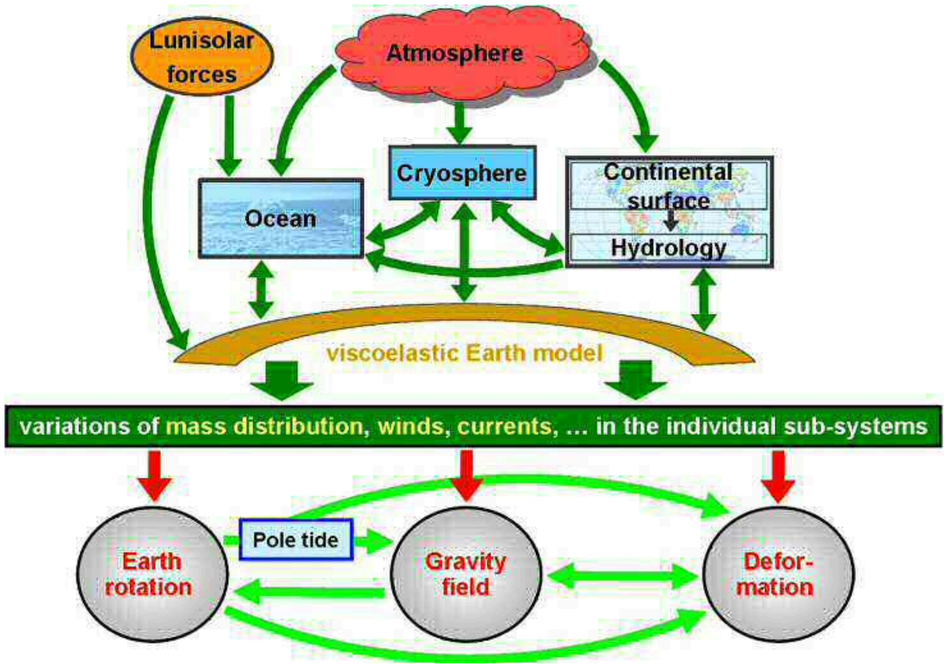

Fig. Y1: *Concept of a modular Earth system model for geodetic applications.*

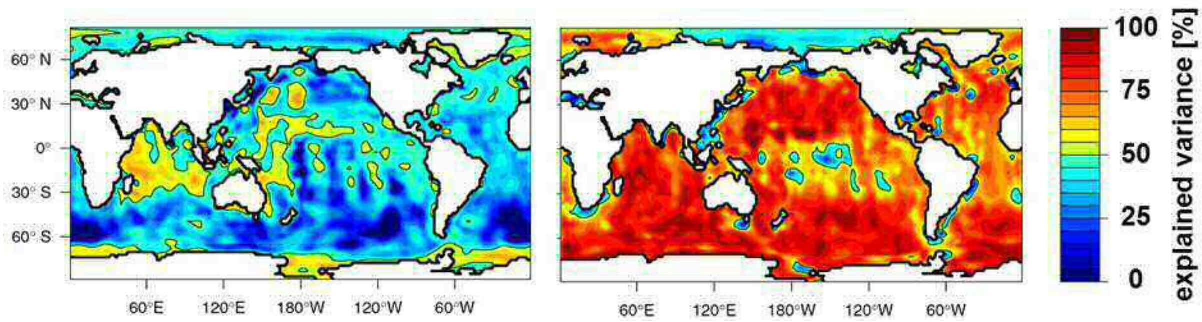

Fig. Y2: *Explained variance of GRACE ocean bottom pressure resulting from an unconstrained (left) and assimilated (right) ocean model simulation (Saynisch et al., 2015; updated).*

BPS WG1: ITRS Standards for ISO TC 211

Chair: Claude Boucher (France)

Members

- *Detlef Angermann (Germany)*
- *Sten Bergstrand (Sweden) chair IERS WG Site surveys and collocations*
- *Claude Boucher (France) chair WG, ISO project leader*
- *Xavier Collilieux (France) IAG SC1.2 chair*
- *Thierry Gattacceca (France) ISO project editor*
- *Larry Hothem (USA)*
- *Guy Woppelmann (France)*

Additional contributors via ISO group:

- *Zuheir Altamimi (France and IAG)*
- *Michael Craemer (Canada)*

Purpose and Scope

The mission of the WG is to coordinate the IAG community in the support of the development of the ISO standard on ITRS.

In order to ensure this support, some specific objectives has been identified (this list may be updated if needed):

1. To establish the list of IAG contributors to the work of the WG
2. To collect comments and proposals on any draft documents provided by the ISO TC211/19161-1
3. To establish a glossary of geodetic terms in relation with the scope of the WG

Activity report

1 IAG contributors

The present status of WG members is given at the beginning of this report. Additional contributors were provided through ISO 19161-1.

2 ISO TC211/19161-1

This group initially worked to establish a draft standard (versions 1 to 12)

In 2018, the ISO19161-1 Project Team consolidated and expanded the Working Draft, and successfully presented a Committee Draft (CD) to the TC211 on September 3. The CD was submitted in time to have the ballot completed before the TC211 plenary in Wuhan, in November 2018. Ballot results were: P-members in favour: 25; P-members against: 0; Abstentions: 11

A total of 130 comments (including 106 editorial ones) were received.

The first Editing Committee Meeting took place in Wuhan, China, on November 13, 2018, with 9 experts attending. All non-trivial editorial comments were processed.

The document was then edited to take into account the remaining comments (the trivial ones, and those less trivial or non-editorial that were discussed at the meeting and for which an answer was agreed on), thus producing the Draft International Standard (DIS). The DIS was circulated along with the updated table of comments to the EC members by the end of November, and submitted to ISO Central Secretariat in January 21, 2019.

The DIS ballot started on March 26, 2019 and will end June 18, 2019.

3 Glossary of terms

For information, here is the extract of the CD document related to the terminology part:

3.1 Coordinate system

Set of mathematical rules for specifying how coordinates are to be assigned to points
[SOURCE: ISO 19111:2018, 3.11]

3.2 Geocentric terrestrial reference system (GTRS)

System of geocentric space-time coordinates within the framework of General Relativity, co-rotating with the Earth and related to the Geocentric Celestial Reference System by a spatial rotation, which takes into account the Earth's orientation parameters
[SOURCE: IAG and IUGG resolutions of 1991 and 2007]

3.3 Positioning process

Computational process that determines directly from measurements the geodetic coordinates of points (absolute positioning), or that derives geodetic coordinates of points from previously determined geodetic coordinates (relative positioning)

3.4 Satellite ephemeris

Numerical representation of the trajectory of the centre of mass of an Earth orbiting artificial satellite expressed in an Earth centred terrestrial reference frame

3.5 Terrestrial reference frame (TRF)

Realization of a TRS, by specifying its origin, orientation, scale, and its time evolution
[SOURCE: IERS Conventions 2010]

Note 1 to entry: The realization is achieved through a set of physical points with precisely determined coordinates in a specific coordinate system, which may include the rate of coordinate change.

Note 2 to entry: The realization is called static when no rates of coordinate change are defined, and kinematic when rates of coordinate change are defined without considering the underlying forces causing the motion. The realization may be called dynamic when these external forces are considered. “Dynamic” is also used colloquially to describe both the dynamic and kinematic cases without distinction.

3.6 Terrestrial reference system (TRS)

Set of conventions defining the origin, scale, orientation and time evolution of a spatial reference system co-rotating with the Earth in its diurnal motion in space

Note 1 to entry: The abstract concept of a TRS is realized through a terrestrial reference frame.

Note 2 to entry: In such a system, positions of points attached to the solid surface of the Earth have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations). In the Newtonian framework, the physical space is considered as a Euclidean affine space of dimension 3, with an origin, a scale and an orientation.
[SOURCE: IERS Conventions 2010]

BPS WG2: Establishment of the Global Geodetic Reference Frame (GGRF)

Chair: Urs Marti (Switzerland)

Members

Jonas Ågren (Sweden, Commission 2), Detlef Angermann (Germany, GGOS BPS, IERS), Riccardo Barzaghi (Italy, IGFS), Johannes Ihde (Germany, Working Group on Height Systems), Hansjörg Kutterer (Germany, GGOS), Jaakko Mäkinen (Finland, Tidal Systems), Pavel Novak (Czech Republic, ICCT), Roland Pail (Germany, Commission 2), Nikolaos Pavlis (USA, Global Gravity Field Models), Laura Sánchez (Germany, Working Group on Height Systems), Harald Schuh (Germany, IAG), Hartmut Wziontek (Germany, Global Gravity Reference Network)

Corresponding Members

Gary Johnston (Australia, Commission 1, UN GGIM), Johannes Böhm (Austria, Commission 1), Catherine Hohenkerk and Robert Heinkelmann (Representatives of the IAU)

Activities

This WG is a joint activity of IAG Commissions 1 and 2, the ICCT, the IERS and the IGFS.

The start-up meeting of this WG took place during the EGU Assembly 2016 in Vienna. In this meeting, the tasks of the WG were discussed and defined. A clear separation between this WG and the UN GGIM WG on the GGRF was reached. Thus, the IAG WG concentrates on the practical issues of the realisation of the GGRF and the setup of a consistent use of geometry and gravity field related quantities in the global reference frames. A key role in this discussion play the realisation of the International Height Reference System (IHRS) and the definition and realisation of a global Absolute Gravity Reference System (see corresponding reports of these WGs).

At the GGHS2016 conference in Thessaloniki a first official meeting of the WG was held. Some concrete tasks were defined there, such as:

- Work towards a conventional global reference gravity field model
- Develop or define a global, conventional combined gravity field model and a conventional Satellite only model
- Study the influence of permanent tide models on all kind of data (position, potential, gravity, gravity anomalies, heights) and develop transformation methods
- Study the redefinition of a global GRS based on actual values of W_0 / GM / ω and derived quantities
- Study the necessity to replace GRS80
- Study relativistic effects and their influence on the GRS
- Get an overview of parameters and models (e.g. tides, loading effects, atmosphere) used in products and conventions of IAG and other communities. (see BPS Inventory, Angermann et al., 2016)
- Intensify the contacts to IAU and IERS

Main discussions were the assignment of a conventional global gravity field model, where not all WG members agree that it is necessary. A second point of disagreement was, if it is really a good idea to replace GRS80 by a new model. A good summary of the main aspects can be found in 'Considerations on a Concept for future handling Geodetic Parameters/Numerical Standards in Conventions' by J. Ihde.

The concepts and activities of the WG were presented at the TGSMM conference in St. Petersburg in April 2016 , the GGOS days in Cambridge in October 2016, the IAG-IASPEI Scientific Assembly in Kobe (August 2017), the GGOS days in Vienna (November 2017) and the GGHS2018 conference in Copenhagen (September 2018).

Results

An overview of the parameters and models used by various groups in- and outside of Geodesy is available in the BPS inventory (Angermann et al. 2016 and 2018). Mäkinen presented in Kobe (2017) a study about the calculation of the permanent tide, the transformation and use of the various systems and their influence on the ellipsoid, the gravity potential and the physical heights. One main recommendation was to calculate all the influences in the zero tide system and to convert the corrections at the very end into other systems and to neglect very minor second order terms. In Copenhagen (2018), Oshchepkov presented a set of parameters of a reference system, consistent with the W_0 value, adopted in 2015 for the IHRS. All calculations are based on the zero tide system and terrestrial time (TT). As defining parameters W_0, GM, J_2 and ω were chosen. Values for the derived parameters (such as semi-major axis a, flattening f, normal gravity at the equator γ_E) were calculated as well. It was shown that a new set of parameters for a GRS has also small, but non-negligible influences on the gravity anomalies and normal heights. Kopeikin (et al.) published several papers on relativistic effects on a GRS, especially the effects on the reference ellipsoid, the gravity potential and the normal gravity (see list in the references).

Until now, no agreement about the definition of a "standard" global gravity field model was reached. There is even no agreement if such a "standard model" is needed at all. However, such a common reference model (satellite-only and combined) would be very useful for several purposes such as the realization of the International Height Reference System (IHRS) or for consistent regional geoid modelling. The newly installed IAG service COST-G (International Combination Service for Time-variable Gravity Field Solutions) of the IGFS could assist in finding such reference models, although their main focus is on the combination of time variable gravity field models.

One main task - the preparation of an IAG or IUGG resolution for the replacement of GRS80 by a new official GRS – could not be realized yet. Though we have a proposal for a new set of defining parameters (e.g. by Oshchepkov, alternative solutions are still calculated by other groups), we are not ready yet to present a broadly accepted new model. Many users do not see the necessity to change the conventional GRS80. This needs a broader discussion not only in IAG, but also in other related organisation such as the IAU and the IUGG. In the near future, this could become possible in the frame of the renewal of the IERS conventions and the newly established committee working on the definition of "Essential Geodetic Variables" (EGVs), associated with the GGOS Bureau of Products and Standards (BPS). Even if GRS80 will not be replaced as the conventional system, it is necessary to calculate a GRS based on today's knowledge and to propose a consistent set of parameters and formulas.

Presentations and Publications

Angermann D. et al (2016): Inventory of Standards and Conventions used for the Generation of IAG products.

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Recent Activities and Future Plans. International Association of Geodesy Symposia, 10.1007/1345_2018_28, 2018

IAG Executive Committee (2016): Description of the Global Geodetic Reference Frame. Position Paper. April 2016.

Ihde J. (2016): The Role of Gravity and Height for the GGRF. Presentations at the EUREF Symposium May 2016. San Sebastian.

Ihde J. (2016): Future handling Geodetic Parameters/Numerical Standards in Conventions. Presentation at the GGOS Days October 2016. Cambridge.

Ihde J. (2016): Considerations on a Concept for future handling Geodetic Parameters/Numerical Standards in Conventions. November 2016.

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., GruberT., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics, 38(3), 549-570, 10.1007/s10712-017-9409-3, 2017

Kopeikin S., E. Mazurova, A. Karpik (2015): Towards an exact relativistic theory of Earth's geoid undulation, Physics Letters A, 379, 1555.

Kopeikin S (2016): Reference ellipsoid and geoid in chronometric geodesy. Frontiers in Astronomy and Space Sciences, 3, 5

Kopeikin S., W.-B. Han, E. Mazurova (2016): Post-Newtonian reference-ellipsoid for relativistic geodesy, Physical Review D, 93, id. 044069

Kopeikin S. et al. (2018): Normal gravity field in relativistic geodesy. Physical Review D 97(4). DOI: 10.1103/PhysRevD.97.045020.

Mäkinen J. (2017): The permanent tide and the International Height Reference System IHRS. Presentation at the IAG-IASPEI Scientific Assembly, Kobe (Japan).

Marti U. (2016): GGRF. Presentation at the EGU General Assembly. April 2016, Vienna.

Marti U. (2016): GGRF. Presentation at the GGHS2016 Conference. September 2016, Thessaloniki.

Marti U. (2016): Presentation at the GGOS Days October 2016. Cambridge.

Marti U., L. Vitushkin, H. Wziontek (2016): The Role of a new Global Absolute Gravity Reference System in Relation to the GGRF. Presentation at the TGSMM Conference. April 2016. St.Petersburg.

Oshchepkov I. (2018): Geodetic reference system consistent with the IHRF W_0 value. Presentation at the GGHS2018 Conference in Copenhagen.

GGOS Focus Area "Unified Height System" and JWG 0.1.2 "Strategy for the Realization of the International Height Reference System (IHRS)"

Chair: Laura Sánchez (Germany)

Members: J. Ågren (Sweden), M. Amos (New Zealand), R. Barzaghi (Italy), S. De Freitas (Brazil), W. Featherstone (Australia), T. Gruber (Germany), J. Huang (Canada), J. Ihde (Germany), G. Liebsch (Germany), J. Mäkinen (Finland), U. Marti (Switzerland), P. Novák (Czech Republic), M. Poutanen (Finland), D. Roman (USA), D. Smith (USA), M. Véronneau (Canada), Y. Wang (USA), M. Blossfeld (Germany), J. Böhm (Austria), X. Collilieux (France), M. Filmer (Australia), B. Heck (Germany), R. Pail (Germany), M. Sideris (Canada), G. Vergos (Greece), C. Tocho (Argentina), H. Denker (Germany), D. Avalos (Mexico), H. Wziontek (Germany), M. Varga (Croatia), I. Oshchepkov (Russia), D. Blitzkow (Brazil), A.C.O.C. Matos (Brazil), J. Bouman (Germany), H.A. Abd-Elmotaal (Egypt), K. Matsuo (Japan), S. Claessens (Australia), R. Forsberg (Denmark), T. Jiang (China), V.N. Grigoriadis (Greece), D.A. Natsiopoulos (Greece), Q. Liu (Germany), M. Willberg (Germany), B. Erol (Turkey), M. Serkan Isik (Turkey), S. Erol (Turkey).

Activities

The objectives and planned activities of the GGOS-FA "Unified Height System" for the 2015-2019 period are described in the Geodesist's Handbook 2016 (Drewes H. et al., 2016). The main goal at present is the implementation of the International Height Reference System (IHRS) defined by the IAG 2015 Resolution No. 1 (ibid. page 981). The progress is summarized as follows:

- In Dec 2015, the joint working group (JWG) *Strategy for the Realization of the IHRS* was installed with the objective of developing a scheme for the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). This JWG is supported by *the International Gravity Field Service* (IGFS), the IAG Commissions 1 and 2 (*Reference Frames* and *Gravity field*), the *Inter-commission Committee on Theory* (ICCT), the *regional sub-commissions for reference frames and geoid modelling*, and both *GGOS Bureaus* (*Networks and Observations* and *Products and Standards*). In particular, there is a strong cooperation with
  - IAG JWG 2.2.2: *The 1 cm geoid experiment* (chair: Y.M. Wang, USA)
  - IAG SC 2.2: *Methodology for geoid and physical height systems* (chair: J. Ågren, Sweden)
  - ICCT JSG 0.15: *Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy* (chair: J. Huang, Canada)
  - IAG JWG 2.1.1: *Establishment of a global absolute gravity reference system* (chair: H. Wziontek, Germany)
  - J. Mäkinen, *tide systems in the IHRS* (Finnland).

- A brainstorming and definition of action items took place at a JWG meeting carried out during the *International Symposium on Gravity, Geoid and Height Systems 2016* (GGHS2016) in Thessaloniki (Greece) in Sep 2016. This JWG meeting was attended by 70 colleagues and allowed us to identify the activities to be faced immediately (Sánchez, 2016a). A main output of this meeting are the criteria for the selection of IHRF reference stations:
  - GNSS continuously operating reference stations to detect deformations of the reference frame;

- Co-location with fundamental geodetic observatories to ensure a consistent connection between geometric coordinates, potential and gravity values, and reference clocks (to support the implementation of the GGRF);
- Co-location with reference stations of the *International Gravity Reference Frame* (IGRF): the IGRF and IHRF station selection for the co-location of this two reference frames is a contribution of IAG JWG 2.1.1;
- Preference of stations belonging to the ITRF and the regional reference frames (like SIRGAS, EPN, APREF, etc.);
- 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).

- During the *GGOS Days 2016* (Boston (MA), USA, Oct 2016), a preliminary station selection for the IHRF was performed (Sánchez, 2016b). 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).

- Based on the conclusions of the meetings in Thessaloniki and Boston, 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 (see Table 1), the first approximation to the IHRF is based on about 170 reference stations. This station selection is regularly refined in agreement with changes/updates of other geodetic reference frames (ITRF and IGRF and their densifications). Figure 1 shows the IHRF station distribution (as of Apr 2019) and the co-location with SLR, VLBI, DORIS, IGRF, tide gauges and levelling networks' stations.

- With the preliminary station selection, following efforts concentrated on the computation of station potential values and the assessment of their accuracy. Different approaches were evaluated (Sánchez et al., 2017):
  - As national/regional experts provided the JWG with terrestrial gravity data around some IHRF sites, a direct computation of potential values was performed using a combination of terrestrial gravity data and different global gravity models (GGM) as well as different mathematical formulations (least-squares collocation, FFT, radial basis functions, etc.).
  - Computation of potential values by national/regional experts responsible for the geoid modelling using their own data and methodologies.
  - Computation of potential values based on GGM of high-degree (like XGM2016, EIGEN-6C, EGM2008, etc.).
  - Recovering potential values from existing local (quasi-)geoid models.
  - Table 2 lists the colleagues contributing to this first experiment.

- The comparison of the results showed discrepancies up to the dm-level (Sánchez et al., 2017). The main conclusions of this experiment were:

- The use of only GGMs is (at present) not suitable for the estimation of precise potential values. GGMs may be used if there is *no other way* to determine potential values.
- A *standard* procedure for the computation of potential values may be not appropriate as
    - different data availability and different data quality exist around the world
    - regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.)
- A *centralized* computation (like in the ITRF) is complicated due to the restricted accessibility to terrestrial gravity data

• To overcome these inconveniences, during the *IAG-IASPEI Joint Scientific Assembly* (Kobe, Japan, Aug 2017) was agreed to initiate a new experiment towards:
- the computation of IHRF coordinates using exactly the same input data and the own methodologies (software) of colleagues involved in the gravity field modelling, and
- the comparison of the results, to identify a set of standards that allow to get as similar and compatible results as possible.

• In the same IAG-IASPEI 2017 Assembly, J. Ågren (Chair of IAG SC 2.2) and J. Huang (Chair of ICCT JSG 0.15) proposed to establish an interaction with the JWG 2.2.2 (chaired by Y.M. Wang). Aim of JWG 2.2.2 is the computation and comparison of geoid undulations using the same input data and the own methodologies/software of colleagues involved in the geoid computation. The comparison of the results should highlight the differences caused by disparities in the computation methodologies. In this frame, it was decided to extend the "geoid experiment" to the computation of station potential values as IHRS coordinates. With this proposal, the US NGS/NOAA agreed to provide terrestrial gravity data, airborne gravity, and digital terrain model for an area of about 500 km x 800 km in Colorado, USA (Fig. 2). With these data, different groups working on the determination of IHRF coordinates should compute potential values for some virtual geodetic stations located in that region. Afterwards, the results individually obtained should be compared with the *Geoid Slope Validation Survey 2017* (GSVS17), which will provide potential differences inferred from first order levelling measurements and gravity corrections along a validation line (see red line in Fig. 2).

• The Colorado data were distributed in Feb. 2018, together with a document summarizing a minimum set of basic requirements (standards) for the computations. Ten different groups delivered solutions (Table 3) and the results were discussed during the *Gravity, Geoid and Height Systems (GGHS2018) Symposium* (Copenhagen, Denmark, Sep 2018). Main conclusions are (Wang et al., 2018; Sánchez et al. 2018a):
- Two solutions were declared as outliers. They present large discrepancies (at the 1.5 m level) in (quasi-)geoid heights as well in the potential numbers with respect to the other solutions.
- In the geoid comparison, six solutions agree within 3 cm to 10 cm in terms of standard deviation with respect to the mean value.
- In the quasi-geoid comparison, the same six solutions agree within 1 cm to 4 cm in terms of standard deviation with respect to the mean value.
- In the comparison of the potential values, four solutions agree within 1 cm to 2 cm in terms of standard deviation with respect to the mean value.
- The discrepancies present a high correlation with the topography.
- Possible sources of discrepancy:

  - Different handling of terrain corrections/reductions
  - Inconsistent use of the zero-degree term
  - Precision degradation due to the conversion of quasi-geoid heights to geoid heights and vice versa
  - Uncertainties in the processing of the airborne gravity data.

- To continue the Colorado experiment, following action items were formulated:
  - Participants in the experiment should provide a description with the main features of their computations in order to identify possible sources of discrepancies.
  - Participants should follow the basic standards/specifications distributed with the data, especially in the handling of corrections/reductions like the effect of the atmosphere, the consistent use of the zero-term, the global gravity models, etc.
  - The document with the standards/specifications was modified/extended to present more clearly some confusing issues like the handling of the zero degree term and the conversion from quasi-geoid to geoid (Sánchez et al., 2018b).
  - NGS/NOAA provided a pre-processed (cleaned) version of the GRAV-D data (down sampling 20 Hz data, de-biased data) by the end of 2018 in order to facilitate the use of these data in the individual solutions.

- Based on these action items, a second computation for the Colorado experiment was completed in Apr 2019. In total, 14 solutions were delivered (Table 4). At present, we are working on the comparison of geoid heights, height anomalies and potential values. The results will be discussed in the next *IUGG General Assembly* (Montreal, Canada, July 2019). It is expected to present all the results in a special issue of the *Journal of Geodesy*.

Outlook

To close the term 2015-2019, an executive report will be presented to the IAG and GGOS at the IUGG General Assembly 2019. It is expected to support this executive report with a peer-reviewed paper describing the strategy for the realization of the IHRS and a first solution for the IHRF. Aim of this first solution is to evaluate the achievable accuracy under the present conditions (data availability, computation methods, etc.) and to identify key actions to improve the determination of the IHRS/IHRF coordinates. These key actions should be faced in the next 2019-2023 period. For the same term, a joint working group of the GGOS FA-UHS, the IAG Commission 2 and the IGFS should investigate the best way to establish an *IHRS/IHRF element* within the IGFS to ensure the maintenance and availability of the IHRF. This implies regular updates of the IHRFyy to take account for new stations, coordinate changes with time, improvements in the estimation of coordinates (more observations, better standards, better models, better computation algorithms, etc.), geodetic products associated to the IHRF (description and metadata), and the organizational and operational infrastructure to ensure the IHRF sustainability.

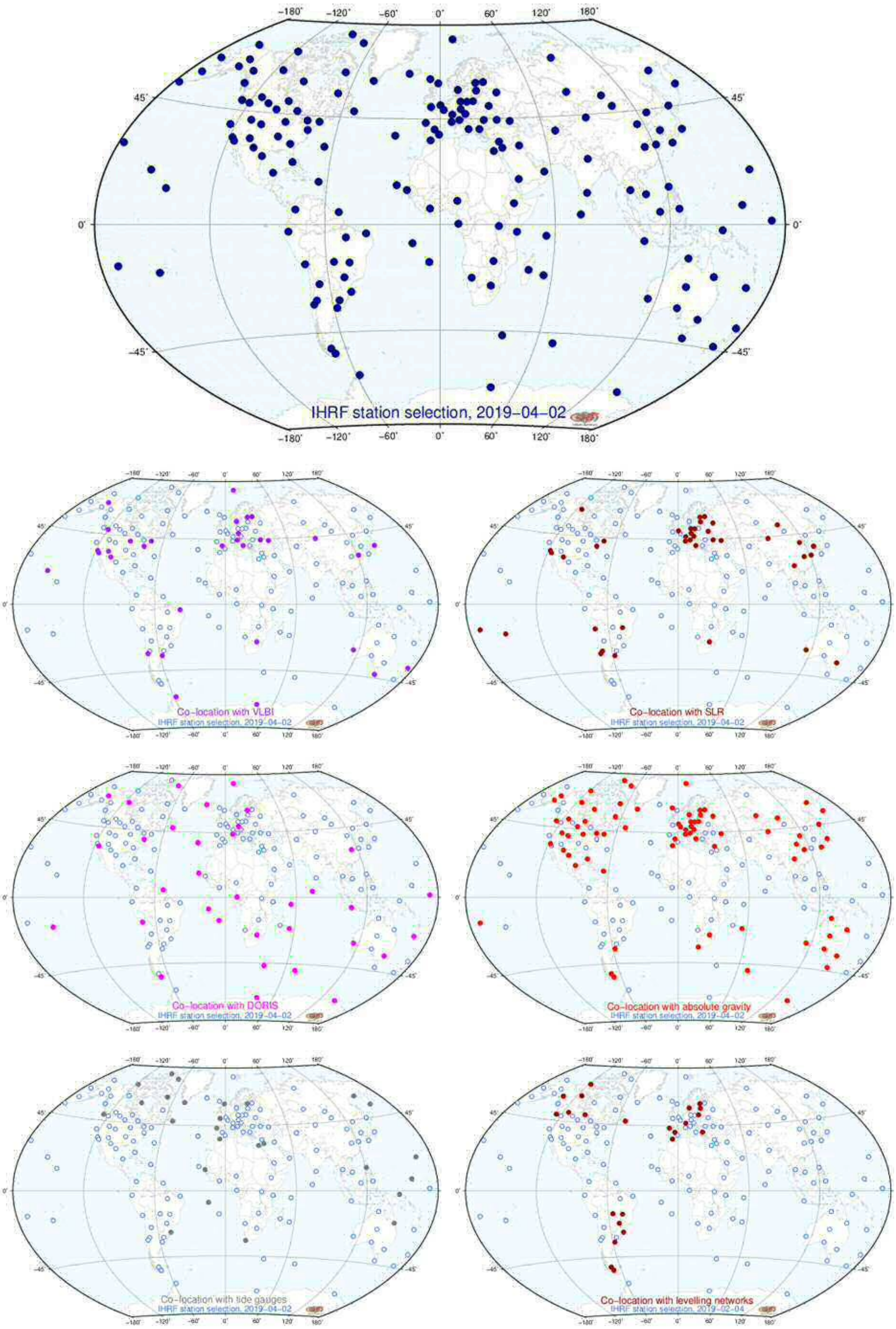

Fig. 1. IHRF stations as of April 2019 and the co-location with VLBI, SLR, DORIS, absolute gravity (IGRF), tide gauges and levelling networks' stations.

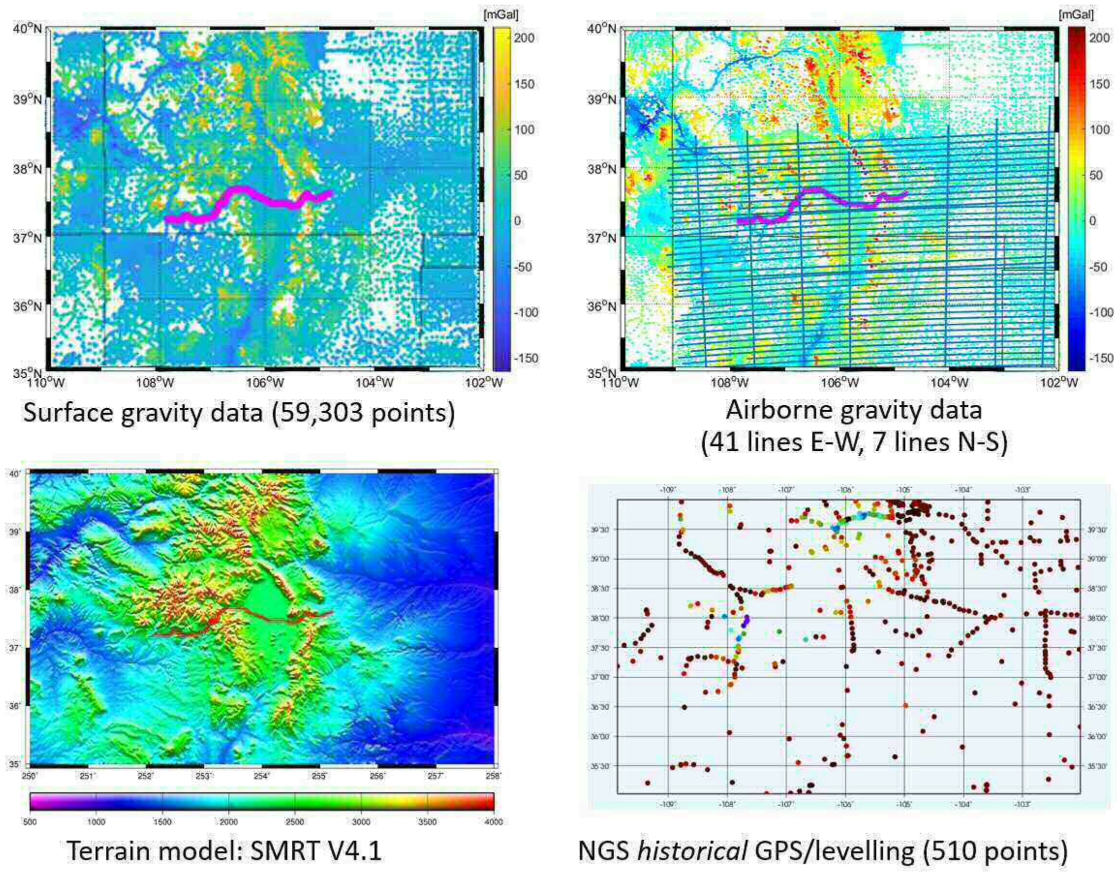

Fig. 2. Data provided by the US NGS/NOAA for the Colorado experiment. The red line represents the validation profile of the Geoid Slope Validation Survey 2017 (GSVS17). For validation, potential differences inferred from first order levelling and gravity corrections along this line will be compared with potential differences inferred from the different Colorado solutions (see Tables 2 and 3).

Table 1: Colleagues contributing to the station selection for the International Height Reference Frame (see Fig. 1)

- M Véronneau, J Huang - Natural Resources Canada, Canada
- I Oshchepkov - Center of Geodesy, Cartography and SDI, Russia
- D Roman, K Choi, K Ahlgren - US National Geodetic Service - NOAA, USA
- R Ruddick - Geoscience Australia, Australia
- M Amos - Land Information New Zealand, New Zealand
- SRC de Freitas - Universidade Federal do Parana, Brazil
- JR Chire Chira - Instituto Geográfico Nacional, Peru
- DA Piñón - Instituto Geográfico Nacional, Argentina
- C Estrella - Instituto Geográfico Militar, Ecuador
- A Álvarez - Instituto Geográfico Nacional, Costa Rica
- A Echalar Rivera - Instituto Geografico Militar, Bolivia
- D Avalos-Naranjo - Instituto Nacional de Estadística y Geografía, Mexico
- S Costa, R Luz - Instituto Brasileiro de Geografia e Estatística, Brazil
- D Blizkow, ACOC de Matos - Universidade de São Paulo, Brazil
- N Suárez - Servicio Geográfico Militar, Uruguay
- J Krynski - Institute of Geodesy and Cartography, Poland
- U Marti - Federal Office of Topography, swisstopo, Switzerland
- K Matsuo - Geospatial Information Authority of Japan, Japan
- H Abd-Elmotaal - Minia University, Egypt
- G Vergos - Aristotle University of Thessaloniki, Greece
- M Poutanen - Finnish Geospatial Research Institute, Finland

- PA Vaquero Fernández - Instituto Geográfico Nacional, Spain
- J Ågren - Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden
- H Wziontek - Bundesamt für Kartographie und Geodäsie, Germany
- V Mackern, W Martínez - SIRGAS
- R Forsberg - National Space Institute, Denmark
- I Liepinš - Latvian Geospatial Information Agency, Latvia
- T Jiang - Chinese Academy of Surveying and Mapping, China

Table 2: Colleagues contributing to the first experiment for the determination of IHRS coordinates (Sánchez et al. 2017)

- M Véronneau, J Huang - Natural Resources Canada, Canada
- G Vergos - Aristotle University of Thessaloniki, Greece
- D Blizkow, ACOC de Matos - Universidade de São Paulo, Brazil
- JL Carrión-Sánchez, SRC de Freitas - Universidade Federal do Parana, Brazil
- H Denker - Leibniz Universität Hannover, Germany
- R Pail - Technische Universität München, Germany
- V Lieb - Technische Universität München, Germany
- L Sánchez - Technische Universität München, Germany

Table 3: Colleagues contributing to the first computation for the Colorado experiment (Wang et al., 2018; Sánchez et al., 2018b)

- VN Grigoriadis, GS Vergos, DA Natsiopoulos - Aristotle University of Thessaloniki, Greece
- H Abd-Elmotaal - Minia University, Egypt
- B Erol, M Serkan Isik - Istanbul Teknik Üniversitesi, Turkey
- YM Wang, X Li, K Ahlgren - US National Geodetic Survey - NOAA, USA
- M Véronneau, J Huang - Natural Resources Canada, Canada
- J Ågren - Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden
- S Claessens, M Filmer - Curtin University, Australia
- EL Nicacio, JL Carrión, SRC de Freitas, R Dalazoana, VG Ferreira, Universidade Federal do Parana, Brazil
- D Blizkow, ACOC de Matos - Universidade de São Paulo, Brazil
- L Sánchez - Technische Universität München, Germany

Table 4: Colleagues contributing to the second computation for the Colorado experiment (results to be presented at the IUGG General Assembly 2019)

- VN Grigoriadis, GS Vergos, DA Natsiopoulos - Aristotle University of Thessaloniki, Greece and R Barzaghi, D Carrion - Politecnico de Milano, Italy
- T Jiang - Chinese Academy of Surveying and Mapping, China
- M Véronneau, J Huang - Natural Resources Canada, Canada
- S Claessens, M Filmer - Curtin University, Australia
- Q Liu, M Schmidt, L Sánchez - Technische Universität München, Germany
- R Forsberg - National Space Institute, Denmark
- K Matsuo - Geospatial Information Authority of Japan, Japan and R Forsberg - National Space Institute, Denmark
- M Willberg, R Pail - Technische Universität München, Germany
- B Erol, M Serkan Isik, S Erol - Istanbul Teknik Üniversitesi, Turkey
- J Ågren - Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden

- YM Wang, X Li, K Ahlgren, US National Geodetic Survey - NOAA, USA
- M Varga, T Bašic - University of Zagreb, Republic of Croatia and M Pitonák, P Novák - University of West Bohemia, Czech Republic
- R Barzaghi, D Carrion - Politecnico de Milano, Italy
- D Blizkow, ACOC de Matos, Escola Politécnica da Universidade de São Paulo, Brazil

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Further reading

Web site

A web site summarizing the main characteristics, achievements and challenges of the GGOS-FA "Unified Height System" is available at http://ihrs.dgfi.tum.de/. This information is mirrored at http://ggos.org/en/focus-areas/unified-height-system/.

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Willberg M., Zingerle Ph., Pail R.: *Least squares collocation with global model information for height systems*. International Symposium on Gravity, Geoid and Height Systems 2018 (GGHS2018), Copenhagen, Denmark, 2018.

GGOS Focus Area "Geohazards"

Chair: John LaBrecque (USA)
Geohazards Focus Area Representative to GGOS Science Panel: Dr. Diego Melgar (USA)

The Geohazards Monitoring Focus Area (GFA) will apply 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 that it would focus the application of 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 (GATEW) (http://kb.igs.org/hc/en-us/articles/218259648-Call-for-Participation-GNSS-Augmentation-to-the-Tsunami-Early-Warning-System). The GATEW CfP identifies the formal recommendations by the IGS, IUGG, IOC, and the APSG that support the CfP. The GATEW initiative will advance and implement the Resolution #4 of the IUGG 2015 General Assembly. The GATEW will build upon the benefits of the IGS Real Time Service (GPSRT) and the Multi-GNSS Experiment (MGEX) within the context of the UN-GGIM program.

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.

GATEW online library:

The GATEW maintains a library containing relevant documents, presentations, newsletters, videos and other files of interest to the GATEW community at the following link https://www.dropbox.com/sh/fg20mtydg136vx6/AABNr2kSnMo429nCxEHhBDfoa?dl=0 . The GFA will shift these files to the GGOS.org website when the appropriate GGOS web page is fully implemented.

The GFA initiated this first initiative with a program to inform influential organizations of the important contributions that real time GNSS analysis brings to effective and efficient tsunami warning systems. These efforts included presentations at significant scientific and governmental meetings.

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.

GGOS Working Group on GNSS Augmentation for Tsunami Warning

(As of January 13, 2018)

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
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, sg@sg@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

Presentations on GATEW were made at the following meetings:

2014, June 23-27, IGS Workshop 2014 , Pasadena, CA. http://kb.igs.org/hc/en-us/articles/204125433-2014-IGS Workshop-Summary-Recommendations
2015, June-22-July 2, IUGG-2015 Prague, Czech Republic
2015, August 10-15 , 9th ACES International Workshop, Chengdu, China
2015, August 24-28, Asia-Pacific Space Geodynamics Project-2015 Moscow, Russia, http://agora.guru.ru/display.php?conf=apsg-2015&page=program
2015, November 1-6, International Committee on GNSS-10, Boulder, US
2015, December 1-4, Asia-Pacific Regional Space Agency Forum (APRSAF 22) Bali, Indonesia
2015, December 14-18, AGU Fall Meeting, Session#8328 Global Naviga6on Satellite System for Natural Hazard Mitigation- Invited Talk, San Francisco, US
2016, February 8-12, International GNSS Service Workshop (IGS-2016) Sydney, NSW, Australia http://kb.igs.org/hc/en-us/articles/205944657-2016-IGS-Workshop-Information
2016, November 6-11, International Committee on GNSS-11, Sochi, Russia
2016, April 17-22, European Geosciences Union General Assembly-2016, Vienna, Austria
2016, May 3-5, COCONet Workshop, Punta Cana, Dominican Republic
2016, September 29 – October 1, Subduction Zone Observatory Workshop, Boise, US
2016, November 14-16, 8th Multi-GNSS Asia (MGA) Conference, Manila, Phillipines
2017, April 23-28, European Geosciences Union General Assembly-2017, Vienna, Austria
2017, July 3-7, 2017 IGS workshop 2017, Paris, http://kb.igs.org/hc/en-us/articles/216574478-2017-IGS-Workshop-Information
2017, July 25-26 GTEWS 2017 Workshop, Sendai, Japan
2017, July 29-30, UNGGIM TECHNICAL SEMINAR REFERENCE FRAME IN PRACTICE, Kobe, Japan
2017, July 30-Aug 4, IAG-IASPEI General Assembly and UN-GGIM-AP meeting in Kobe, Japan.
2017, August 15-18, Asia-Pacific Space Geodynamics Project-2017, Shanghai, China http://english.shao.cas.cn/rh/ca/201705/t20170502_176593.html
2017, December 11-15, AGU Fall Meeting, Gilbert F. White Distinguished Lecture, New Orleans, US
2018, June 18, IX Hotine-Marussi Symposium, LaBrecque J, Crespi M: GGOS Focus Area on Geohazards Monitoring – The role of real-time GNSS data processing, Rome, Italy
2018, December 10-14, AGU Fall Meeting, Washington, DC, US
2019, April 4-11, Institute of Navigation Pacific PNT Conference, Honolulu, Hawaii, US

GTEWS 2017: the 1st Meeting of the GATEW:

The GATEW 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. Over 90% of the GATEW organizations registered for GTEWS2017 and GATEW provided a majority of the presentations.

GTEWS Publications:

The GFA assumed leadership in the assembly and publication of the findings of the GTEWS 2017. The GTEWS workshop report containing video and presentations of the proceedings and workshop recommendations is available on the website of the APRU (http://apru.org/resource/gnss-early-warning-report/) and within the GFA online library https://www.dropbox.com/s/zo4frdmsqis9scf/GTEWS2017.pdf?dl=0 .

The UNISDR has accepted an updated report of the GTEWS 2017 initiative for its GAR19 publication. The UN Global Assessment Report on Disaster Risk Reduction (GAR) is the flagship report of the United Nations on worldwide efforts to reduce disaster risk. The GAR is published biennially by the UN Office for Disaster Risk Reduction (UNISDR), and is the product of the contributions of nations, public and private disaster risk-related science and research, amongst others. GAR19 report is available at this site https://gar.unisdr.org/. A copy of the updated GTEWS report is also available at the GFA online library https://www.dropbox.com/s/15rnypek9vqacp4/Global%20Navigation%20Satellite%20System%20Enhancement%20for%20Tsunami%20Early%20Warning%20Systems.pdf?dl=0.

Recommendations of the GTEWS 2017 report

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.

Future Actions and Milestones:

- The GFA and the GATEW working group will work to develop the recommendations of the GTEWS 2017 workshop.
    - The READI Group has submitted a proposal to fund a cloud based GTEWS analysis system available to all national prototype GTEWS networks as proposed. (Action on Recommendation 2)
    - The GFA will undertake an effort to work with global Internet Service Providers to increase the participation of identified real-time GNSS stations with the GNSS Shield. (Action on Recommendation 3)
    - Wuhan University is in discussions to provide real-time GNSS distribution software to one or more of the national prototype networks to advance real-time data sharing. (Action on Recommendation 4)
- The Geohazards Focus Area recommends changing the status of GATEW to a Standing Committee for GNSS Enhancement of Tsunami Early Warning (GATEW). We expect that the GATEW standing committee will become increasingly important as the Indo-Pacific begins to integrate the several prototype GNSS early warning networks into an Indo-Pacific real time network.
- Expand the membership and influence of the GATEW standing committee.

GGOS Focus Area "Sea-Level Change, Variability and Forecasting"

Chair: *Tilo Schöne (Germany)*
Co-Chairs: *CK Shum (USA), Mark Tamisiea (UK), Phil Woodworth (UK)*

Purpose and Scope

Sea level rise and its impact on human habitats and economic well being have received considerable attention in recent years by the general public, engineers, and policy makers. A GGOS retreat in 2010 has identified sea level change as one of the cross-disciplinary themes for geodesy. Sea Level is also a major aspect in other observing systems, like e.g. GEO or GCOS. The primary focus of GGOS Focus Area 3 is to demonstrate and apply geodetic techniques, under the umbrella of GGOS, to the possible mitigation or adaption of sea level rise hazards including studies of the impacts of its change over the world's coastal and deltaic regions and islands, and to support practical applications such as sustainability. One major topic is the identification of gaps in geodetic observing techniques and to advocate enhancements to the GGOS monitoring network and Services where necessary.

Activities and Actions

Focus Area 3 has identified actions to be undertaken to advance geodetic techniques and technologies applied to sea level research. These are

- Identification or (re)-definition of the requirements for a proper understanding of global and regional/local sea-level rise and its variability especially in so far as they relate to geodetic monitoring provided by the GGOS infrastructure, and their current links to external organizations (e.g., GEO, CEOS, and other observing systems).
- Identification of organizations or individuals who can take forward each requirement, or act as points of contact for each requirement, where they are primarily the responsibility of bodies not related to GGOS.
- Identification of a preliminary set of practical or application (as opposed to scientific) pilot projects, which will demonstrate the viability, and the importance of geodetic measurements to mitigation of sea-level rise at a local or regional level. This identification will be followed by construction of proposals for pilot projects and their undertaking.

In the long-term, the aim is to support forecasting of global and regional sea level for the 21st century with an expected forecast period of 20 to 30 years or longer.
An open Call for Participation was issued in 2012. Special emphasis is given to local and regional projects which are relevant to coastal communities, and which depend on the global perspective of GGOS. Three projects have been accepted. Thus, GGOS Focus Area 3 now has approved "Landmark" projects:

The Use of Continuous GPS and Absolute Gravimetry for Sea Level Science in the UK (NERC British Isles continuous GNSS Facility (BIGF), University of Nottingham, UK), (NERC National Oceanography Centre (NOC), Liverpool, UK).

Revisiting the Threat of Southeast Asian Relative Sea Level Rise by Multi-Disciplinary Research (Delft University of Technology (DUT), Delft, Netherlands; University of Leeds, Leeds, United Kingdom; Ecole Normale Supérieure, Paris, France; Chulalongkorn University, Bangkok, Thailand; Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands)

Bangladesh Delta Relative Sea-Level Rise Hazard Assessment (Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, Ohio, USA; University of Bonn, Bonn, Germany; GeoForschungsZentrum Potsdam (GFZ), Germany)

and additionally

Subsidence Monitoring in Urban Areas of the Republic of Indonesia with GNSS-controlled tide gauges and supporting methods (National Geospatial Agency (BIG) of Indonesia; Helmholtz Centre Potsdam GFZ, Germany; Institut Teknologi Bandung, Indonesia) together with the University of Cologne working on social aspects,

which is in preparation for submission.

All projects have their major focus on the combination of sea level and geodetic monitoring in an integrative approach. Also in the reporting period, Focus Area 3 continued communications with organizations, dealing with other than geodetic aspects of sea level monitoring. These are, e.g., the UNESCO International Oceanographic Commission Group of Experts (UNESCO/IOC GE) and the World Glacier Monitoring Service (WGMS). In Germany in 2016 a special research program (SPP 1889 - Regional Sea Level Change and Society, www.spp-sealevel.de) started and is dealing with many aspects relevant to GGOS Focus Area 3. Also cooperation with the IGS Tide Gauge Benchmark Monitoring Working is continued. A major step for GGOS Focus Area 3 was the alignment of its activities with the GGOS Bureau of Networks and Observations (B&O). The improvement of the observation network for sea level research is a major open topic. In 2015, the GLOSS Group of Experts (GLOSS-GE), the IGS TIGA-WG and the GGOS Focus Area 3 had submitted the Report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges" for consideration by GGOS. This report is now accepted by the GGOS CB and the GGOS B&O.
The GNSS-controlled tide gauges are an important monitoring component in climate and geodetic science. Over the years, the network of collocated stations has been growing, not at least through the constant effort of IOC/GLOSS Group of Experts, the IGS TIGA-WG, and GGOS. Focus Area 3 plays a significant role in improving the network coverage and the establishment of local ties between GNSS and tide gauges.

Objectives and Planned Efforts for 2017-2019 and Beyond

- Review and Refine current and future aspects of geodetic contributions for sea level research with groups identified in AS-SL-01/AS-SO-02
- Work on to identify and contact emerging Focus Area 3 pilot projects
- Support Focus Area 3 projects
- Establish/improve the outreach activities with the help of the GGOS-CO
- Work with IGS/TIGA on results of the TIGA reprocessing
- Work with GGOS CB and GGOS B&O on the findings of the report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges"
- Identify geodetic monitoring aspects relevant to Focus Area 3
- Maintain the GGOS web space for the Focus Area 3.

Website
http://www.ggos.org/en/focus-areas/sea-level-change-variability-and-forecasting/

Publications and Presentations

Woodworth, P., Aarup, T., Gaël, A., Donato, V., Enet, S., Edwing, R., Heitsenrether, R., Farre, R., Fierro, J., Gaete, J., Foden, P., Pugh, J., Perez, B., Rickards, L., Schöne, T. (Eds.)(2016):Manual on Sea-level Measurements and Interpretation, Volume V: Radar Gauges, (IOC Manuals and Guides ; 14) (JCOMM Technical Report ; No. 89), Paris : Intergovernmental Oceanographic Commission of UNESCO, 2016

Michael R. Pearlman, Chopo Ma, Ruth Neilan, Carey Noll, Erricos Pavlis, Jérôme Saunier, Tilo Schoene, Riccardo Barzaghi, Daniela Thaller, Sten Bergstrand, and Juergen Mueller: The GGOS Bureau of Networks and Observations: an update on the Space Geodesy Network and the New Implementation Plan for 2017 - 18,Geophysical Research Abstracts, Vol. XX, General Assembly European Geosciences Union (Vienna 2017), http://meetingorganizer.copernicus.org/EGU2017/EGU2017-10814.pdf

Schöne, T., Shum, C., Tamisiea, M., Woodworth, P. (2015): GGOS Theme 3: Understanding and Forecasting Sea-Level Rise and Variability - Scientific programme, 26th IUGG General Assembly (Prague 2015). http://gfzpublic.gfzpotsdam.de/pubman/item/escidoc:1437893:5/component/escidoc:1437892/GGOS_Theme3

Tilo Schöne, Ck Shum, Mark Tamisiea, and Philip Woodworth: GGOS Focus Area 3: Understanding and Forecasting Sea-Level Rise and Variability, Geophysical Research Abstracts, General Assembly European Geosciences Union (Vienna 2017), http://meetingorganizer.copernicus.org/EGU2017/EGU2017-8814.pdf

Tilo Schöne, Ck Shum, Mark Tamisiea, and Philip Woodworth: GGOS Focus Area 3: Understanding and Forecasting Sea-Level Rise and Variability, 10th GEO European Projects Workshop 2016, Berlin, 31.5.-2.6.2016, https://ec.europa.eu/easme/en/geo-european-projects-workshop-2016

GGOS Focus Area "Geodetic Space Weather Research"

Chair: Michael Schmidt (Germany)
Vice-Chair: Klaus Börger (Germany)

Members:

- *Andres Calabia Aibar (Spain)*
- *Fabricio dos Santos Prol (Bazil)*
- *Ehsan Forootan (Iran)*

Purpose and Scope

The issue "Space Weather" is an interdisciplinary field of research, where the subject geodesy contributes essentially by its expertise on ionosphere and thermosphere. The Focus Area on "Geodetic Space Weather Research" concentrates on the upper atmosphere, i.e. the compartments ionosphere and thermosphere, being original manifestations of space weather. Thus, in a nutshell, the main **objectives of the Focus Area** are (1) the development of improved ionosphere models and (2) the development of improved thermosphere models.

Objective (1) aims at the high-precision as well as the high-resolution (spatial and temporal) modeling of the electron density. This finally allows to compute a signal propagation delay, which can be used for different geodetic applications, in particular for "positioning, navigation and timing (PNT)". Moreover, it is also important for other techniques using electromagnetic waves, such as satellite- or radio-communications. Concerning objective (2), satellite geodesy will obviously benefit when working on "precise orbit determination (POD)", but there are further technical matters like the "collision analysis" or the "re-entry calculation", which will become more reliable when using high quality thermosphere models.

For a "Geodetic Space Weather Research", geodesy has to extend its traditional perspective on thermosphere and ionosphere, i.e. geodesy has to move away from the limited concept of regarding the atmosphere as only being a disturbing effect affecting electromagnetic waves. "Geodetic Space Weather Research" has to take into account the complete chain of cause and effect, which means it has to start with processes and events on the Sun. Next, it has to continue with the effects on the geosphere and finally it has to consider the impact on (geodetic) applications and systems. Besides this general chain of cause and effect interactions, the physics and especially coupling processes between thermosphere and ionosphere have to be regarded. Geodetic Space Weather Research is "fundamental research" too, particularly when intending to detect and to survey structures of the ionosphere, e.g. bubbles, or when proving special phenomena like electrojets. Summarized, geodetic space weather research has to be based on a) the use and combination of all space geodetic observation methods, b) the use of sun observations, c) real-time modeling, d) the development of deterministic and stochastic forecast approaches and e) assimilation strategies.

Finally, it should be mentioned that the work within the proposed Focus Area will be carried out in close relation to the International Association of Geomagnetism and Aeronomy (IAGA), since this organisation is also concerned with the understanding of properties related, e.g. to the ionosphere and magnetosphere as well as the Sun and the solar wind.

Activities during the period 2017-2019

Four new GGOS Joint Study Group (JSG) and Joint Working Groups (JWG) have to be installed into the IAG structure within the 4-year period 2019 to 2023. These are

- JSG 1: **Coupling processes between 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).

The chair positions of JWG 2 and JWG 3 are still vacant. Appropriate candidates have been selected and approached, but they not yet confirmed their commitment. Ehsan Forootan (Institute of Physics and Meteorology, University of Hohenheim, Stuttgart, Germany) became member of the GGOS Science Panel.

During the last two years, the work and the activities of the Focus Area were presented at different meetings, see section "Presentations".

Next actions of the Focus Area are:

- to find the chairs of JSG 1 and JWG 1
- to find the members of the JSG/JWGs and
- to set up the Terms of Reference of the JSG/JWGs.

In the following IAG four-year period the Focus Area will mainly work on the following three aspects:

- extensive simulation studies have to be performed 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.

Website

http://www.ggos.org/en/focus-areas/geodetic-space-weather-research

Presentations

- poster presentation at the GEO WEEK 2017 in Washington D.C., October 23 to 27, 2017
- poster presentation at the EGU 2018 in Vienna, GGOS Session, April 10, 2018
- poster presentation at the IX Hotine-Marussi Symposium in Rome in June 18 to 22, 2018
- poster presentation at the EGU 2019 in Vienna, GGOS Session, April 9, 2019
- poster presentation at the ESA Living Planet Symposium in Milan, May 13 to 17, 2019

Communication and Outreach Branch

http://www.iag-aig.org

President: József Ádám (Hungary)
Secretary: Szabolcs Rózsa (Hungary)
Editor IAG Newsletter: Gyula Tóth (Hungary)

Introduction

The period of 2015-2019 is the fourth term in the operation of the Communication and Outreach Branch (COB) hosted at the Department of Geodesy and Surveying of the Budapest University of Technology and Economics (BME).

The Communication and Outreach Branch is one of the components of the Association. According to the new Statutes (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members.

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 2016 (Drewes et al., 2016; Ádám and Rózsa, 2016; Rózsa, 2016), respectively.

In the past period of the fourth term (since the 2015 IUGG General Assembly in Prague till June, 2019) the COB's President attended the IAG Executive Committee (EC) meeting in three cases (Potsdam, April 25-26, 2016; Vienna, April 28, 2017 and Vienna, April 13, 2018), while COB's Secretary represented COB on the EC meeting in Washington D.C., December 10, 2018. Note that the COB's Secretary also represented IAG in the UN GGIM GGRF WG (focus group on Outreach and Communication) and on its telecon and personal meetings (Vienna, April 12, 2018).

A joint meeting of the IAG Office (H. Drewes and F. Kuglitsch), the IAG GGOS Coordinating Office (CO: G. Stangl, Ph. Mitterschiffthaler and M. Madzek) and the IAG COB (J. Ádám and Sz. Rózsa) was organized in Vienna at BEV in February 24, 2017, where the following topics were discussed:

- the structure and operation of the IAG/GGOS website;
- issues of the cooperation among the IAG Office (Munich), IAG GGOS CO (Vienna) and IAG COB (Budapest).

Note that the IAG COB's Secretary also attended at the Potsdam IAG EC meeting in April of 2016. Both the COB's President and Secretary participated at the IAG Retreat organized at Potsdam immediately after the EC meeting in April 25-26, 2016 (Beutler, 2016).

The COB provides communication, public information and outreach links, in particular via the official IAG Website and the monthly IAG Newsletters. These are the main activities of the IAG Communication and Outreach Branch.

The IAG Website

The Communication and Outreach Branch maintained the IAG Website. The website has been operational, no significant downtime has been experienced in the service. A regular update of the content has been carried out using the material provided by Association and Commission leaders, conference organizers and other members of the Association.

In the second half of the period the website has been redesigned after a consultation with the IAG Office and the Steering Committee members. Since the IT infrastructure (both the software and hardware) is becoming outdated, a complete refurbishment of the hardware and the development of a new IAG webpage has been initiated in late 2018.

The event calendar of the website is currently redesigned according to the decision of the joint meeting of the COB, GGOS CO and the IAG Office in order to enable all of the aforementioned entities to use the same database for event calendars all over the IAG. Moreover the synchronization of IAG events with the Google calendar is being developed.
The IAG Website is visited by ca. 50 users per day. The daily number of visitors significantly increase at online publication of the IAG Newsletter, that denotes the importance and the efficiency of the latter communication channel, too (Fig 1.).

Furtunately website audience comes from almost all over the world, except some African countries. The demographic distribution of the visitors show that almost 40% of the visitors are aged between 25 and 34 years.

All organizers of the IAG meetings were asked to send the announcements for meetings as well as summarising reports on these events to the COB in order to put these texts into the IAG Website and IAG Newsletter informing the whole community.

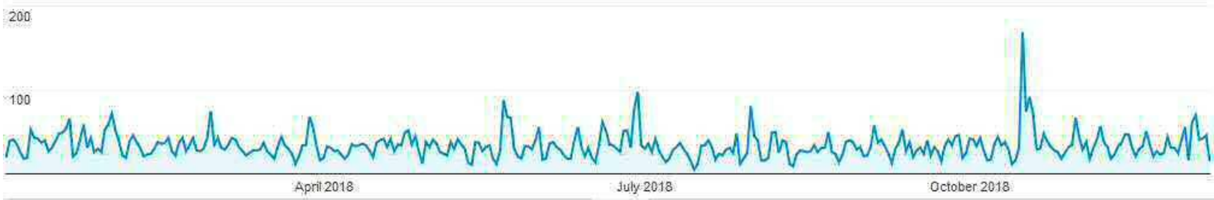

Figure 1. Weekly visitors from January 2018 to December 2018.

Figure 2. IAG website audience (year 2018)

IAG on Social Media

The COB is maintaining the Facebook and Twitter page of the Association. Our Facebook page is: https://www.facebook.com/InternationalAssociationOfGeodesy/ while you may follow us on Twitter at https://twitter.com/iag_geodesy . It is remarkable that the geographic distribution of Facebook followers do not agree with the IAG website. There are many African, Asian and South American countries among the top 10 countries, like Egypt, India, Brazil, Chile, Ethiopia (Fig. 3.). Since social media is becoming a more and more important communication channel, we would like to encourage the geodetic community to follow and like the above mentioned pages!

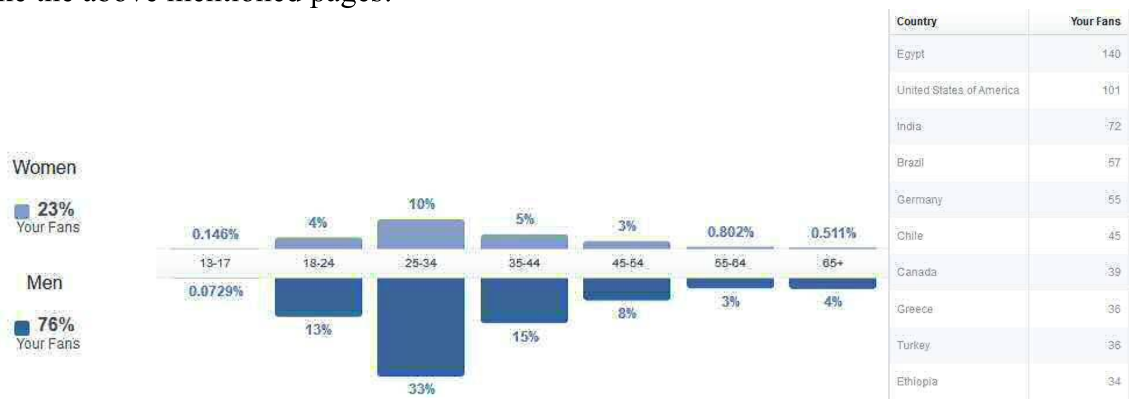

Figure 3. Demographic and geographic distribution of the Facebook followers.

In the next term COB plans to open the LinkedIn page of IAG and the establishment of the Chinese WeChat page is being considered, too.

The IAG Newsletter

The IAG Newsletter is regularly issued monthly, usually at the last working day of the month. Altogether 48 IAG Newsletters have been published from July 2015 till June 2019 and can be accessed on the IAG new website in HTML, HTML print version and in PDF formats. Since December 2016 the IAG Newsletter contains a new IAG/IUGG logo. We strive to publish only relevant information by keeping the Newsletter updated on a per-monthly basis. IAG Individual Members, IUGG and JB GIS Presidents and Secretaries as well as interested persons mainly in developing countries received it in PDF and/or text attachments, with a link in the e-mail message to access the actual HTML Newsletter on the IAG website. As of June 2019 the IAG Newsletter is sent to 862 subscribers by e-mail. Selected content of the electronic Newsletters were compiled and have been sent regularly to Springer for publication for 45 issues of the Journal of Geodesy (Vol 89/9 – 93/8).

Outreach Activities

The COB has been active in the publishing of information material in the reporting period. A new version of the IAG brochure has been published (16 coloured pages), which targets the wider public and decision makers by introducing Geodesy in general as well as the role of the Association to the readers (Ádám and Rózsa, 2017). It has a chapter on the Global Geodetic Observing System, and provides information on the IAG components (Commissions, Inter-Commission Committee, Services, etc.).

The brochure can be downloaded from the opening page of the IAG website, together with the updated IAG leaflet (Ádám and Rózsa, 2017).

H. Drewes and J. Ádám (2016) prepared a summary on “The International Association of Geodesy (IAG) – Historical Overview” which appeared in The Geodesist’s Handbook 2016.

Since the website and the newsletter are living from the input of the IAG community, we regularly request (in the middle of the month) the Executive Committee (EC) members, service directors, IAG national delegates, etc to provide us any interesting news, notices, reports, scientific highlights, etc. Note that the four IAG Commissions, the ICCT, the GGOS and the 13 IAG Services maintain their individual websites (which all accessible via the official IAG website) and in some cases newsletters, therefore obviously it's hard to get materials from them. However, the IAG presence on social media needs more frequent geodesy news, short articles, new scientific highlights, reports on satellite missions, etc.

The EC at its meeting is San Francisco in December of 2015 decided to continue publishing short articles in GIM International journal. Therefore, all commissions and services were requested to contribute once per year, and also to report about all IAG sponsored symposia. Since the SF-meeting every month, one report and/or article (up to one page) by a commission/service/symposium was available and submitted to the GIM International (and IAG Newsletter as well). Chris Rizos acts as the editor of the text and submit them to the GIM editors. The scheduling of the monthly report submissions is mainly organized by the COB President. Thus the IAG appeared and is visible monthly on the level of a wider geospatial community. We keep a balance of IAG EC stories, reports on major meetings, highlights of commissions and services, IAG schools, etc.

The COB also keeps track of all IAG related events by the meetings calendar.

Summary

In sum, the following activities were done:
a) the IAG website was updated, improved and continuously maintained;
b) four years ago IAG joined to both Facebook and Twitter;
c) the IAG Newsletter was regularly issued monthly and distributed electronically, and selected parts of them were prepared to publish in the Journal of Geodesy as IAG News;
d) regularly publishing IAG-related short articles in the GIM International journal;
e) new version of the IAG Leaflet was prepared, printed and distributed at different IAG meetings;
f) the large IAG Brochure was reprinted;
g) some works were made in preparation and for finalizing The Geodesist's Handbook 2016 (Drewes et al., 2016), and
h) many e-mail correspondences to the community as part of the outreach activities.

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IAG Office – Report of the Secretary General

http://iag.dgfi.tum.de

Secretary General: Hermann Drewes (Germany)
Assistant Secretary: Franz Kuglitsch (Germany)

Introduction

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

Council meetings took place during the IUGG General Assembly 2015 in Prague, Czech Republic and the IAG/IASPEI Scientific Assembly 2017 in Kobe, Japan. The list of national correspondents forming the IAG Council was regularly updated in contact with the IUGG Secretary General, who is responsible for the official accreditation. The Council was informed by e-mail about activities of the Bureau and the Executive Committee.

IAG Executive Committee (EC)

The Executive Committee consists of the IAG Bureau, the immediate Past-President, the four Commission Presidents, the Chair of the GGOS, the President of the COB, three representatives of the Services, and two Members-at-Large. Seven EC meetings were held from July 2015 to December 2018: Prague, Czech Republic, July 2015, San Francisco, CA/USA, December 2015, Potsdam, Germany, April 2016, Vienna, Austria, April 2017, Kobe, Japan, July 2017, Vienna, Austria, April 2018, and Washington, USA, December 2018. Minutes were prepared for the EC members, and the meeting summaries were published in the electronic IAG Newsletter and in the Journal of Geodesy (Springer-Verlag). They are available online at the IAG Website (http://www.iag-aig.org) and in the IAG Office Homepage (http://iag.dgfi.tum.de).

IAG Bureau

The IAG Bureau, i.e. the IAG President, Vice-President and Secretary General, communicated by e-mail, held teleconferences and met before the EC meetings. It discussed the membership of IAG's Journal of Geodesy with the Editor-in-Chief, recommended IAG Honorary Officers and IAG Fellows for decision of the Executive Committee, and 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 assists the Secretary General in the administrative organization 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 activities were the organization and execution of the joint IAG-IASPEI Scientific Assembly 2017 in Kobe, Japan, and the preparation of the IUGG General Assembly 2019 in Montreal, Canada. The Geodesist's Handbook 2016, 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 2015–2017 (Travaux de l'AIG Vol. 40) and the IAG Reports 2015-2019 (Vol. 41) 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 2016 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 Committee on Theory (ICCT). 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 2015–2017 and 2015-2019 (Travaux de l'AIG Vols. 40 and 41). Each Commission maintained its individual Homepage and held several symposia, workshops and other meetings (see below). All of them were organising symposia at the IAG-IASPEI Scientific Assembly 2017 and the IUGG/IAG General Assembly 2019.

Services

The presently thirteen IAG Services split into three general fields: geometry (IERS, IDS, IGS, ILRS, and IVS), gravity (IGFS, ICGEM, IDEMS, IGeS, IGETS and BGI) and overlapping (BIPM and 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 2015–2019 in the Geodesists' Handbook 2016, and the progress reports in the IAG Reports 2015–2017 and 2015-2019 (Travaux de l'AIG Vols. 40 and 41). Most of the Services held international meetings (see below). The Combination Service for Time-variable Gravity models (COST-G) was established as a product centre with in the International Gravity Field Service (IGFS), and there was an initiative to re-establish the International Altimetry Service (IAS).

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 period 2015 to 2019. It 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 new Focus Area on Geodetic Space Weather Research was established in 2018, and 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. GGOS organized symposia at the IAG/IASPEI Scientific Assembly 2017 and IUGG/IAG General Assembly 2019.

Coordination with other organisations

IAG maintains close cooperation with several organizations outside IUGG. There were frequent meetings with

- 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 IAG counts 213 individual members, students are free of charge.

Meetings

IAG sponsored meetings from July 2015 to July 2019 were:

- International DORIS Service (IDS) Analysis Working Group Meeting, Greenbelt, MD, USA, 15-16 October 2015.
- International Laser Ranging Service (ILRS) Analysis Working Group Meeting, Matera, Italy, 24 October 2015.
- International Laser Ranging Service (ILRS) Technical Workshop 2015, Matera, Italy, 26-30 October 2015.
- Latin American Reference System (SIRGAS) Symposium, Santo Domingo, Dominican Republic, 18-20 November 2015.
- 9th International Symposium on Mobile Mapping Technology (MMT2015), Sydney, Australia, 9-11 December 2015.
- IGS Workshop, Sydney, Australia, February 15 – 19, 2016;
- 9th IVS General Meeting, Ekudeni (Johannesburg), South Africa, March 13 – 17, 2016;
- 3rd Joint Symposium on Deformation Monitoring, Vienna, Austria, March 30 – April 1, 2016;
- 4th IAG Symposium "Terrestrial gravimetry: Static and mobile measurements", Saint Petersburg, Russia, April 12 – 15, 2016;
- European Reference Frame Symposium (EUREF 2016), San Sebastian, Spain, May, 25 - 27, 2016;

- 18th Geodynamics and Earth Tide Symposium 2016, Trieste, Italy, June 5 – 9, 2016;
- Joint IAU/IAG/IERS Symposium "Geodesy, Astronomy and Geophysics in Earth Rotation (GAGER2016)", Wuhan, Hubei, China, July 18 – 23, 2016;
- Int. Symposium on Geodesy and Geodynamics (ISGG2016), Tianjin, China, July 22 – 26, 2016;
- 1st International Conference on GNSS+ (ICG+2016), Shanghai, China, July 27 – 30, 2016;
- IAG Commission 4 "Positioning and Applications" Symposium, Wroclaw, Poland, September 4-7, 2016;
- 18th General Assembly of WEGENER "Understanding earth deformation at plate boundaries", Ponta Delgada, Azores, Portugal, September 12-15, 2016;
- 1st Joint Commission 2 and IGFS Meeting, International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS2016), Thessaloniki, Greece, September 19-23, 2016;
- First International Workshop on VLBI Observations of Near-field Targets, Bonn, Germany, October 5-6, 2016;
- 20th International Workshop on Laser Ranging, Potsdam, Germany, October 9 – 14, 2016;
- GGOS Days, Cambridge, MA, USA, October 24 – 28, 2016;
- IDS Workshop, La Rochelle, France, October 31 – November 1, 2016;
- Reference Frame for South and Central America Symposium (SIRGAS2016), Quito, Ecuador, November 16 – 18, 2016;
- 1st International Symposium - Applied Geomatics and Geospatial Solutions, Rosario, Argentina, April 3 – 7, 2017;
- 9th IVS Technical Operations Workshop, Westford, MA, USA, April 30 – May 4, 2017;
- EUREF 2017 Symposium, Wroclaw, Poland, May 17 – 19, 2017;
- DORIS Analysis Working Group Meeting, London, UK, May 22 – 24, 2017;
- 21st Meeting of the Consultative Committee for Time and Frequency, Sèvres, France, June 6-9, 2017;
- 1st IUGG Symposium on Planetary Science, Berlin, Germany, July 3 – 5, 2017;
- IGS Workshop 2017, University of Paris-Diderot, France, July 3 – 7, 2017;
- IAG/GGOS/IERS Unified Analysis Workshop, Paris-Diderot, France, July 10 – 12, 2017;
- 2017 GNSS Tsunami Early Warning System Workshop, Sendai, Japan, July 25 – 27, 2017;
- IAG and IASPEI Joint Scientific Assembly, Kobe, Japan, July 30 – August 4, 2017.
- Asia-Pacific Space Geodynamics Symposium, Shanghai, China, August 15-18, 2017;
- Workshop on Glacial Isostatic Adjustment and Elastic Deformation, Reykjavik, Iceland, September 5-7, 2017;
- 3rd COSPAR Symposium "Small Satellites for Space Research", Jesu, South Korea, September 18-19, 2017;
- IAG Workshop "Satellite Geodesy for Climate Studies", Bonn, Germany, September 19-21, 2017;
- Journées des Systèmes de Référence et de la Rotation Terrestre, Paris, France, September 25-27, 2017;
- International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications, Chania, Greece, April 23-26, 2018;
- EUREF Symposium 2018, Amsterdam, Netherlands, May 30 - June 01, 2018;
- 10th IVS General Meeting, Longyearbyen, Spitsbergen, Norway, June 3-8, 2018;
- 1st Workshop of the International Geodynamics and Earth Tide Service (IGETS), Potsdam, Germany, June 18-20, 2018;
- IX Hotine-Marussi Symposium on Mathematical Geodesy, Rome, Italy, June 18-22, 2018;
- 42nd COSPAR Scientific Assembly including IAG Commission 1 Symposium, July 14-22, 2018;
- IAG Commission 1 Symposium Reference Frames for Applications in Geosciences (REFAG2018), Pasadena, CA, USA, July 15-21, 2018;
- 8th UN-GGIM Session, New York, USA, August 1-3, 2018;
- XXXth General Assembly of the IAU, Vienna, Austria; August 20-31, 2018;

- 19th General Assembly of WEGENER, Grenoble, France, September 10-13, 2018;
- Gravity, Geoid and Height Systems (GGHS 2) Symposium, Copenhagen, Denmark, September 17-21, 2018;
- International DORIS Service (IDS) Workshop, Ponta Delgada, Azores Portugal, September 24-26, 2018;
- GGOS Days 2018, Tsukuba, Japan, October 2-4, 2018;
- SIRGAS Symposium 2018, Aguascalientes, Mexico, October 9-12, 2018;
- SIRGAS Workshop on Vertical Reference System, Mexico, October 15-17, 2018;
- IGS 2018 Workshop, Wuhan, China, October 29 - November 2, 2018;
- International Workshop on GNSS Ionosphere (IWGI2018), Shanghai, China, November 4-6, 2018;
- 21st Workshop on Laser Ranging, Canberra, Australia, November 5-9, 2018.
- 24th Meeting of the European VLBI Group for Geodesy and Astronomy (EVGA) and 18th IVS Analysis Workshop, Las Palmas, Gran Canaria, Spain, March 14-20, 2019;
- IGS 2019 Analysis Workshop, Potsdam, Germany, April 15-17, 2019;
- 10th IVS Technical Operations Workshop, Westford, MA, USA, May 5-9, 2018;
- 4th Joint International Symposium on Deformation Monitoring (JISDM), Athens, Greece, May 15-17, 2019; Tallinn, Estonia, May 22-24, 2019.
- EUREF 2019 Symposium,

The following IAG Schools were sponsored from July 2015 to June 2017:
- VII SIRGAS School on Reference Systems, Santo Domingo, Dominican Republic, 16-17 November 2015.
- 2nd IVS Training School on VLBI for Geodesy and Astrometry, Hartebeesthoek, South Africa, March 9 – 12, 2016;
- ISG Geoid School, Ulaanbaatar, Mongolia, June 6 – 10, 2016;
- SIRGAS School on Vertical Reference Systems, Quito, Ecuador, November 21 – 25, 2016;
- 3rd IVS Training School on VLBI for Geodesy and Astrometry, Las Palmas, Gran Canaria, Spain, March 14-20, 2019.

Publications

The Journal of Geodesy, the official IAG scientific periodical with an Editor in Chief approved by the IAG Executive Committee, published continuously monthly issues in Springer-Verlag.

The IAG Symposia Series published the following volumes 2015-2019:
- VIII Hotine-Marussi Symposium on Mathematical Geodesy 2013, IAG Symposia Vol. 142, Springer 2016;
- IAG Scientific Assembly, Potsdam 2013, IAG Symposia Vol. 143, Springer 2016;
- 3rd International Gravity Field Symposium 2014, IAG Symposia Vol. 144, Springer 2017;
- International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH), IAG Symposia Vol. 145, Springer 2017;
- IAG Commission 1 Symposium REFAG 2014, IAG Symposia Vol. 146, Springer 2016;
- International Symposium on Earth and Environmental Sciences for Future Generations, IAG Symposia Vol. 147, Springer 2018;
- International Symposium on Gravity, Geoid and Height Systems 2016, IAG Symposia Vol. 148, Springer 2019;
- International Symposium on Advancing Geodesy in a Changing World, IAG Symposia Vol. 148, Springer 2019.

The IAG Reports (Travaux de l'AIG) Vol. 39 (2015), Vol. 40 (2017) and Vol. 41, 2019 include reports of all IAG components about their activities in the past periods.

Awards, anniversaries, obituaries

The following medals and prices have been awarded:
- Levallois Medal to Rainer Rummel, Germany (2015);
- Bomford Prize to Yoshiyuki Tanaka, Japan (2015);
- Young Author Award to Xingxing Li, Germany (2015);
- Young Author Award to Olga Didova, The Netherlands (2016);
- 61 Travel Awards to young scientists for participation in IAG sponsored symposia with a total of 58892 EURO (15 awardees for IAG-IASPEI 2017).

Obituaries were written for former IAG officers and outstanding geodesists who passed away:
- Bob Schutz, USA, 1940 – 2015;
- Suriya Tatevian, Russia, 1937 – 2015;
- Graciela Font, Argentina, 1940 – 2015;
- John Wahr, USA, 1951 – 2015;
- Camil Gemael, Brazil, 1922 - 2015
- Hermann Seeger, Germany, 1934 – 2016;
- Alexander Kopaev, Russia, 1962 – 2016;
- Heinz Henneberg, Venezuela, 1926 – 2016;
- Barbara Kolaczek, Poland, 1931 – 2017;
- Bernard Guinot, France, 1925 – 2017;
- Klaus Linkwitz, Germany, 1927 – 2017;
- József Závoti, Hungary, 1949 - 2017
- Dieter Lelgemann, Germany, 1939 - 2017
- Yoshihide Kozai, Japan, 1928 - 2018
- Olumuyiwa Adebekun, Nigeria, 1928 - 2017
- Jean Dickey, USA, 1945 – 2018
- Marcin Barlik, Poland, 1944 – 2018
- Jean Kovalevsky, France, 1929 - 2018
- Michel Louis, France, 1930 - 2018
- Mikhail Prilepin, Russia, 1929 – 2018
- Hermann Mälzer, Germany, 1925 – 2018
- Richard Biancale, France, 1952 – 2019

International Bureau on Weights and Measures
Bureau International des Poids et Mesures (BIPM)
– Time Department –

https://www.bipm.org/en/bipm/tai/

Director of BIPM Time Department: Patrizia Tavella (France)

Introduction

The International Bureau on Weights and Measures (Bureau International des Poids et Mesures, BIPM) is an intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards. There is a close cooperation with the International Association of Geodesy (IAG) and its forerunners since its foundation during the Metre Conference in Paris, France, on 20 May 1875.

Key products of the BIPM Time Department:

- The atomic time scales TAI and UTC are disseminated monthly through the BIPM *Circular T*.
- A rapid solution of UTC (UTCr) is published weekly, and allows participating national institutes to monitor the steering of their local realizations of UTC at shorter intervals than the monthly *Circular T*.
- The *BIPM Annual Report on Time Activities* provides all relevant information, data and results for the year previous to its publication.
- Reports on time-transfer techniques are also issued regularly.
- Other activities related to the time scales are developed in the Department; these contribute to improving the calculation algorithms and increasing knowledge about time transfer techniques. Coordination with the national time laboratories contributing data to UTC, and with international organizations acting on fields related to time keeping and regulations represent a significant part of the Time Department activities.

Reports 2015 – 2018

- https://www.bipm.org/utils/en/pdf/time_ann_rep/Time_annual_report_2015.pdf
- https://www.bipm.org/utils/en/pdf/time_ann_rep/Time_annual_report_2016.pdf
- https://www.bipm.org/utils/en/pdf/time_ann_rep/Time_annual_report_2017.pdf
- https://www.bipm.org/utils/en/pdf/time_ann_rep/Time_annual_report_2018.pdf

International Earth Rotation and Reference Systems Service (IERS)

http://www.iers.org

Chair of the Directing Board: Brian Luzum (USA)
Director of the Central Bureau: Daniela Thaller (Germany)

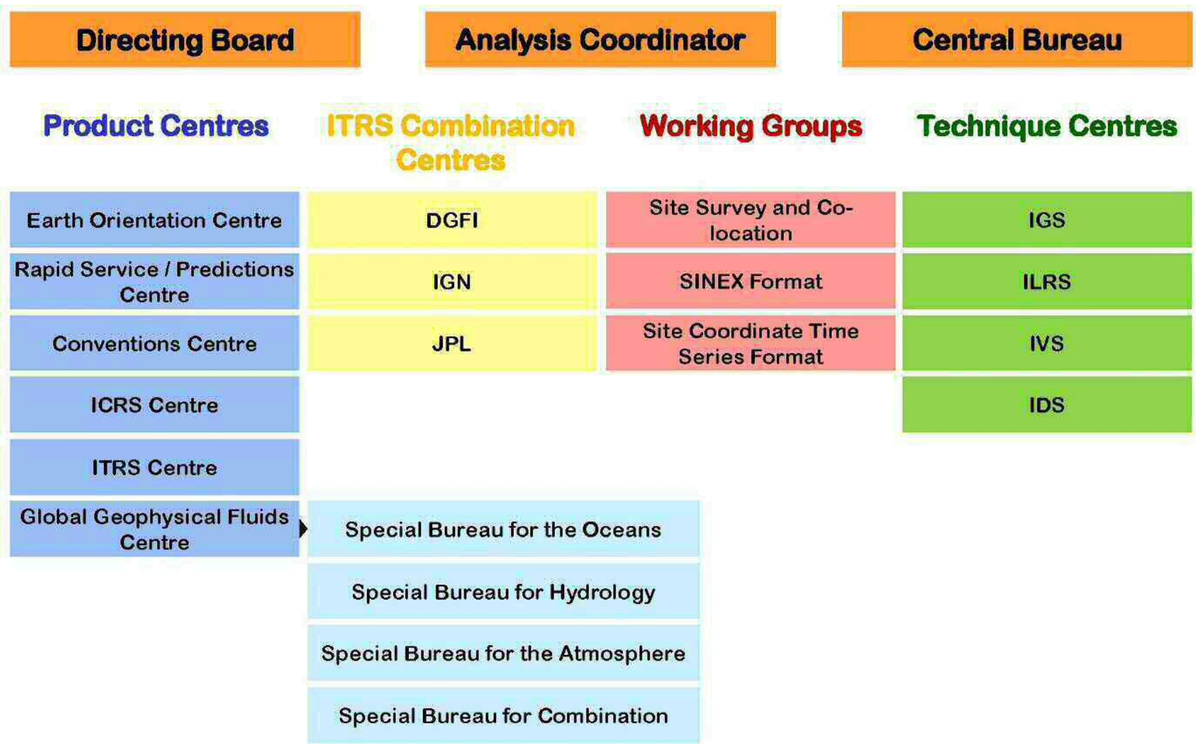
Structure

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 2019, the IERS consists of the following components:



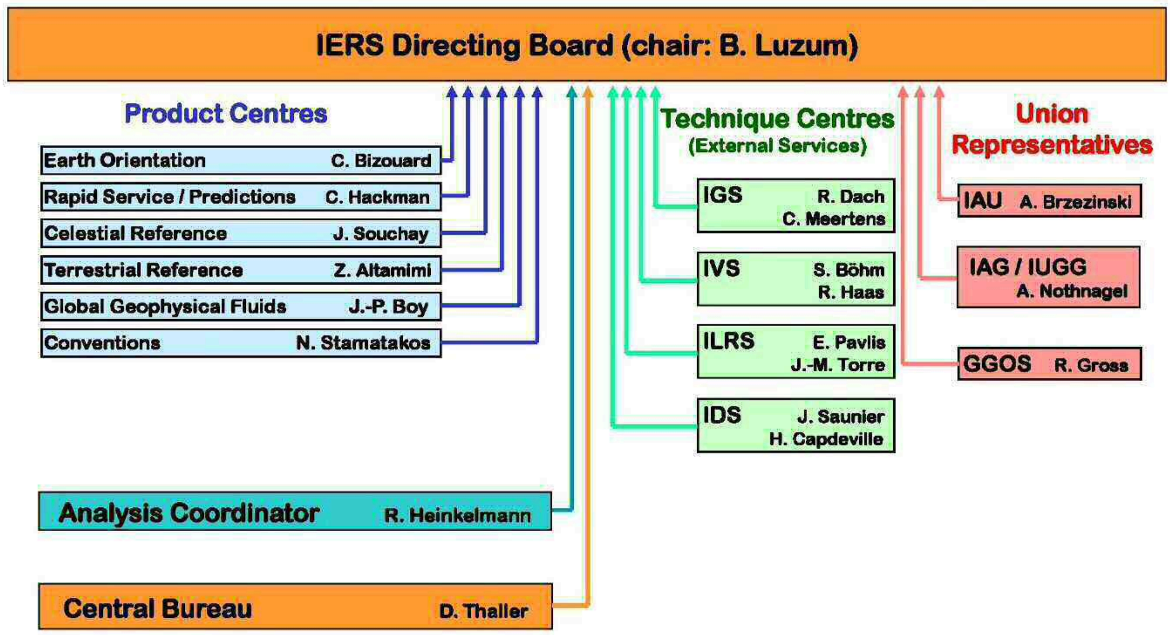
Responsible persons are (as of May 2019):

- Product centres
  - Earth Orientation Centre: *Christian Bizouard (France)*
  - Rapid Service/Prediction Centre: *Christine Hackman (USA), 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: *Richard Gross (USA)*
  - 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
  - Working Group on Site Survey and Co-location: *Sten Bergstrand (Sweden), John Dawson (Australia)*
  - Working Group on SINEX Format: *Daniela Thaller (Germany)*
  - Working Group on Site Coordinate Time Series Format: *Laurent Soudarin (France)*

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. A new realization of the International Terrestrial Reference System (ITRF2014) was released in January 2016 and was adopted by the IERS product and technique centres in early 2017. Ongoing documentation of the ITRF2014 resulted in the release of the Journal of Geophysical Research: Solid Earth paper in 2016 and the first of the IERS Technical Notes being released in early 2017. A new realization of the International Celestial Reference System (ICRF3) was published in mid-2018 and officially adopted by IAU on January 2019. The IERS Conventions (i.e. standards etc.) have been updated regularly, and a fully revised release of the IERS Conventions is in preparation. The Bureau de Poids et Mesures (BIPM) phased out their support of the IERS Conventions Centre in 2016. In response, the Observatoire de Paris joined with the U.S. Naval Observatory in co-directing the IERS Conventions Centre. The IERS Working Group on Combination at the Observation Level finished its activities in 2016.

The IERS continued to issue Technical Notes, Annual Reports, Bulletins, and electronic newsletters. It co-sponsored the symposium "Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016)", which was held 18–23 July 2016 in Wuhan, Hubei, China, and co-organised the IAG/GGOS/IERS Unified Analysis Workshop (UAW), July 10–12, 2017 in Paris.

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-2015 and May 2019:

- IERS Technical Note No. 38 (2017): Z. Altamimi, P. Rebischung, L. Métivier, X. Collilieux: Analysis and results of ITRF2014
- IERS Technical Note No. 39 (2017): Jean-Claude Poyard, with contributions by Xavier Collilieux, Jean-Michael Muller, Bruno Garayt and Jérôme Saunier: IGN best practice for surveying instrument reference points at ITRF co-location sites
- IERS Annual Reports 2014, 2015, 2016, and 2017
- IERS Bulletins A, B, C, and D (weekly to half-yearly)
- IERS Messages Nos. 270 to 377

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. 61 in San Francisco, December 13, 2015;
- No. 62 in Vienna, April 17, 2016;
- No. 63 in San Francisco, December 10, 2016;
- No. 64 in Vienna, April 23, 2017;
- No. 65 in New Orleans, December 8, 2017;
- No. 66 in Vienna, April 8, 2018;
- No. 67 in Washington, D.C., December 8, 2018;
- No. 68 in Vienna, April 7, 2019.

Among the most important decisions made by the DB in 2015–2019 were the following:

- New list of IERS Associate Members confirmed and annually updated.
- Two IERS Technical Notes should be prepared on ITRF2014.

- Nutation series dEps / dPsi should be maintained.
- ITRS Combination Centres should compare the 9 co-located sites of the single technique solutions and the combined solution.
- Extend antenna serial number in SINEX format.
- Confirmed roadmap to switch to ITRF2014.
- Publish a Technical Note on site survey guidelines.
- Closed the IERS Working Group on Combination at the Observation Level.
- Elected Brian Luzum for a second term (2017–2020) as Chair of the Directing Board.
- An external evaluation of ITRF should be done.
- Publish a Technical Note on 14 C04 series.
- Establish an IERS Working Group to investigate possible improvements related to the distribution of the IERS products.
- Issue Call-for-Experts for next major revision of IERS Conventions.
- Issue Call for Participation in ITRF2020.
- Endorsed ICRF3.
- Elected Robert Heinkelmann as new Analysis Coordinator (succeeding Tom Herring on 1 January 2019).
- Establish a Working Group on Geocenter motion.

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.

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 delay (Gambis, 2004; Bizouard and Gambis, 2009; Gambis and Luzum, 2011). The EOC is located at Paris Observatory.

Activities and publications during the period 2015–2019

During the period 2015–2019 the EOC issued two leap seconds through Bulletin C (2015 July 1 and 2017 January 1).

An important issue is the maintenance of the consistency between the EOP system and both the International Terrestrial and Celestial Reference Frames (ITRF and ICRF). So far, Earth Orientation Parameters and the terrestrial frame are separately computed. This led in the past to increasing inconsistencies between both systems. All IERS reference solutions (C01, Bulletin B, C04 as well as Bulletin A derived by the Rapid Service/Predictions Centre, US Naval Observatory) were recomputed and aligned to the EOP solution associated with the new version of the ITRF (ITRF2014) in March 2017. Inconsistencies are now negligible compared to the current accuracies, i.e. limited to about 10 microarcseconds for polar motion and a few microseconds for UT1.

Recently C04 software and data base procedures have been upgraded. The celestial pole offsets are combined directly with respect to the IAU 2000 precession-nutation model. If IVS analysis centres provide them with respect to the IAU 1980 model, they are transformed into IAU 2000 consistent offsets according to a rigorous procedure based upon Standards of Fundamental Astronomy software libraries (SOFA). Moreover uncertainties are directly estimated from the formal uncertainties of the individual series and their weights reflecting the intra-technique dispersion (Bizouard et al., 2017).

The C04 series were updated to provide EOP series consistent with the set of station coordinates of the ITRF 2014. The new C04, referred to as IERS EOP 14C04, is aligned onto the most recent versions of the conventional reference frames (ITRF 2014 and ICRF2). Additionally, the combination algorithm was revised to include an improved weighting of the intra-technique solutions (Bizouard et al., 2018).

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Bizouard C., S. Lambert, C. Gattano, O. Becker, and J.Y. Richard, 2018, The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014. Journal of Geodesy Vol. 93, pp. 621–633, DOI 10.1007/s00190-018-1186-3

Bizouard C., S. Lambert, J.Y. Richard, and O. Becker, 2017, Combined solution C04 for Earth Rotation Parameters consistent with International Terrestrial Reference Frame 2014, Technical Note, http://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf

Deleflie F., D. Gambis, C. Barache, and J. Berthier, 2011, Dissemination of UT1–UTC through the use of virtual observatory VO, in AAS Proceedings, AAS 11-680

Gambis, D., 2004, Monitoring Earth Orientation at the IERS using space-geodetic observations. J. of Geodesy 78, pp. 295–303

Gambis, D. and B. Luzum, 2011, Earth rotation monitoring, UT1 determination and prediction, Metrologia 48, S165–S170

Rapid Service/Prediction Centre

Primary scientist: Christine Hackman (USA)
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 2015–2019

The RS/PC successfully implemented the 30 June 2015 and 31 December 2016 leap seconds. It also successfully transitioned its products to the ITRF 2014 reference frame in March 2017. The RS/PC provided input to the National Institute of Standards and Technology (NIST; USA) in the NIST development of a Network Time Protocol UT1–UTC server, and set up an additional ftp download site for RS/PC products at the National Aeronautics and Space Administration (NASA; USA) Crustal Dynamics Data Information System (CDDIS) data archive. The cooperation of NIST and NASA is gratefully acknowledged.

The RS/PC continued to study the effects of implementing atmospheric angular momentum (AAM) and oceanic angular momentum (OAM) values/predictions in its EOP estimation/prediction algorithms, presenting results at the 2015 to 2018 American Geophysical Union (AGU) Fall Meetings and at the 2016, 2018, and 2019 European Geosciences Union General Assemblies. The RS/PC provided support to the IERS Conventions Centre regarding issues associated with the definition of mean pole, presenting its findings at the 2016 AGU Fall Meeting and spurring discussion that was continued in a technical session at the July 2017 Global Geodetic Observing System (GGOS) Unified Analysis Workshop. The RS/PS also developed an improved simulation program allowing it to more easily pre-test the impact of modelling/data changes under consideration on its results.

Finally, the RS/PC implemented changes to its software to use the dX dY celestial pole offset observations for its core processing consistent with IERS Conventions 2010 precession and nutation models; this change will replace core processing done with the older $d\psi$ and $d\varepsilon$ paradigm.

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.

Activities and publications during the period 2015–2019

In 2016, the Paris Observatory (OP) took over responsibility for the co-chairmanship that was previously held by the Bureau International des Poids et Measures (BIPM); the other co-chairmanship is held by the US Naval Observatory (USNO). The Centre has created new web and ftp sites containing updated Conventions versions and associated software. Those sites are located at:

http://iers-conventions.obspm.fr/ and http://maia.usno.navy.mil/conventions
(The same information can be found at both the Obervatoire de Paris and U.S. Naval Observatory Conventions websites.)

ftp site ftp://maia.usno.navy.mil/conventions .

A versioning system has been implemented to handle intermediate updates of the conventions. The centre has also begun preparing for a future IERS Conventions update. In February 2018, it issued a Call for Participation in the next 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 and publications during the period 2015–2019

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). The first Gaia data release in September 2016 provided the possibility of extensive comparisons between the preliminary Gaia optical reference frame and the ICRF, the results of which are very promising. Together with the IAU Division 1 Working Group on ICRF3, the ICRS Centre prepared the next ICRF, which was published in mid-2018. Comparisons were made between the ICRF and the Gaia Data Releases 1 and 2 optical reference frame.

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ITRS Centre

Primary scientist: Zuheir Altamimi (France)

Overview

The main activities of the ITRS Centre during the period 2015–2019 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.

Activities and publications during the period 2015–2019

The main activities of the ITRS Centre during this period include:

- The ITRF network database, which contains the descriptions of the sites and points, is continually updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web site <http://itrf.ign.fr>, and should be sent to domes@ign.fr. An updated list of all available DOMES numbers 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 (see below). As a result of the ITRF2014 analysis, several new stations, mainly GNSS permanent stations where added to the ITRF network and database.
- The ITRS Centre has started the initial study analysis and preparation for a new design of the ITRF web site. It will be designed to provide more ITRF-related information to the users using more user-friendly interfaces. The specification document is finalized and the development started in 2013.
- The ITRS Centre collects all new surveys operated by either IGN or the hosting agencies of ITRF co-location sites. The reports of these surveys are posted at the ITRF Website and available to users at <http://itrf. ign.fr/local_surveys.php>. The local ties SINEX files used in the ITRF combinations are also available on that web site.
- In preparation for the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Centre. These new survey results were made available via the ITRF website after the release of the ITRF2014.
- The operational entity of the ITRS Centre at the IGN Survey department has prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not accustomed to working at mm precision. The document was published as IERS Technical Note 39.
- Producing and publishing the ITRF2014, with a dedicated website: http://itrf.ign.fr/ITRF_solutions/2014/. See also the report of the ITRS Combination Centre at IGN France.

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Global Geophysical Fluids Centre

Primary scientist: Jean-Paul Boy (France)
Co-chair: Tonie van Dam (Luxembourg)

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. 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), 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 2015–2019

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 updated all fields from atmospheric angular momentum (AAM).

The Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analysing, archiving, and distributing data relating to nontidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocentre. Products from the ECCO/JPL ocean model were updated.

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) satellite gravity measurements. The NASA GLDAS and GRACE data products are updated on a regular basis.

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).

GGFC organized sessions on global geophysical fluids at AGU Fall Meetings and EGU General Assemblies.

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 2015–2019

The CC DGFI-TUM computed the realization DTRF2014, which for the first time considers non-linear station motions caused by atmospheric and hydrological loading. The corrections are derived from the atmosphere model NCEP and the hydrology model GLDAS, respectively, and are provided by Tonie van Dam. The final DTRF2014 product comprises besides the solution SINEX files and the EOP file (including terrestrial and celestial pole coordinates, the rates of the terrestrial pole coordinates, UT1–UTC and LOD values) also the model values introduced for non-tidal loading correction, the residual time series of station positions and translation time series of the DTRF2014 origin. The time series allow for a computation of the real station positions at each epoch of observation.

Furthermore, DGFI-TUM researched a consistent realization of ITRS, ICRS and the EOP. In particular the impact of the combination of station coordinates and of the combination of EOP on the CRF was investigated.

ITRS CC at IGN

Primary scientist: Zuheir Altamimi (France)

See 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 2015–2019

KALREF was used to determine trial solutions using the same input SINEX files that were used to determine ITRF2005 and ITRF2008 (Wu et al., 2015). KALREF was also used to determine JPL's official JTRF2014 solution that was determined from the ITRF2014 input SINEX files (Abbondanza et al., 2017). Soja has compared terrestrial reference frames determined by Kalman filters to other realizations (Soja et al., 2016) and has explored the stability and the effect of process noise on reference frames determined by Kalman filters (Soja et al., 2018a, 2018b). He has also estimated a celestial reference frame using a Kalman filter (Soja et al., 2017).

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Analysis Coordinator

Analysis Coordinator: Thomas Herring (USA, until 2018), Robert Heinkelmann (Germany, since 2019)

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 2015–2019

The work of the Analysis Coordinator focused on an analysis of the ITRF2014 extended model presentation of post-seismic deformation after large earthquakes and a comparison of recent diurnal and semidiurnal EOP models with the IERS Conventions (2010). He has also been looking at the scale differences between the SLR and VLBI systems that persist in ITRF2014 and coordinating with the IERS combination centres to better understand the origin of the difference. He organized and developed recommendations from the 2014 Unified Analysis Workshop held in Pasadena, CA (USA) and participated in preparing the 2017 Unified Analysis Workshop held in Paris, France.

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 2015–2019

For most of the IERS products, metadata according to ISO 19115 were produced and are available through the IERS web pages on products and now also at the IERS ftp server ftp.iers.org.

Several tools for visualization and analysis of IERS data and products, developed in the framework of the German research unit "Earth Rotation and Global Dynamic Processes", were improved and added to the IERS website. These are: Plot tool; EOP of today; Timescales; EOP Reader. Furthermore links to tools of other IERS components were added.

Based on the EOP Reader and on the Timescales tools, web services for Earth Orientation Parameters, leap seconds and time scales were developed.

It became apparent that the internal processes of the data management component of the IERS DIS are in need of improvements. The requirements were formulated and a contract was concluded. The optimized system was tested and implemented.

The Central Bureau published and distributed IERS Technical Notes Nos. 38 and 39, IERS Annual Reports 2014, 2015, 2016, and 2017, as well as IERS Messages Nos. 270 to 377. It compiled reports by IERS to IAU Commission 19/A2, IAG, and the ICSU World Data System.

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Working Groups

Reports, meeting summaries, presentations and other documents of all working groups are available at the IERS web site.

Working Group on Site Survey and Co-location

Chair: Sten Bergstrand (Sweden)
Co-chair: John Dawson (Australia)

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 2015–2019

Due to different national surveying procedures, local constraints etc., a detailed plan, handbook or instruction for how to perform a local survey has previously been disregarded. However, for the benefit of future surveying work the operational entity of IGN worked on local survey guidelines. These were published as IERS Technical Note 39 "IGN best practice for surveying instrument reference points at ITRF co-location sites".

Local survey campaigns were performed at Onsala space observatory, at Australian observatories (Katherine VLBI Observatory, Mt Stromlo Observatory and Kiribati), on Mauna Kea, Hawaii, and at many other sites.

Working Group on Combination at the Observation Level

Chair: Richard Biancale (France)
Co-Chairs: Daniel Gambis (France), Manuela Seitz (Germany)

Overview

The Working Group on Combination at the Observation Level (WG COL) reviewed the interest in combining techniques at the observation level for EOP and reference frames. Its main goal was to bring together groups capable to do combinations on the observation level and to improve the homogeneity, precision and resolution of the products. After 7 years of activities concluded its efforts in 2016.

Activities and publications during the period 2015–2016

The WG COL contributed to the ITRF2014 realization by combining geodetic techniques (DORIS, GNSS, SLR, and VLBI) at the Normal Equation Level. Twelve years of daily Normal Equations (NEQs) from 2002 to 2013 have been processed for each technique (Tab. 1). The combined Normal Equations at weekly bases in SINEX format has been produced and delivered to IGN for comparisons of the Earth Orientation Parameters solutions (EOP) and station positions with respect to the new reference frame ITRF2014.

Table 1: Parameters to estimate for comparison with ITRF2014 and added parameters for further studies

Parameters	SINEX format	GINS format	Sampling	Initial values
Polar motion	XPO, YPO	PX, PY	PWL @ 12Hr	IERS EOP 08-C04 series Interpolated @12h
Delta time UT1-TAI	UT1	PT	PWL @ 12Hr	IERS EOP 08-C04 series Interpolated @12h
Nutation angles X, Y corrections to the IAU2000A/2006 model	NUT_X, NUT_Y	NX, NY	PWL @ 12Hr	Set to 0.0
Station coordinates	STAX, STAY, STAZ	SX, SY, SZ	1/w @ mid epoch	ITRF2008
Radio sources coordinates right ascension & declination	RS_RA, RS_DE	QRA, QDE	1/w @ mid epoch	ICRF2
Added parameters not used for ITRF2013 purposes but proposed for GRGS studies				
Zenithal Troposphere Delay for wet component limited for stations (*)	ZBIAS: Adjustment of the wet component to the model	MZB	Every 2-hours: 00, 02, 04, ...20, 22hr per day	GPT/GMF model for radio waves and Mendes/Pavlis for optical waves
Troposphere gradient north & east limited for stations (*)	TGETOT, TGNTOT	MGE, MGN	1 pt/d @ 00Hr	gradient troposphérique per Day and per station
Possible parameters for future investments				
Polar motion rate	XPOR, YPOR	PXR, PYR	1pt/d @ 12Hr	Set to 0.0
Length of Day LOD	LOD	PTR	1pt/d @ 12Hr	IERS EOP 08-C04 LOD Interpolated @12h
Rate for nutation angle	NUTR_X, NUTR_Y	NXR, NYR	1pt/d PWL @ 12Hr	Set to 0.0

Conclusions about the COL activities have been presented during the closure meeting at the BKG in Frankfurt, February 19, 2016. The main result consists in having developed a new method to homogenize the terrestrial frame, Earth Orientation and celestial frame in a global solution. Further developments have been pursued in the context of the Earth Orientation Centre to produce and analyse the EOP solutions using this method and to maintain efforts studying this combination technique and analysing products.

References

Jean-Yves Richard, Daniel Gambis, Christian Bizouard, Sébastien Lambert, Olivier Becker, Teddy Carlucci, Sylvain Loyer, Laurent Soudarin, Géraldine Bourda, Antoine Bellanger, Florent Deleflie, David Coulot, Arnaud Pollet, Jean-Michel Lemoine, Richard Biancale, Jean-Charles Marty, Felix Perozanz, "GRGS Solutions EOP, TRF, CRF by multi technique Combination DORIS, GPS, SLR, VLBI at normal equation

level, period 2002–2013", presented at COL meeting Federal Agency for Cartography and Geodesy (BKG), Frankfurt am Main, Germany, 19 February 2016.

Poster presentation: Jean-Yves Richard, Christian Bizouard, Sébastien Lambert, Olivier Becker, Richard Biancale, "A combined GNSS/VLBI solution for EOP and TRF", EGU2016, Vienna, 17–22 April 2016.

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 2015–2019

The Working Group on SINEX Format has been working on modifications for representations of non-linear station motions due to post-seismic movements, of parameters describing radio source positions and of the antenna serial number, as well as on other topics. Also, there have been activities for setting up a more user-friendly SINEX description as a web interface for each block, which will be easier to maintain and to update and will be more user-friendly to implement or check.

Working Group on Site Coordinate Time Series Format

Chair: Laurent Soudarin (France)

Overview

The objectives of the Working Group on Site Coordinate Time Series Format, a joint WG of IERS and IAG, are a user-friendly format with data and metadata by definition of a common exchange format for coordinate time series for all geodetic techniques (DORIS, GNSS, SLR, VLBI) with all necessary information (data and metadata). The goal is to access products via web interfaces.

Activities and publications during the period 2015–2019

A meeting of the WG took place in Vienna, on April 15, 2015, during the EGU General Assembly week. Based on a non-exhaustive list of existing formats at IAG services and GPS time series providers, metadata and data have been examined. The content of existing formats have been listed and compared, regarding the metadata and the data. The examination allows to identify three types of metadata (file information, site information, and product information) as well as a list of variables forming the data block. The next step is to define the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system.

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

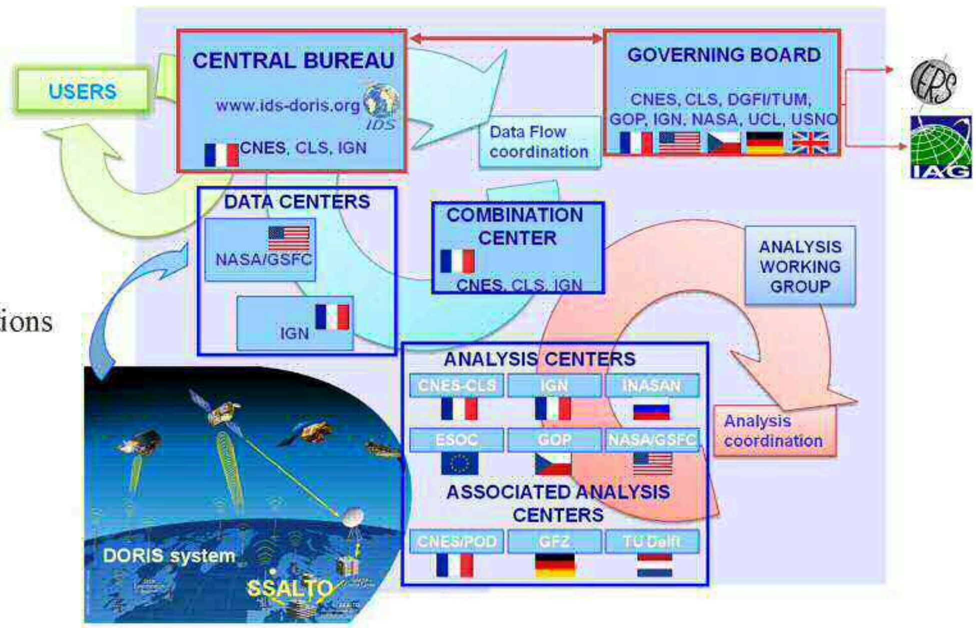
The main achievements of the International DORIS Service (IDS) over the period July 2015-June 2019 were (1) the contribution to ITRF2014, (2) the preparation of articles for the DORIS Special Issue in the journal "Advances in Space Research", and (3) the initiation of a routine operational delivery of an IDS combination on a quarterly basis. Six IDS analysis centers (ACs) used five separate analysis packages to create IDS products as well as to reprocess all DORIS data since 1993 for inclusion in the DORIS combination for ITRF2014. The Combination Center in Toulouse creates the routine combinations in close collaboration with the Analysis Coordinators and the Analysis Centers. The components of the IDS meet regularly primarily during Analysis Working Group (AWG) meetings to discuss progress on current technical questions. The Governing Board of the IDS provides long-term direction while the Central Bureau manages the day-to-day activities, brings its supports to the IDS components and operates the information system. The next months will be focused on the preparation of the next ITRF, the activities are already underway.

The current report presents the different activities held by all the components of the IDS for the period from the middle of 2015 to the middle of 2019.

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**, three new satellites were launched over the report period: Jason-3 and Sentinel-3A, in early 2016, and Sentinel-3B in 2018. They all use the new 7-channel DGXX-S DORIS on-board receiver. The DORIS constellation has steadily increased, and now includes seven satellites at altitudes between 720 and 1336 km, with near-polar or TOPEX-like inclination (66 deg).

Table 1: DORIS data available at IDS data centers, as of June 2019

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	PRESENT	NASA/CNES	Altimetry
CRYOSAT-2	30-MAY-2010	PRESENT	ESA	Altimetry, ice caps
HY-2A	1-OCT-2011	PRESENT	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

In the next few years, more DORIS satellites are planned: Sentinel-3C and 3D, HY-2C and 2D, Jason-CS1/SENTINEL-6A and Jason-CS2/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 in the past last years, four or more DORIS satellites have been available to IDS users, which is a key requirement for the precision of the geodetic products.

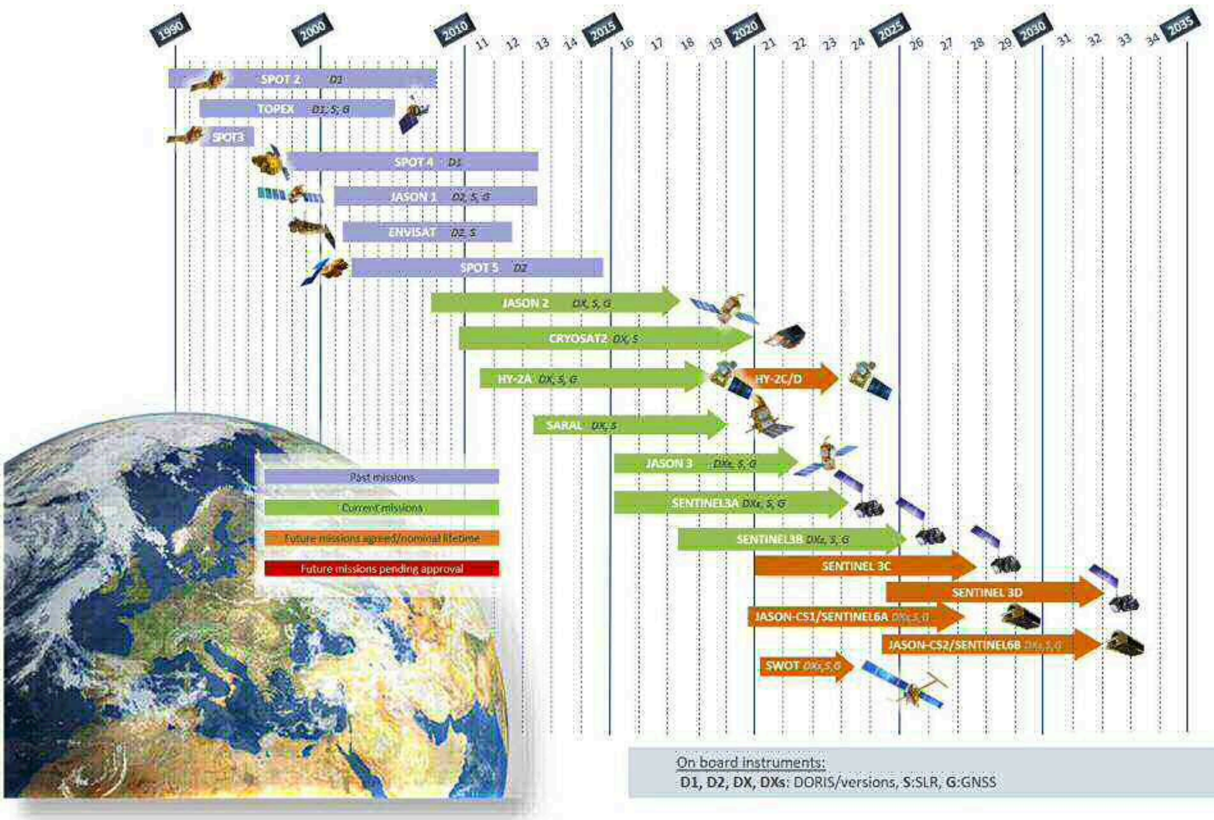


Figure 1: DORIS satellite constellation. As of June 2019.

1.2 DORIS network

DORIS has a globally distributed network of 57 permanent stations dedicated for precise orbit determination and altimetry with four master beacons (Papeete, Hartebeesthoek, Kourou, Toulouse) and one time beacon (Terre-Adélie). Two additional DORIS stations are used for other scientific purposes: Wettzell (Germany) and Mangilao (Guam Island, USA). See **Figure 2**.

There have been many developments and maintenance operations for the ground network during the report period.

In 2015, a new DORIS station, “GONC”, was installed at the Goldstone Deep Space Communications Complex (GDSCC) in California. DORIS occupied this site at Goldstone between 1988 and 2004 but the station was moved 300 km south to Monument Peak (east of San Diego, California) for co-location with the SLR tracking station “7110” and the GNSS station “MONP”. Unfortunately, following insoluble conflict at the 2 GHz frequency with a nearby TV microwave relay system, which manifested itself after the US switched to digital television transmissions in 2009, the DORIS station of Monument Peak had to be decommissioned in 2010 after only four and a half years of service. After discussion with NASA, it was determined that the remote location of the GDSCC in the heart of the Mojave Desert was the best option to ensure a safe and unencumbered environment for the DORIS station. The return to service of DORIS in California is of great importance for the development of altimetry data products. A gap in coverage leads to degradation in orbit determination, which affects both the real-time orbits computed by the DIODE instrument on-board the DORIS satellites, as well as for the precise orbits that are computed later. This much-awaited station fills a hole in the DORIS data coverage over the northern Pacific Ocean.

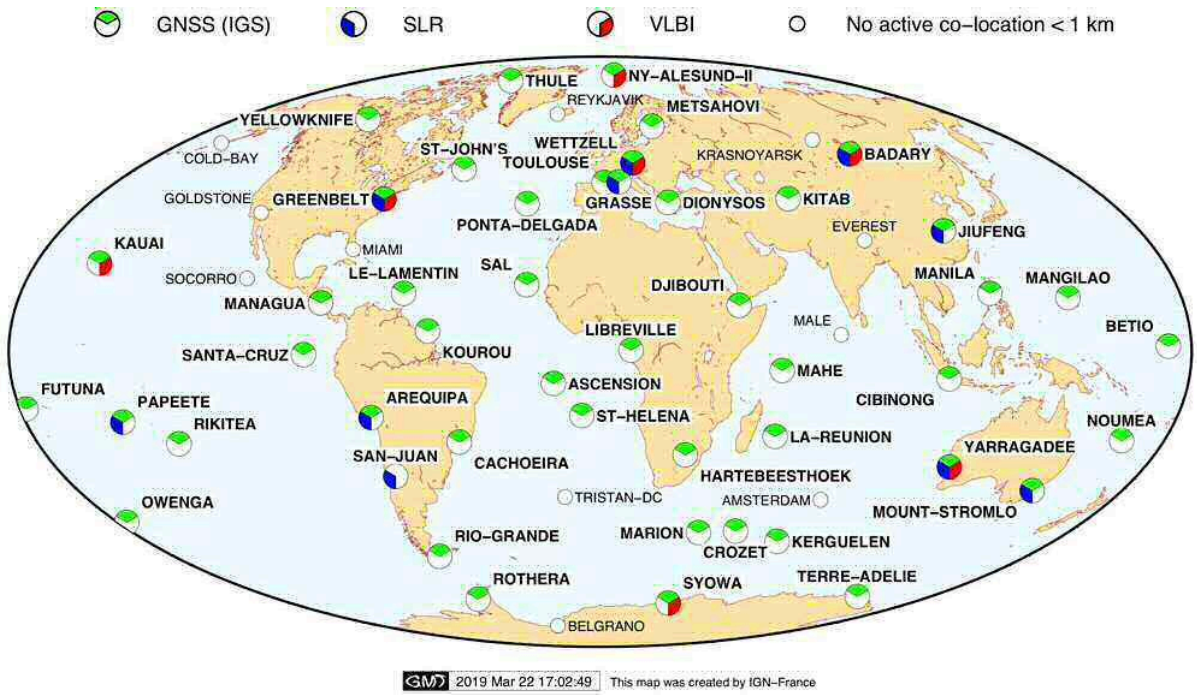


Figure 2: DORIS tracking network. Co-location with other IERS techniques as of March 2019.

On September 27, 2016, the new DORIS station at the Geodetic Observatory Wettzell started work with shifted frequencies to avoid internal jamming with the nearby stations of the permanent network. The most challenging requirement was to manage potential interference with VLBI. After some months of intensive tests carried out on site, a compromise was reached to minimize potential problems for both systems. Greenbelt and Wettzell are now two examples of core sites complying with the GGOS requirements with the four space geodetic techniques (co-located DORIS/GNSS/SLR/VLBI).

Another main event of 2016 was the installation of a new DORIS station in Managua, Nicaragua. Fully integrated within the data coverage map, this new station is also well located to provide reliable information on the Caribbean tectonic plate motion when combined with the DORIS station data of "Le Lamentin", on the island of Martinique in the French West Indies.

In April 2018, a new DORIS site was set up on Guam, at Mangilao, close to the IGS station "GUUG" and the tide-gauge of Pago Bay (PSMSL 2130). This station provides a significant contribution to the coverage of the western North Pacific Ocean over the Micronesia and the Mariana Trench.

Two other main events occurred in 2018, both in Argentina: the restarting of Rio Grande (province of Tierra del Fuego) after a 2-yr outage and the station installation at San Juan (province of San Juan, northwest of Mendoza). These two stations were both expected to fill the coverage gap in this area. Finally, in October, the station in Svalbard was relocated about 3 km away to be part of the new geodetic observatory Ny-Ålesund II. The new twin telescopes of the VLBI Geodetic Observing System at Ny-Ålesund II were dedicated in June 2018.

Since 2015, the DORIS network has provided reliable service with the total number of operating stations approaching an annual average of about 90% of active sites, thanks to the responsiveness and the combined efforts of CNES, IGN and all agencies hosting the stations.

As regards the ground equipment, the 4th beacon generation is under development with a view to starting deployment in 2019. Designed with new electronic components and new architecture, this new beacon model will provide better performance and reliability and will allow the DORIS antenna to be installed up to 50 m from the beacon (the limit is currently 10 m). This will improve options for placement of new stations, while still satisfying the station visibility constraint of minimizing obstructions at low elevation.

Efforts continue towards increasing the number of co-located sites, improving the monument stability at any new installation and carrying out high precision local tie surveys. There are currently several projects under way in North Australia (Katherine), in China and in French Polynesia (Papenoo), in the framework of the future geodetic observatory of Tahiti.

All tie vectors between DORIS and the other techniques are compiled in a maintained file available on the IDS data centers: 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 a number of 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**).

In the Fall 2016, the CB organized the elections for the Analysis Centers' representative, the Data Centers' representative, and one Member-at-Large. In addition, IDS proceeded to the renewal of four representatives appointed respectively by CNES (DORIS system), IGN (network), IAG 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 for the GB elected its new chairman.

The members who were elected or appointed for the term 2017-2020 are:
- Frank Lemoine (NASA/GSCF) as Analysis Center Representative,
- Patrick Michael (NASA/GSCF) as Data Center Representative,
- Denise Dettmering (DGFI/TUM) as Member-at-Large,
- Pascale Ferrage (CNES), reappointed by CNES as the DORIS system representative,
- Jérôme Saunier (IGN), reappointed by IGN as the Network representative.
- Brian Luzum (USNO), reappointed by IERS as the IERS representative.
- Petr Štěpánek (Geodetic Observatory Pecny), nominated by IAG Executive Committee in February 2017 as the IAG representative to succeed Michiel Otten who served two terms.

The new Governing Board has designated Frank Lemoine as the new Chairperson of the IDS Governing Board for 2017-2020.

In addition, the CB carried out the selection of the Combination Center for 2017-2020. The call for proposals for the successor to the current Combination Center closed on October 15. Only one proposal was submitted, that of CNES/CLS who applies to continue the activities of the Combination Center. The GB accepts the application and selects it as the IDS Combination Center for a new period of four years, starting on January 1, 2017. Guilhem Moreaux (CLS) remains the representative of the Combination Center within the GB.

In the fall 2018, elections were organized for the Analysis Coordinator and the other Member-at-Large. the new members elected by the IDS Associates for the term 2019-2022 are:

- Hugues Capdeville (CLS) and Petr Štěpánek (Geodetic Observatory Pecny) as Analysis Coordinator,
- Claudio Abbondanza (NASA/JPL) as a Member at Large.

It is important to note that Hugues Capdeville and Petr Štěpánek will share the responsibility and the work of the Analysis Coordination. From January 1st, 2019, the IDS Analysis Coordinator team can be contact at ids.analysis.coordination@ids-doris.org.

Because of his new responsibility within the IDS Governing Board, Petr Štěpánek resigned from his position of IAG Representative. Another representative will be designated by IAG for 2019-2020.

2.2 IDS retreat

After 15 years of activity, the IDS organized its first retreat on June 13 and 14 at Château de Mons, near the small town of Caussens, in Gascony, in the Southwest of France (country of the Musketeers and Armagnac). In addition to the members of the IDS Governing Board, eleven people including outside members of IDS such as Christian Bizouard (Observatoire de Paris), Klaus Börger (University of Bonn), Pierre Exertier (OCA), Oliver Montenbruck (DLR), Paul Poli (SHOM) were asked to work on the strengths, weaknesses, opportunities and threats of the IDS. To support the general discussions dealing with how to grow or to increase the visibility of the IDS, five subjects of special interest (possible evolution of the DORIS technology, Precise Orbit Determination, interest in ionospheric-tropospheric derived products, DORIS geocenter and pole estimations, IDS scientific goals and organization) were addressed. From the minutes of all the discussions, the IDS Governing Board will write a preliminary version of the IDS strategic plan. The next step will be consultation with the DORIS system stakeholders. Then, the first IDS strategic plan including both medium and long-term actions will be made available.

2.3 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 and the IDS Workshop held between 2015 and 2019 (see **Table 5**). 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.

Table 2: IDS GB members since 2003, with members in office on January 1st, 2019, indicated in bold.

Position	Term	Status	Name	Affiliation	Country
Analysis coordinator	**2019-2022**	**Elected**	**Hugues Capdeville** **Petr Štěpánek**	**CLS** **Geodetic Obs. Pecny**	**France** **Czech Republic**
	2015-2018	*Elected*	*Hugues Capdeville* *Jean-Michel Lemoine*	*CLS* *CNES/GRGS*	*France*
	2013-2014	*Ext'd*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2009-2012	*E.b.GB*	*Frank Lemoine*	*NASA/GSFC*	*USA*
	2005-2008		*Frank Lemoine (subst.)*	*NASA/GSFC*	*USA*
	2003-2005		*Martine Feissel-Vernier*	*IGN/Paris Obs.*	France
Data Centers' representative	**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	**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	Univ. Texas/CSR	USA
	2009-2012	E.b.GB	John Ries	Univ. Texas/CSR	USA
	2003-2008		John Ries	Univ. Texas/CSR	USA
Member at large	**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**	**App.**	**Laurent Soudarin**	**CLS**	**France**
Combination Center representative	**Since 2013**	**App.**	**Guilhem Moreaux**	**CLS**	**France**
Network representative	**2017-2020**	**App.**	**Jérôme Saunier**	**IGN**	**France**
	2013-2016	*App.*	***Jérôme Saunier***	*IGN*	*France*
	2010-2012		Bruno Garayt (subst.)	IGN	France
	2009	E.b.GB	Hervé Fagard	IGN	France
	2003-2008		Hervé Fagard	IGN	France
DORIS system representative	**2017-2020**	**App.**	**Pascale Ferrage**	**CNES**	**France**
	2013-2016	*App.*	***Pascale Ferrage***	*CNES*	*France*
IAG representative	**2019-2020**	**App.**	**To be appointed**		
	2017-2018	*App.*	***Petr Štěpánek***	*Geodetic Obs. Pecny*	*Czech Republic*
	2013-2016	*App.*	***Michiel Otten***	*ESOC*	*Germany*
	2009-2012	*App.*	Michiel Otten	ESOC	Germany
	2003-2008		Not designed		
IERS representative	**2017-2020**	**App.**	**Brian Luzum**	**USNO**	**USA**
	2013-2016	*App.*	***Brian Luzum***	*USNO*	*USA*
	2009-2012	*App.*	Chopo Ma	NASA/GSFC	USA
	2003-2008		Ron Noomen	TU Delft	Netherlands

App. = Appointed ; 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

The Central Bureau maintains the web resources of the IDS. A new version of the IDS website was proposed in early 2017 with an updated design and structure. The website is now accessed using the secure HTTPS protocol. Besides the regular updates of pages and additions of documents, the website was upgraded and enriched with new pages. The IDS video channel was created on YouTube (https://www.youtube.com/channel/UCiz6QkabRioCP6uEjkKtMKg) to host a set of existing videos for outreach, and new videos showing the DORIS-equipped satellites in orbit. These videos were produced with the Visualization Tool for Space Data (VTS) free software from CNES.

A new page of outreach material was created. It gathers links to the videos, leaflets and newsletters as well as some material to discover DORIS https://ids-doris.org/ids/reports-mails/outreach-material.html.

A new version of the IDS web service (http://ids-doris.org/webservice) was proposed in early 2017. It is based on the latest Highcharts/Highstock library, and a new version of the network viewer. Improvements were brought to make the service more ergonomic, simpler and more practical, especially on mobile devices. The webservice is now accessed using the secure HTTPS protocol.

It has been upgraded with new plot tools to visualize the time series of Earth Orientation Parameters and the position residuals (North, East, Up) of the cumulative solution derived from the routine analysis of the IDS Combination Center.

Several new features were added to the network viewer (https://apps.ids-doris.org/apps/map.html). In addition to the DORIS network and the IGS co-located stations, it is now possible to display the boundaries of the tectonic plates (Bird, 2003), the large Earthquakes (magnitude greater or equal to 6) within a 500 km radius of the DORIS stations (source USGS), as well as the horizontal and vertical velocity vectors of the DPOD2014 solution. When the velocity vectors are showed, rates are displayed on mouse-over. Rates (North, East and Up; in mm/yr) can also been seen in the list of information linked to each station, obtained by clicking on a station. This list includes now local events, i.e., the events of the station (dates of installation, change of beacon equipment, Earthquakes in the vicinity).

At its meeting in Washington in October 2015, the Governing Board asked the Central Bureau to consider the publication of a newsletter. The intention is to improve the flow of information within the community of providers and users of DORIS data and products, to highlight the activities of the groups participating in the IDS, and to bring the DORIS and IDS news to a wider audience, from the host agencies to the other sister services. In March 2016, the Central Bureau proposed a draft to the Governing Board who approved the concept. So, the IDS Newsletter was created. Three issues were published in 2016 (#1 in April, #2 in July, and #3 in December), one in 2017 (#4 in November), one in 2018 (#5 in September) and one in 2019 (#6 in February). The issues are distributed via email to the subscribers to the DORISmail and a number of identified managers and decision-makers. They are also available from the IDS website (https://ids-doris.org/ids/reports-mails/newsletter.html).

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, meta-data and documentation of the three missions Jason-3, Sentinel-3A and Sentinel-3B, were put online the IDS data and information sites as they become available

During the change to the new file upload system at the CDDIS, the Central Bureau also interacted with the CDDIS staff, SSALTO, and the IDS components in order to ease the transition.

2.4 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 of these 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.

On 1 December 2016, CDDIS moved its entire operations to new facilities associated with its parent organization the Earth Observing System Data and Information System (EOSDIS). At the same time, it moved away from the old ftp protocol to a https-based upload procedure for data uploads; this new procedure offers both web and command line interfaces. The move to https was necessitated by security and operational concerns. Before the transition all DORIS data and products were supplied by seven individuals/groups. On 1 December 2016, five (5) of the suppliers (GSFC, ESA, SSALTO, INA, IDS ACC) had made the transition to the new procedure with the remaining two groups (GOP, IGN) transitioning to the new procedure in March 2017.

In 2017, CDDIS developed all new software to automate the ingest of data submitted by SSALTO and in 2018 add product ingest as well. This new software is a significant improvement over the previous process and performs a full range of quality-checks and metadata extraction. The software uses these new checks and metadata to generate a summary file for each data file. All incoming DORIS data have its metadata extracted and stored in a local database. These metadata, which includes satellite, time span, station, and number of observations per pass, and are utilized to generate data holding reports on a daily basis.

2.5 Analysis Centers and Analysis Coordination

The activities of all the DORIS analysts over the last four years were dominated by 1) the IDS contribution to ITRF2014, 2) assessing the three TRFs 2014 solutions and the DPOD2014, 3) the implementation of the data processing of DORIS RINEX, 4) considering the last DORIS satellites Jason-3, Sentinel-3A and Sentinel-3B, 5) defining the best strategy to mitigate the impact of the sensitivity to the South Atlantic Anomaly (SAA) effect of DORIS Ultra Stable Oscillator (USO), and 6) starting the preparation of the next ITRF contribution.

Analysis working group met six times, in Toulouse (France), May 28-29, 2015 (*hosted by Collecte Localisation Satellites*), in Greenbelt, Maryland (USA), October 15-16, 2015 (*hosted by NASA Goddard Space Flight Center in Greenbelt, Maryland, USA*), in Delft (The Netherlands), May 26-27, 2016 (hosted by Technical University of Delft), in London (UK), May 22-23, 2017 (hosted at the University College London), in Toulouse (France), June 11, 2018 (*hosted by CNES),* and in Munich (Germany), April 4, 2019 (hosted by DGFI). Two IDS Workshops were organized in 2016 and 2018. The first one was held in La Rochelle (France), October 31 to November 01, 2016, in conjunction with the Ocean Surface Topography Science Team (OSTST) meeting. The second was held from 24 to 26 September 2018 in Ponta Delgada (Azores Archipelago, Portugal), as part of the 25 Years of Progress in Radar Altimetry Symposium with the Ocean Surface Topography Science Team (OSTST) 2018.

For ITRF2014, the six active analysis centers agreed to submit new SINEX solutions. In addition, the CNES POD center is a lead DORIS analysis center. They do not submit SINEX solutions for the IDS combination, but since they have prime POD responsibility for many of the DORIS satellites, they are the source for much of the spacecraft information needed for processing. In addition, they prepare the DORIS format 2.2 data (the range-rate format) that is used by the IDS ACs. We have also the participation by three other institutions: GFZ, TU/Delft, The University College/London. The GeoForschung Zentrum (GFZ) has participated in several of the IDS meetings, and focused on the POD analysis for altimeter satellites. TU/Delft is analyzing data from Cryosat-2, and has made available the spacecraft quaternions for use by other team members. UCL is interested in working with individual DORIS ACs on the refinement of non-conservative force modeling for DORIS satellites. GFZ was recognized by the Governing Board as an Associated Analysis Center (AAC) in October 2015. CNES POD and TU/Delft became AAC in May 2017.

So to summarize, the IDS includes six Analysis Centers and three Associated Analysis Centers who use seven different software packages, as summarized in **Table 3**. We also note which analysis centers on a routine basis perform POD analyses of DORIS satellites using other geodetic techniques (c.f. Satellite Laser Ranging (SLR), or GNSS). The multitechnique analyses are useful since they can provide an independent assessment of DORIS system performance, and allow us to validate more easily model changes and the implementation of attitude laws for the different spacecraft, in the event spacecraft external attitude information (in the form of spacecraft quaternions) is not available.

Several groups expressed interest in the analysis of DORIS data, as well as in multi-technique analyses, such as the Norwegian Mapping Authority (NMA) and the Deutsches Geodaetisches Forschungsinstitut der Technischen Universitaet Muenchen (DGFI-TUM). Their respective representatives, Geir Arne Hjelle and Mathis Blossfeld, have regularly attended the IDS meetings. Their participations and that of other potential IDS ACs are strongly encouraged.

Table 3: Summary of IDS Analysis Centers

Name	AC	AAC	Location	Contact	Software	Multi-technique
ESA	X		Germany	Michiel Otten	NAPEOS	SLR, GNSS
GOP	X		Czech Republic	Petr Stepanek	Bernese	
GRG	X		France	Hugues Capdeville	GINS	SLR, GNSS
GSC¶	X		USA	Frank Lemoine	GEODYN	SLR
IGN	X		France	Pascal Willis	GIPSY	
INA	X		Russia	Sergei Kuzin	GIPSY	
CNES		X	France	Alexandre Couhert	Zoom	SLR, GNSS
GFZ		X	Germany	Rolf Koenig	EPOS-OC	SLR, GNSS
TU Delft		X	The Netherlands	Ernst Schrama	GEODYN	SLR

Following the DORIS processing for the realization of the ITRF2014, there were still many substantive issues that remained to be addressed. Some issues, such as the jump in the DORIS scale (2012 and later) have been analyzed. The IDS scale jump in 2012 is now fully explained by a variation in the number of low-elevation measurements included in the processing. Indeed, the increase of the scale factor for Jason-2 and Cryosat-2 is linked to the change of tropospheric model used by CNES in its POD processing (GDR standards): from CNET (GDR-C) to GPT/GMF (GRD-D). It caused a reduction of the amount of data marked as “rejected” in the doris2.2 file (input DORIS data file) and then, an increase of the data used considered to be good in CNES pre-processing. The larger amount of data, especially at low elevation, could thus be the cause of the change observed in the scale factor. The date of change is mission dependent. The scale increase of the multi-satellite solutions is due to the jump of the scale of the Jason-2 and Cryosat-2 solutions as well as to the high scale of HY-2A, whose DORIS data became available starting in November 2011. So, IDS ACs need to do their own pre-processing. Investigation to solve the large value of the scale observed on HY-2A is still ongoing.

Since 2008, starting with Jason-2, the satellites equipped with a DORIS receiver carry the new generation of receivers called DGXX which provides phase and pseudo-range measurements. They are distributed in a dedicated format, called RINEX/DORIS 3.0 derived from the RINEX/GPS format. One major advantage of these new measurements is that they are available with a very short latency. They also allow analysis centers to be less dependent on the CNES since the new data format provides the raw information that is necessary for computing the ionosphere delays and the precise time-tagging of the measurements. This was not the case for the former data format where this information was only given in a pre-processed form, following a pre-processing done by the CNES. While CNES supplies data files in doris2.2 and RINEX/DORIS 3.0 formats for the missions equipped with DGXX (Jason-2, Cryosat-2, HY-2A and Saral), only the latter format is available for the missions from Sentinel-3A and Jason-3 and following. To help ACs to implement the RINEX data processing in their software a dedicated web page about DORIS RINEX data was created on the IDS website:
https://ids-doris.org/analysis-coordination/about-doris-rinex-format.html

IDS completed an assessment of the three realizations of the Terrestrial Reference Frame which are the outcome of the “ITRF2014 effort”: the ITRF2014 (IGN), DTRF2014 (DGFI) and JTRF2014 (JPL). While ITRF2014 and DTRF2014 are qualitatively similar, differing mainly by the Post Seismic Deformation model (PSD), which was introduced into the IGN solution, the JPL solution was quite different, being a time series of weekly solutions obtained through a Kalman filter process. Due to editing criteria the JPL solution contains less stations at a given time than the two other realizations, particularly at the beginning of the DORIS data period, in 1993. The three TRF realizations were evaluated in terms of DORIS observation residuals, orbit overlaps and transformation parameters of the DORIS network. All TRF realizations show a clear improvement over the previous realization, ITRF2008. Based on the different criteria used for evaluation, analysis by IDS components showed that the ITRF2014(IGN) realization provides the best overall performance. It is this realization that will serve as a basis for the operational processing of future DORIS data. For that purpose, the ITRF2014 needs to be augmented (e.g. with new DORIS stations not present in the ITRF2014 solutions, or if necessary, correction of the position and velocity for the stations which had a short observation interval in the ITRF2014). This extension of ITRF2014 for the DORIS network is called DPOD2014: an update of the position/velocity of all stations is performed and aligned on the ITRF2014, leading to possible minor adjustment of older stations. The DPOD2014 built by the IDS CC (G. Moreaux) was validated by a POD group (P. Willis, F. Lemoine, A. Couhert, N. Zelensky and Ait Lakbir Hanane). The DPOD2014 solution will be updated twice a year. Some IDS ACs have switched to ITRF2014 by using the DPOD2014 solution for their IDS

operational products at the end of 2017 and some others in 2018. More information about DPOD2014 is available from the URL:
https://ids-doris.org/analysis-coordination/combination/dpod.html

The behavior of the various DORIS on-board oscillators in the vicinity of the high radiation area “South Atlantic Anomaly” (SAA) was also studied. DORIS ACs showed that all DORIS receivers are sensitive to the crossing of the SAA, though to different degrees. Thanks to the extremely precise time-tagging provided by the T2L2 experiment on-board Jason-2, A. Belli and the GEOAZUR team showed that the Jason-2 DORIS Ultra Stable Oscillator (USO) is approximately 10 times less sensitive to the SAA than that of Jason-1. The IGN AC has shown, thanks to the “DORIS PPP method” on uncorrected Jason-2 DORIS data, that the positioning error due to the SAA can reach up to 10 cm for some stations with this satellite. The GRG AC and C. Jayles from CNES both showed that Jason-3 is also sensitive to the SAA, at a level that is lower than that of Jason-1, but still 4 to 5 times higher than that of Jason-2. The CNES POD team showed that Sentinel-3A is also sensitive to the SAA. Using a novel method based on the clock determination of the GNSS receiver on-board Sentinel-3A, the CNES POD team showed that it is possible to obtain an accurate and continuous observation of the satellite’s USO frequency excursions. One of the conclusions of these studies was that, while no noticeable effect of the SAA influence was shown on POD or reference frame transformation parameters, there is an important impact on the station position estimation for some stations in the vicinity of the SAA area. Building accurate models of frequency variations in response to the temperature and to the SAA radiation effects for each DORIS USO is therefore a task that is encouraged by the IDS community for the accurate position estimation of all DORIS stations. Currently we have the following possibilities to mitigate the SAA effect. For SPOT-5 and Jason-1, ACs can use the DORIS2.2 data corrected by the models available at CDDIS and IGN Data Centers. Note, for Jason-1 the corrective model is also available. For Jason-2 and Jason-3, ACs can adjust at least a bias+drift by pass for SAA stations in their POD processing. We could use better corrected frequency model for Jason-2 and Jason-3 USO when Belli et al. will demonstrate their efficiency and will make them available. We can also use the strategy to add single satellite solution affected by the SAA in the multi-satellite solution. This method was tested and adopted for Jason-1 for the ITRF2014. Before combining single satellite solution affected by SAA to the other single satellite solutions, we rename the SAA stations (and all their adjusted parameters) so these SAA stations from this single satellite do not contribute to the realization of the combined solution.

The next months will be focused on the preparation of the next ITRF. ACs must complete the implementation of the DORIS/RINEX data processing in order to be able to process the data of Jason-3, Sentinel-3A and Sentinel-3B, which are only available in this format. They will work on the mitigation of the non-conservative force model error on satellites, the assessment of the new models/standards (TVG, HF-EOP model, ocean tides, …), the mitigation of the SAA effect on DORIS USOs for Spot-5 and Jason series, and the determination of the scale factor (choice of the elevation cut off and the data down-weighting).

The next IDS Analysis working group meeting will be held in Paris (France), on September 30 and October 1, 2019 (*hosted by CNES*). It will be devoted exclusively to the IDS contribution to the next ITRF realization

2.6 Combination Center

In addition to its operational activities of evaluation and combination of all the individual ACs weekly solutions, the IDS Combination Center (CC) has been involved in several studies proposed by the AWG and the Analysis Coordinator such as the scale jump in 2012 and the evaluation of the three 2014 TRF realizations from DGFI, IGN and JPL.

DORIS position and velocity cumulative solution
In line with the successful IDS contribution to the ITRF2014 (see Moreaux et al., 2016a)., the IDS CC initiated the elaboration of a DORIS position and velocity cumulative solution. To validate the stacking procedure and the DORIS mean velocities, the IDS CC compared the DORIS velocities with global tectonic models as well as with GNSS velocities at co-located sites. The analysis of the velocity differences (Moreaux et al., 2016b) validated the new stacking procedure. Then, early in 2017, the IDS CC started to regularly (on a quarterly basis) process and deliver (via the IDS Data Centers) a DORIS position and velocity cumulative solution from the latest IDS combined series. So far, this solution does not include Post-Seismic Deformation corrections; a piecewise linear (position+velocity) model is used to describe the station motions (see **Figure 3**). A dedicated webpage (https://ids-doris.org/analysis-coordination/combination/cumulative-solution.html) was also added to the IDS website to give further information on the IDS cumulative solution (ex: residual time series, DORIS-to-DORIS tie vector residuals, DORIS-to-GNSS tie vector comparisons, position and velocity differences with ITRF2014…).

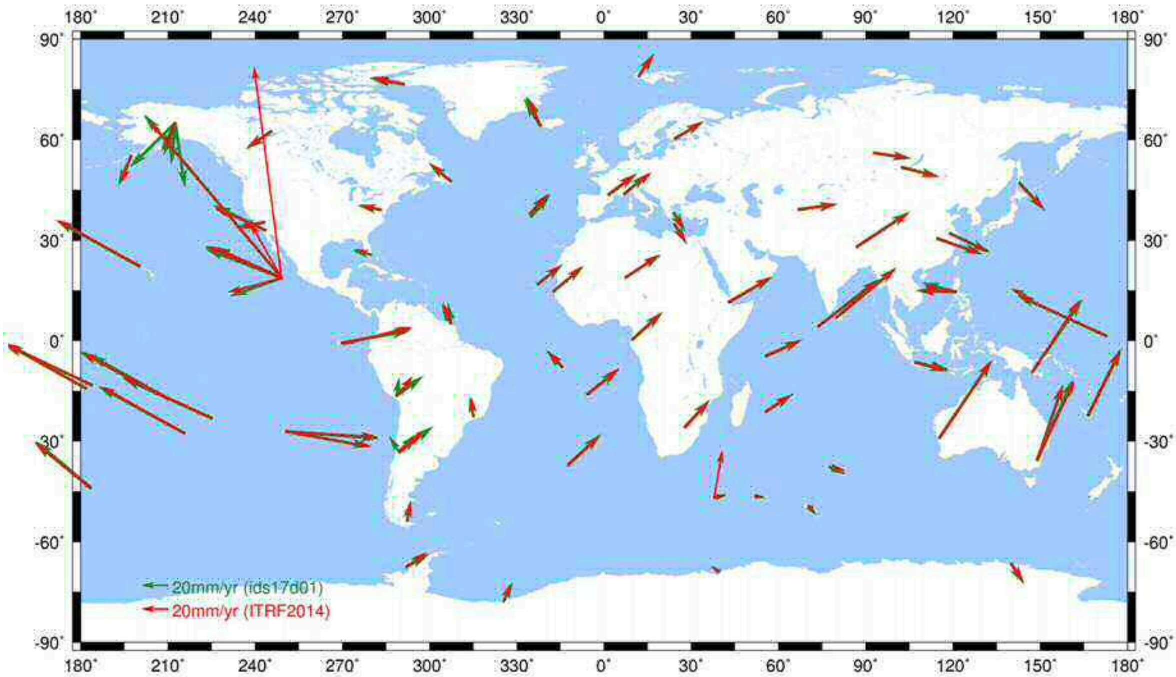


Figure 3: Horizontal velocities of the DORIS sites from ITRF2014 (red) and the first DORIS cumulative solution

DPOD2014

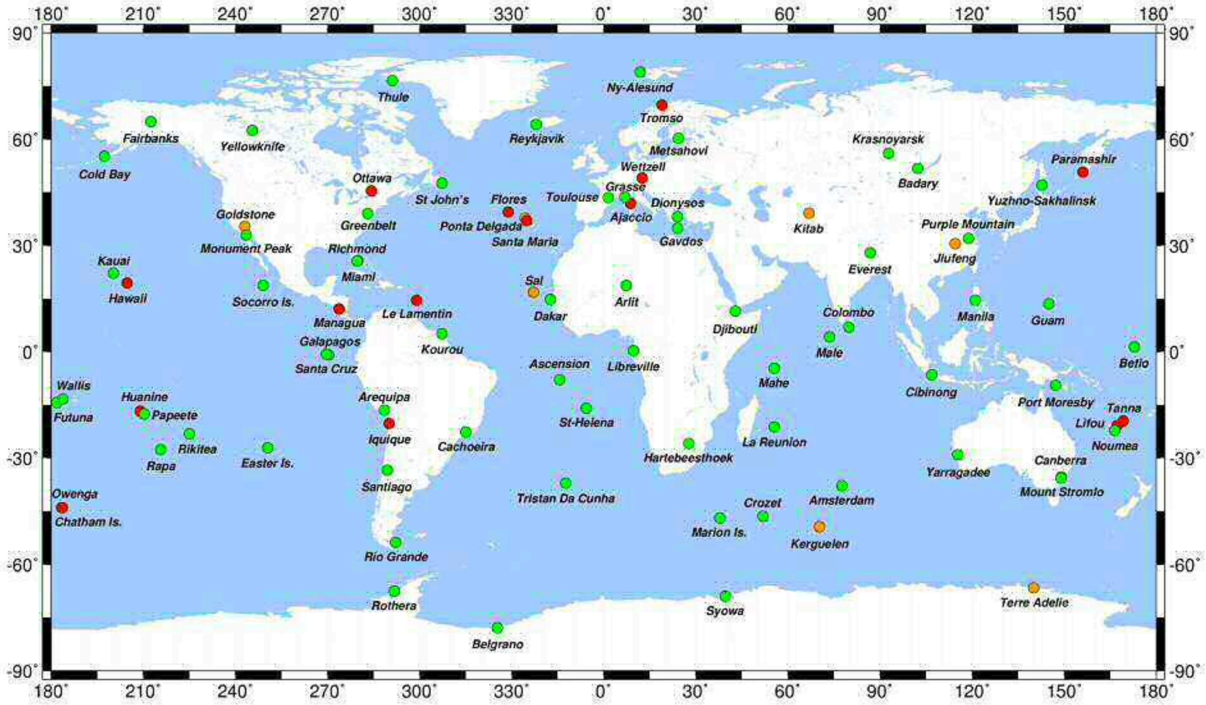


Figure 4: DORIS sites in DPOD2014_v01 produced by the IDS Combination Center; green indicates sites in ITRF2014 and DPOD2014_v01; orange indicates sites in both coordinate sets but updated in DPOD2014_v01; red indicates sites **not** in ITRF2014, but included in DPOD2014_v01.

During the first 2015 IDS AWG held in Toulouse, the IDS CC agreed to take over from P. Willis the routine production of the DPOD: "the DORIS extension of the ITRF for Precise Orbit Determination". The DPOD solutions were initiated to overcome some intrinsic drawbacks of using the latest ITRF: i) some stations are added to the tracking network after the completion of the ITRF; ii) some stations might be affected by coordinate and/or velocity discontinuities that could occur after the realization of the ITRF; iii) the precision of the position and velocities of the stations with few observations at the time of the ITRF can be increased with a longer data span and; iv) some problems in data processing may be found after the computation of the ITRF (e.g. USO sensibility to the SAA). Based on the latest IDS position and velocity cumulative solution, the IDS CC constructs the DPOD2014 solutions aligned to the ITRF2014 (see **Figure 4**). After some IDS CC internal validation tests (including coordinate and velocity differences with the previous DPOD solution and ITRF realization), the IDS POD validation group lead by P. Willis performs some POD tests with many of the DORIS satellites. After approval by the POD validation group, the new version of DPOD2014 solution is released. DPOD2014 is available from the two IDS Data Centers and is added to the dedicated IDS website page (https://ids-doris.org/analysis-coordination/combination/dpod.html). The DPOD2014 will be updated twice a year.

All the details on the realization and validation processes of the DPOD2014 are described in Moreaux et al., 2019 (that paper is in open access until the end of 2019). In preparation to the realization of the IDS contribution to the next ITRF (ITRF2020), the IDS CC started to review the whole combination strategy with the objective of improving the station positioning and EOP performances, mainly over the time period 1993.0-2002.3.

IDS products

Table 4 presents the current IDS products available through the two IDS data centers. All Analysis Centers provided at a least a long-term weekly solution of SINEX files.

Table 4: Summary of IDS Products.

Type of Products	**Contributing Analysis Centers ¶**							
	ESA	**GOP**	**GRG§**	**GSC**	**IGN**	**INA**	**IDS✚**	**SSA**
Time series of SINEX solutions (***sinex_series***)	X	X	X	X	X	X	X	X
Global SINEX solutions (***sinex_global***)			X		X		X	
Geocenter time series (***geoc***)			X	X				X
Satellite Orbits (*orbits*)			X	X				X
Ionosphere products/sat. (***iono***)								X
Time series of EOP (***eop***)					X	X		
Time series of station coordinates (***stcd***)	X		X	X	X	X	X	X
Time series of SINEX solutions (***2010campaign***)		X	X	X	X	X		
	✚ Combination Center of the IDS. **§ The GRG analysis center was renamed from the "LCA" analysis center in 2015.** **Previous analysis centers who have contributed products include GAU (Geoscience Australia) and CNES POD team under the ID "SOD"**							

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2.7 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 Dettemering (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. In 2018, two main topics has been handled by members of the Working Group, namely (1) the validation of real-time global ionospheric maps by DORIS data sets and (2) the usage of DORIS data in near real-time ionospheric modeling. Based on the present experiences and in line with some of the recommendations from the IDS retreat in June 2018, currently, CNES is studying a potential extension of its services in order to allow the ground segment to export the DORIS measurements in near real-time to the users.

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 5: IDS Meetings (2015-2019)

Meeting	Location	Country	Dates
DORIS AWG Meeting	Toulouse	France	28-29 May 2015
DORIS AWG Meeting	Greenbelt	Maryland, USA	15-16 October 2015
DORIS AWG Meeting	Delft	Netherlands	26-27 May 2016
IDS Workshop	La Rochelle	France	31 October – 1 November 2016
DORIS AWG Meeting	London	UK	22-24 May 2017
DORIS AWG Meeting	Toulouse	France	11 June 2018
IDS Workshop	Ponta Delgada	Portugal	24-26 September 2018
DORIS AWG Meeting	Munich	Germany	4 April 2019

3.2 Publications

During the last four years, IDS published several activity reports:

International DORIS Service (IDS), Report of the International Association of Geodesy 2011-2015, Travaux de l’Association Internationale de Géodésie, Pascal Willis (chairman of the Governing Board), 2015.
https://ids-doris.org/documents/report/IDS_Report_mid2011_mid2015_for_IAG.pdf

International DORIS Service (IDS), Report of the International Association of Geodesy 2015-2017, Travaux de l'Association Internationale de Géodésie, Frank Lemoine (chairman of the Governing Board), 2017.
https://ids-doris.org/documents/report/IDS_Report_mid2015_mid2017_for_IAG.pdf
International DORIS Service Activity report 2014, Laurent Soudarin and Pascale Ferrage (Eds), 122 pages, 2015. https://ids-doris.org/documents/report/IDS_Report_2014.pdf
International DORIS Service Activity report 2015, Laurent Soudarin and Pascale Ferrage (Eds), 99 pages, 2016. https://ids-doris.org/documents/report/IDS_Report_2015.pdf
International DORIS Service Activity report 2016, Laurent Soudarin and Pascale Ferrage (Eds), 120 pages, 2017. https://ids-doris.org/documents/report/IDS_Report_2016.pdf
International DORIS Service Activity report 2017, Laurent Soudarin and Pascale Ferrage (Eds), 118 pages, 2018. https://ids-doris.org/documents/report/IDS_Report_2017.pdf

3.3 Peer-reviewed publications related to DORIS

Following two DORIS Special Issues published in Journal of Geodesy in 2006-2007, and Advances in Space Research in 2010, a third DORIS Special was launched in 2014. A total of 18 manuscripts passed the peer-reviewed process and were published in Advances in Space Research on December 15, 2016, in Volume 58, Number 12. This special issue is entitled "The scientific applications of DORIS in Space Geodesy" and is edited by Frank G. Lemoine and Ernst J.O. Schrama. The papers cover five themes: ITRF2014; DORIS Ultra Stable Oscillator (Jason-2); Precise orbit determination; DORIS System and Network; Intertechnique comparisons of DORIS products.

The list of the DORIS special issues with the direct links to the indexes are given hereafter:

DORIS Special Issue: Scientific Applications of DORIS in Space Geodesy, F. Lemoine and E.J.O. Schrama (Eds.), ADVANCES IN SPACE RESEARCH, 58(12):2477-2774 (15 December 2016)
https://www.sciencedirect.com/journal/advances-in-space-research/vol/58/issue/12
DORIS Special Issue: Precise Orbit Determination and Applications to Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1483-1660 (15 December 2010)
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https://www.sciencedirect.com/journal/advances-in-space-research/vol/45/issue/12
DORIS Special Issue, P. Willis (Ed.), JOURNAL OF GEODESY, 80(8-11):401-664 (November 2006
https://link.springer.com/journal/190/80/8

IDS also 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 four years, the following articles were published (by year):

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International GNSS Service (IGS)

http://www.igs.org/

Chair of the GB: Gary Johnston (Australia)
Director of the Central Bureau: Allison Craddock (USA)

July 2015 - June 2019

Overview

For 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. The IGS was first approved by its parent organization, the International Association of Geodesy (IAG), at a scientific meeting in Beijing, China, in August of 1993. A quarter century later, the IGS community gathered for a workshop in Wuhan, China to blaze a path to Multi-GNSS through global collaboration. An overview of the current state of the organization is depicted on Fig. 1.

The IGS is a central component of the IAG's 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 ITRF. As it enters its second quarter-century, the IGS is evolving into a truly multi-GNSS service, and at its heart is a strong culture of sharing expertise, infrastructure, and other resources for the purpose of encouraging global best practices for developing and delivering GNSS data and products all over the world.

In 2015, the IGS Governing Board (GB) started the process of reviewing its Strategic Plan. Issues under consideration include the scope of products and services, appropriate acknowledgement of participants and contributors, interface with IAG and GGOS, data and product licensing, continued Global Positioning System (GPS) to GNSS transition, and new activities around GNSS system monitoring and assessment. A follow-on 2017 Strategic Plan was published in early 2018; and preliminary discussions regarding a 2020 strategic plan have commenced. This plan recognizes the extensive contribution of the IGS participants, and encourages further engagement with a broader stakeholder set, that now relies implicitly on IGS products and services.

From 2015-2019, the IGS continued to evolve its work program to meet user 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 continued with the harmonization of the Multi GNSS Experiment (MGEX) network sites into the existing IGS network. The IGS has also engaged with the International Committee on Global Navigation Systems (ICG) in the ICG-IGS Joint Trial Project (IGMA), which aims to provide monitoring and assessment products for all GNSS constellations.

In 2018, there was a change within the IGS Central Bureau (CB), with the long-standing Director of the CB, Ruth Neilan, moving on to other ventures after serving the IGS community since before its inception. The contribution Neilan has made to science and society through the IGS cannot be underestimated, and the IGS wishes her well in her future endeavors. We also recognize the contributions of Steve Fisher, who departed the CB in 2017, after many years of service.

Figure 1: IGS "at glance", as of May 2019

The IGS continues to function as a service of the IAG, and a contributor to GGOS. Accordingly, a number of the GB members continue to participate in IAG and GGOS governance, bureaus, commissions and WG, ensuring the IGS retains its strong level of relevance, and therefore sustainability. Importantly, GB members also participate in the United Nations Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy, which aims to enhance the sustainability of the GGRF through intergovernmental advocacy for geodesy. GB members also routinely invited to present and provide valuable input at the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board, exerting an influence at high levels in the United States government.

IGS Structure, Membership Growth, and Internal Engagement

In 2019, IGS membership reached 329 Associate Members (AM), representing 45 countries. The 36-member IGS GB guides the coordination of over 200 contributing organizations participating within IGS, including 108 operators of GNSS network tracking stations, 6 global Data Centers (DCs), 13 Analysis Centers (ACs), and 4 product coordinators, 21 associate ACs, 23 regional/project DCs, 14 technical Working Groups (WG), two active pilot projects (i.e., Multi-GNSS and Real-time), and the CB. The IGS structure is depicted on Fig.2.

In order to best understand who among the listed members are still active, the CB and Elections Committee Members conducted an online campaign asking all AM to verify their continued interest in participating in the IGS, and to update their contact information. Further engagement with AMs included removing the 10 person per organization cap in favor of a case-by-case review of AM applications.

A comprehensive overhaul of AM engagement documents, including GB elections and other mentions in the IGS Terms of Reference, will take place in 2019.

Governing Board

The IGS is led by an international GB (Table 1) that is comprised of seats elected by AMs who represent the principal IGS participants, as well as chairs of IGS WGs, members appointed by the Board to fill competence or geographical representation gaps, and representatives of stakeholder organizations. The GB discusses the activities of the various IGS components, sets policies and monitors the progress with respect to the agreed strategic plan and GB directives.

IGS Central Bureau

Executive management of the IGS (Table 2) is carried out by the CB, whose office is hosted at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), 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 CB 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 GB. The CB coordinates the IGS tracking network and operates the CB Information System (CBIS), the principal information portal where the IGS web, ftp (https) and mail services are hosted. The CB also represents the outward face of IGS to a diverse global user community, as well as the general public.

Staff of the CB, as part of its work program carrying out the business needs of the IGS, implements actions defined by the GB. This include a thorough analysis and refresh of the IGS Terms of Reference, supporting the ongoing update of the AMs list, prepare and support the GB elections, and plays an active role in supporting the organization of regular IGS Workshops and GB meetings. Additionally, CB works closely with members of the GB Executive Committee (EC) in developing and addressing feedback pertaining the Strategic Plan.

The CB continued to develop communications, advocacy, and public information initiatives on behalf of the GB. CB members also led a communications interest and development session at all IGS Workshops. The CB actively works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office.

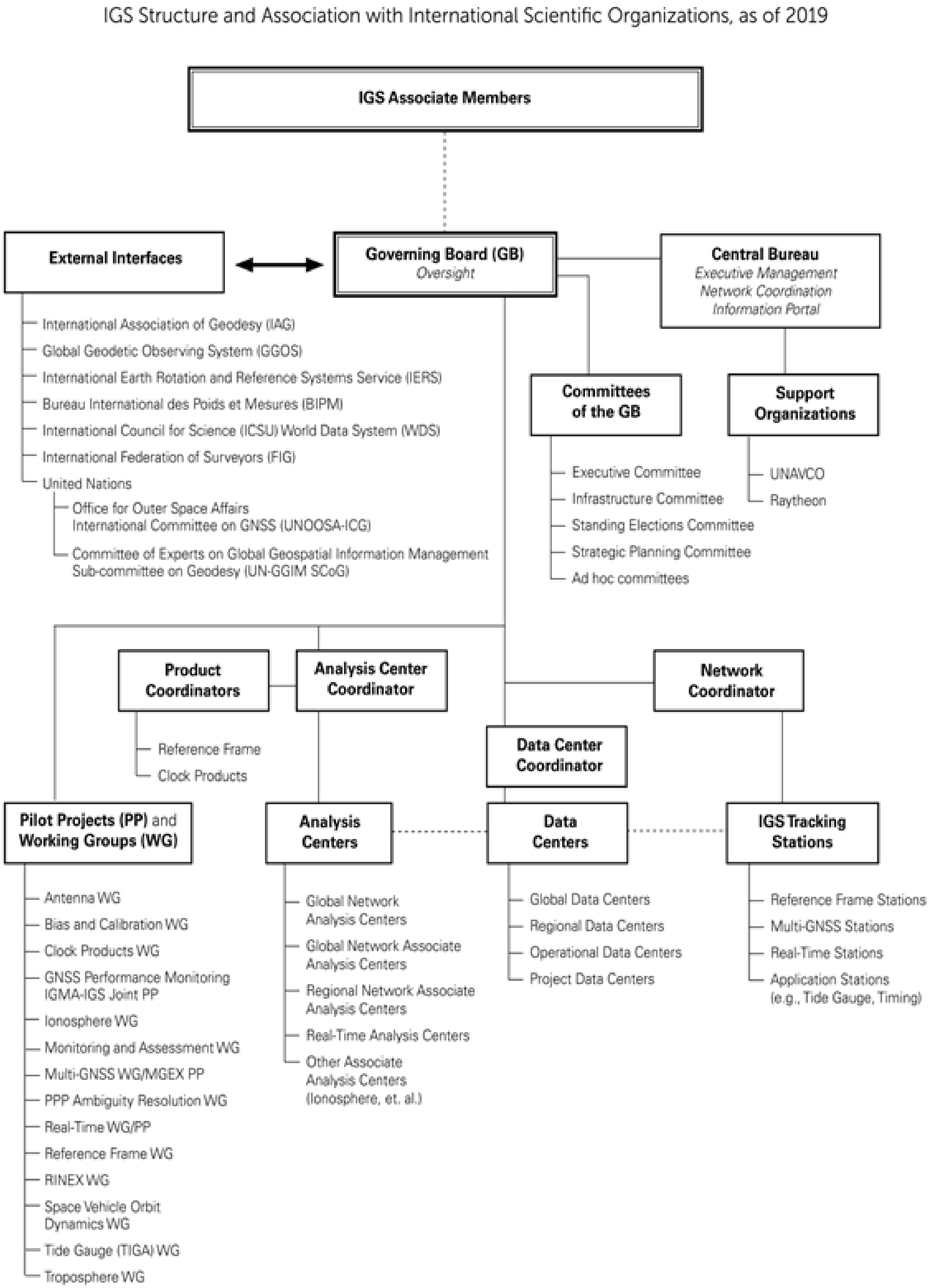

Figure 2: IGS Structure as of 2019

Table 1: Governing Board (as of May 2019)

Status		*Affiliation*	*Country*	*Role*
	G. Petit	Bureau International des Poids et Mesures	France	BIPM/CCTF Representative (Appointed)
EC-V	G. Johnston	Geoscience Australia	Australia	Board Chair
	M. Moore	Geoscience Australia	Australia	AC Co-Coordinators
EC-V	C. Rizos	University of New South Wales	Australia	IAG Representative
	S. Banville	Natural Resources Canada / Ressources naturelles Canada	Canada	PPP-AR WG Chair
	VACANT	VACANT	VACANT	RINEX/RTCM Group Chair
V	Q. Zhao	Wuhan University	China	Appointed (IGS)
	F. Perosanz	Centre National d'Etudes Spatiales	France	Vice Board Chair
V	Z. Altamimi	Institut National de l'Information Géographique et Forestière	France	IAG Representative
V	P. Rebischung	Institut National de l'Information Géographique et Forestière	France	IGS Reference Frame Coordinator
V	L. Sánchez	DGFI-TUM	Germany	Network Representative
	O. Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt	Germany	Multi-GNSS WG Chair
	T. Schöne	Deutsches GeoForschungsZentrum Potsdam	Germany	TIGA WG Chair
	T. Springer	ESA/European Space Operations Center	Germany	IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair
V	L. Agrotis	ESA/European Space Operations Centre	Germany	Real-time Analysis Coordinator
V	W. Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)
	I. Romero	ESA/European Space Operations Centre	Germany	Infrastructure Committee Chair
	A. Hauschild	Deutsches Zentrum für Luft- und Raumfahrt	Germany	Real-time WG, Chair
	W. Söhne	Federal Agency for Cartography and Geodesy (BKG)	Germany	Network Representative
V	S. Kogure	National Space Policy Secretariat (NSPS), Cabinet Office	Japan	Appointed (IGS)
	A. Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere WG Chair
EC-V, IR	R. Dach	Astronomical Institute, University of Bern	Switzerland	AC Representative
	A. Villiger	Astronomical Institute, University of Bern	Switzerland	Antenna WG Chair
	S. Schaer	Federal Office of Topography - swisstopo	Switzerland	Calibration & Bias WG Chair
	M. Ziebart	University College London	UK	Satellite Vehicle Orbit Dynamics WG Chair
V	S. Desai	NASA Jet Propulsion Laboratory	USA	AC Representative
V	R. Gross	NASA Jet Propulsion Laboratory	USA	Representative to the IERS

V	T. Herring	Massachusetts Institute of Technology (MIT)	USA	AC Coordinator
	C. Noll	NASA Goddard Space Flight Center	USA	DC WG Chair
EC-V	A. Craddock	NASA Jet Propulsion Laboratory	USA	Director of IGS CB
V	D. Stowers	NASA Jet Propulsion Laboratory	USA	DC Representative
	VACANT	VACANT	VACANT	AC Representative
V	M. Coleman	U.S Naval Research Laboratory	USA	IGS Clock Products Coordinator
	D. Maggert	UNAVCO	USA	Network Coordinator
EC-V, IR	C. Meertens	UNAVCO	USA	Appointed (IGS)
	S. Byram	United States Naval Observatory	USA	Troposphere WG, Chair

EC-V = Executive Committee Voting Member • V = Voting Member • • RI = Representative to the IERS

Table 2: IGS Central Bureau Staff (2019)

Name	*Affiliation*	*Role*
Allison Craddock	NASA Jet Propulsion Laboratory	Director
Mayra I. Oyola	NASA Jet Propulsion Laboratory	(Acting) Deputy Director and GB Executive Secretary
David Maggert	UNAVCO	Network Coordinator
Robert Khachikyan	Raytheon Corporation	CBIS Engineer
David Stowers	NASA Jet Propulsion Laboratory	CBIS Advisor
Michael Connally	NASA Jet Propulsion Laboratory	Accounts Manager

United Nations GGIM Subcommittee on Geodesy

Members of the IGS GB actively participated in the fifth session of the UN–GGIM at UN Headquarters in New York. IGS GB members involved in the UN-GGIM Global Geodetic Reference Frame (GGRF) WG played an active role in drafting a resolution for "A Global Geodetic Reference Frame for Sustainable Development" – the first resolution recognizing the importance of a globally–coordinated approach to geodesy. This resolution was adopted in February 2015 by the UN General Assembly. IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS. IGS Associate and GB members continue to participate in contributing to five WGs developed to draft the implementation plan for the GGIM GGRF Roadmap. Details and updates may be viewed on the UN-GGIM website: http://ggim.un.org.

United Nations International Committee on GNSS

IGS GB members also served in leadership roles in the United Nations International Committee on GNSS (ICG), including the WG D on Reference Frames, Timing, and Applications, and other components.

IGS Working Groups

The IGS technical WGs work on topics of particular interest to the IGS, such as improving the IGS products and infrastructure. Within the WGs, a Pilot Project structure has been defined whereby new capabilities or products are envisioned, developed, tested, and prepared for production. Policy for the Establishment of IGS WGs, Pilot Projects, and New Operational Products. The currently active WGs, and their corresponding Chairs are included on Table 3.

Table 3: IGS Working Groups

Working Group	*Chair*	*WG Established*
Antenna	Arturo Villiger (2016-Present) Ralf Schmid (2008-2016)	2008
Bias and Calibration	Stefan Schaer	2008
Clock Products	Michael Coleman	2003
Data Center	Carey Noll	2002
GNSS Monitoring (IGMA)	Tim Springer (2018-Present) Urs Hugentobler (2017-2018)	2017
Ionosphere	Andrzej Krankowski	1998
Multi-GNSS	Oliver Montenbruck	2003
Precise Point Positioning with Ambiguity Resolution	Simon Banville	2018
Real Time	André Hauschild (2018-Present) Axel Rülke (2016-2018)	2001
Reference Frames	Paul Rebischung (2017-Present) Bruno Garayt (2010-2017)	1999
RINEX	VACANT Ken MacLeod (2011-2019)	2011
Space Vehicles Orbit Dynamics	Tim Springer (2018-Present) Marek Ziebart (2011-2018)	2011
Tide Gauge (TIGA)	Tilo Schöne	2001
Troposphere	Sharyl Byram (2015-Present) Christine Hackman (2011-2015)	1998

IGS Operational Activities

Daily operations are the heart of the IGS. Various components of the service ensure that tracking data and products are made publicly available every day. Over 500 IGS Network tracking stations (Fig. 3) are maintained and operated globally by many institutions and station operators, making tracking data available at latencies ranging from daily Receiver INdependent EXchange (RINEX) files to real-time streams available for free public use.

The transition of the IGS network to multi-GNSS capability was highlighted in the 2018 Workshop, with all WG chairs introducing multi-GNSS topics in their splinter sessions. Significant effort on behalf of the MGEX Pilot Project and WG has also continued, with approximately 55% of IGS network stations being capable of tracking multiple GNSS constellations (GPS + Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) + at least one other) as of December, 2018 (Fig. 4).

The amount of IGS tracking data and products hosted by each of the four global DCs on permanently accessible servers increased significantly over the last four years, supported by significant additional storage capabilities provided by Regional DCs.

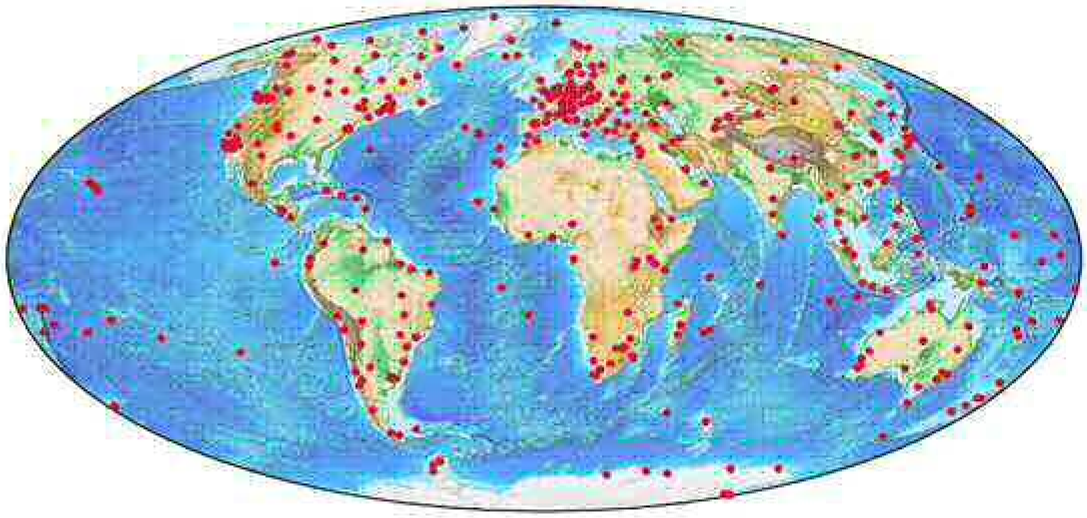

Figure 3: Global Distribution of IGS Stations as of May 17, 2019.

Twelve ACs and a number of Associate ACs utilize tracking data from between 70 to more than 350 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 GLONASS-only product files, as well as 126 ionosphere files weekly. A total of 1.4 billion tracking data files (121 TB) and 16 million product files (43 TB) were downloaded in 2018 from the NASA CDDIS, one of four IGS global DCs, by more than 10,000 unique hosts – demonstrating the intense interest of users in IGS data and products. Troposphere files for more than 300 stations are produced on a daily basis. For Tropospheric downloads, CDDIS reports over 46M files totaling over 125 GB in 2016 from 500K unique hosts each month.

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. By the beginning of 2019, the deployment of the Galileo constellation was completed with 24 active satellites.

With the assistance of the CB Network Coordinator, the IGS network added 14 stations and decommissioned 12 stations in 2018, bringing the total to 507 stations. In early 2018, the CB Network Coordinator updated the Site Log Manager database and website to accommodate the 9-character station codes. All internal CB operational scripts were also updated to accommodate the 9-character station codes. Later in 2018, the CB real-time caster was updated to use the 9-character station code as recommended by the Real Time WG. Throughout the year, the CB Network Coordinator worked with station operators on various topics including recommended firmware upgrades, antenna alignment, receiver constellation tracking, and missing station photos.

The CB Network Coordinator supported the IGS user community by reviewing and accepting 487 IGS site log updates, and worked in collaboration with the Antenna WG Chair and equipment manufacturers to provide 54 changes to the rcvr_ant.tab and antenna.gra equipment files.

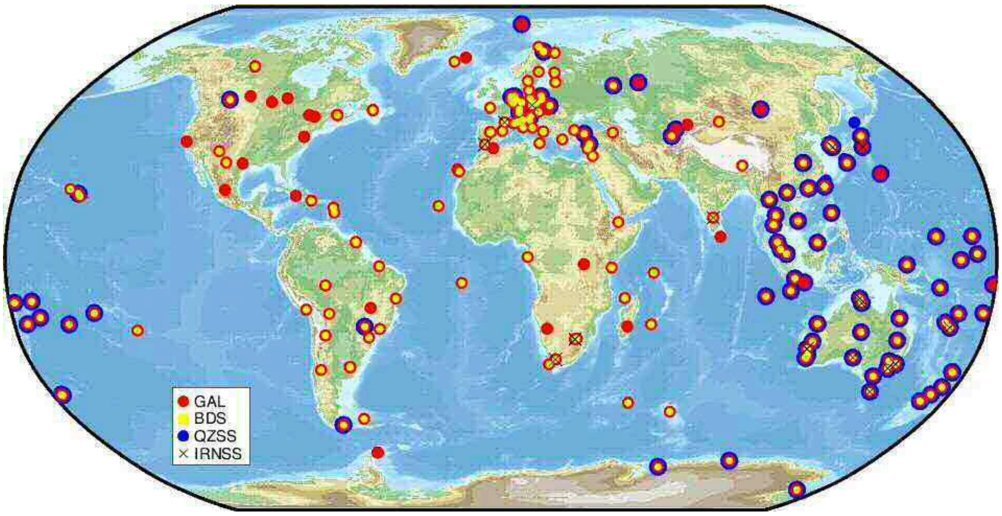

Figure 4: IGS Multi-GNSS Tracking Network map (P. Steigenberger)

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IGS Highlights (2015-2019)

The following is a brief summary of key highlights between 2015-2019 (Fig. 1):

Membership growth and engagement

Increased outreach and engagement with the IGS AM has taken place, particularly after the second open AM meeting in December 2017. IGS has also foster increased interactions with AMs via IGS social media platforms.

Analysis Center Coordinator

At the end of 2015, the Analyses Center Coordinator (ACC) role was transferred from Kevin Choi (US National Geodetic Survey (NGS)) to a joint management by Geoscience Australia (GA) and Massachusetts Institute of Technology (MIT). The proposal for this joint ventured, identified Dr. Thomas Herring (MIT) as the lead ACC, with operational support from Dr. Michael Moore (GA). This proposal utilizes Amazon Web Services (AWS) for the computing platform, and a collaborative operational model where the monitoring of combination systems is undertaken by MIT during their working day, and GA at other times. This reduced the need for 24hour /day monitoring by one individual. This proposal was subsequently accepted and endorsed by the GB. Joint management of the IGS ACC continues to this date, with operations based at GA in Canberra, Australia. The ACC 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 GA and MIT. The IGS continues to maintain a very high level of product availability.

MGEX experiment and ICG Monitoring and Assessment Joint Pilot Project

The success of the MGEX (Multi-GNSS Experiment) demonstrated the inevitability of a transition of the IGS to a full multi–GNSS Service. Accordingly, the GB decided to acknowledge this by terminating the "experiment" status and move MGEX to the status of a Pilot Project. In 2015 discussions occurred between the IGS GB and representatives from the ICG concerning the establishment of joint pilot to undertake monitoring and assessment of the GNSS constellations. The IGMA Project has experienced growth, and idea of using the existing monitoring infrastructure of IGS MGEX was introduced in 2017. The Trial Project established a Terms of Reference document, and has distributed Calls for Participation both geared toward ICG providers as well as the IGS community. The IGMA WG was formed as a complement to the ICG-IGS Joint Trial Project. Continued efforts are required to negotiate access to satellite specific information for new satellites from system providers, allowing for more realistic models of satellite behavior to be developed and utilized by the IGS ACs.

New Global Data Centers in China and Spain

Wuhan University was added as an IGS Global DC in 2017, and the GB officially endorsed fully-weighted adoption of Wuhan Rapid products. The Wuhan DC offers access to the full collection of IGS data and products to any user globally, especially those within the Asia Pacific Region. Importantly the DC gives direct access to the IGS data holdings to the very large research sector within China.

The European Space Agency's European Space Astronomy Centre (ESA/ESAC) also became an IGS Global DC in 2017, and is based in Madrid, Spain.

Reprocessing campaign: repro2

Following the first reprocessing campaign performed by the IGS in 2008, a second reprocessing campaign (repro2) was finalized in 2015. Nine different ACs reanalyzed the history of GNSS data collected by a global tracking network back to 1994 using the latest available models and methodology. Besides supplying an improved consistent set of GNSS geodetic products, one major goal of the repro2 campaign was to provide the IGS input to the latest release of the International Terrestrial Reference Frame (ITRF2014). The individual AC products were combined into official IGS repro2 products called "ig2". Results from the repro2 terrestrial frame combinations are described in Rebischung et al. (2016; https://doi.org/10.1007/s00190-016-0897-6), while results from the repro2 orbit and clock combinations are summarized in IGSMAIL-7411 (https://igscb.jpl.nasa.gov/pipermail/igsmail/2017/008601.html). Troposphere repro2 results are currently being processed and evaluated.

Adoption of IGS14 Reference Frame

The IGS adopted a new reference frame, called IGS14, on 29 January 2017 (GPS Week 1934). At the same time, an updated set of satellite and ground antenna calibrations, igs14.atx, was implemented. IGS14 is the latest in a series of GNSS reference frames adopted by the IGS. These reference frames form the basis of the IGS products, and are derived from each new version of the ITRF. Updating to IGS14 aligned IGS products to ITRF2014, and increased precision of that alignment by integrating additional available reference frame stations with more precise and up-to-date coordinates.

Antenna calibration updates

Coincident with the IGS14 Reference Frame release, IGS adopted antenna calibration updates in igs14.atx. These updates included robot calibrations for additional ground antenna types, increasing the percentage of ground stations in the IGS network with absolute calibrations to over 90%. This resulted in increased coordinate accuracy for stations equipped with these antennas. Data for the second reprocessing campaign can be found at: http://acc.igs.org/reprocess2.html

Standards development support

The IGS continues to contribute to the development of international standards related to GNSS, principally through participation within the RTCM (Radio Technical Commission for Maritime Service), where IGS leads the RINEX WG, as well as participating within the standards activities related to real time systems. RINEX is an internationally recognized GNSS observation and navigation data format. The first version of RINEX was developed in 1989, to support a European GPS data collection campaign. The key objective was to develop an open and human readable (ASCII) GNSS data format that removed the need of specialized decoders/interpreters for each GNSS receiver type. Under the leadership of Werner Gurtner (Astronomical Institute, University of Bern, Switzerland) and Lou Estey (UNAVCO, Boulder, Colorado, USA), RINEX evolved from version 1 to 2 and then to 3. Since 2013 (RINEX Version 3.02) the RINEX GNSS format has been maintained by the RINEX WG, which consists of members from the IGS, the RTCM Special Committee 104 (RTCM-SC104) and the GNSS industry.

Adoption of RINEX V3.04 and 9-character identification format

The GB agreed to adopt the official RINEX V3.04 format. It contains a new convention for file naming including the ability for 9-character ID and fixing the definition of GNSS reference time scales. The RINEX WG has assumed leadership in maintenance and further development of the RINEX data exchange standard, in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.03. The RINEX WG has worked in cooperation with the Infrastructure Committee (IC) to prepare a plan to transition from RINEX 2.x to RINEX 3.x. The IGS network map was enhanced to provide information about stations providing data in RINEX 2 and RINEX 3 formats, which may be viewed in real time at: http://www.igs.org/network. The current RINEX 3.04 release supports all publicly available signals, including the United States' GPS, Russia's GLONASS, Europe's Galileo, China's BeiDou, Japan's Quasi Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS) constellations. RINEX 3.04 contains updates to support planned GLONASS CDMA signals, as well as new BeiDou III and QZSS II signals.

In addition to the new signals, the RINEX 3.04 text has been edited to improve the description of messages, fields and overall readability. The RINEX 3.04 data standard documentation is available from the following addresses: ftp://igs.org/pub/data/format/rinex304.pdf, ftp://igs.org/pub/data/format/rinex304-release-notes.pdf and http://www.rtcm.org/differential-global-navigation-satellite—dgnss—standards.html.

The IC and DC Coordinator are working on integrating long filenames, RINEX3 data into operational archives. The Troposphere WG is also incorporating long names in its SINEX output files.

IGS web-based assets (IGS.org)

The IGS CB has moved IT services to external cloud hosted servers, in order to allow global access. IGS product access was redirected from IGS CB mirrors to the Crustal Dynamics Data Information System (CDDIS, ftp://cddis.gsfc.nasa.gov/gnss/products/), Institut National de l'Information Géographique et Forestière (IGN, ftp://igs.ensg.ign. fr/pub/igs/products/) and the Scripps Institution of Oceanography (SIO, ftp://garner. ucsd.edu/pub/products/) to ensure global access to over 20 years of analysis products, as well as enabling access to data. The IGS also moved its Real-Time Service (RTS) caster to a supercomputing center to ensure performance, availability, and service monitoring.

Content and resources in the IGS Knowledge Base, http://kb.igs.org, continue to be enhanced and expanded. Workshop resources, including images, posters, presentation slides, and videos, also continue to be made available on the website. The next generation of the website is currently under development by the IGS CB and will be released during Fall 2019.

IGS GB Meetings

Table 4 summarizes the numerous meetings that have taken place over the period between 2015-2019.

Table 4: IGS Governing board Meetings 2015-2019

Date	*Place*	*Comments*
12 April, 2015	Vienna, Austria	Prior European Geophysical Union Meeting
23 June, 2015	Prague, Czech Republic	During 26th IUGG/IAG General Assembly
13 December, 2015	California, USA	Prior American Geophysical Union Meeting
7 February, 2016	Sydney, Australia	Session 1 out 2: Prior IGS Workshop
12 February, 2016	Sydney, Australia	Session 2 out 2: After IGS Workshop
17 April, 2016	Vienna, Austria	Prior European Geophysical Union Meeting
11 December, 2016	California, USA	Prior American Geophysical Union Meeting
23 April, 2017	Vienna, Austria	Prior European Geophysical Union Meeting
02 July, 2017	Paris, France	Session 1 out 2: Prior IGS Workshop
07 July, 2017	Paris, France	Session 2 out 2: After IGS Workshop
11 December, 2017	Louisiana, USA	Prior American Geophysical Union Meeting
08 April, 2018	Vienna, Austria	Prior European Geophysical Union Meeting
28 October, 2018	Wuhan, China	Session 1 out 2: Prior IGS Workshop
02 November, 2019	Wuhan, China	Session 2 out 2: After IGS Workshop
09 December, 2018	Washington, DC, USA	Prior American Geophysical Union Meeting
07 April, 2019	Vienna, Austria	Prior American Geophysical Union Meeting
15 July, 2019 (upcoming)	Montreal, Canada	During IUGG Meeting

IGS Workshops

In 2016, it was decided to move the workshops to an 18-month cycle, due to the wealth of topics and quickening pace of technological development impacting the IGS.

IGS Workshop on GNSS Biases 2015

This workshop was held at the University of Bern on 5–6 November 2015. All related information, including all presentations, may be found at: http://www.biasws2015.unibe.ch. The main focus of this workshop was on:

- Characteristics and handling of GNSS biases: Most of the presentations ad-dressed related topics and provided corresponding updates.
- Bias-SINEX Format Version 1.00: A first draft format document was prepared and presented at the workshop. Essential format aspects and issues were discussed in the plenum. An accordingly updated format document will be prepared for the upcoming IGS Workshop in Sydney.

2016 Sydney Community Workshop

In 2016, the IGS had its first workshop to be held outside of North America or Europe, with the Sydney Workshop being held in February 2016 at the University of New South Wales, Sydney, Australia. This workshop, the first in South East Asia, signaled the stronger involvement of BeiDou and QZSS into the IGS's GNSS futures.

2017 Paris Community Workshop

The 2017 IGS Workshop, with the theme of "Pathways to Improved Precision" took place 3-7 July, 2017. This workshop was hosted locally by IGN and the Centre National d'Études Spatiales (CNES) at the University of Paris-Diderot in Paris, France. Almost 300 individuals from over 30 countries around the world participated in the sessions.

The workshop also featured a special keynote lecture on the Galileo system, given by Marco Falcone of ESA.

2018 Wuhan Community Workshop

The latest IGS Workshop, with the theme of "Multi-GNSS through Global Collaboration" took place 29 October to 2 November, 2018. The workshop was hosted locally by Wuhan University at the East Lake Conference Center in Wuhan, China, and was the first IGS Workshop to be held on the Asian continent. Over 300 individuals participated in the sessions.
The workshop featured two keynote presentations:

- "Introduction to BeiDou-3 Navigation Satellite System" presented by Yuanxi Yang of the State Key Laboratory of Geo-Information Engineering, based in Xi'an, China.
- "BeiDou Augmentation and its Future" presented by Liu Jingnan, an Academician of the Chinese Academy of Engineering, based at Wuhan University in Wuhan, China.

Videos, posters, and plenary presentation slides of community workshops are available on the IGS website, IGS.org.

2019 Potsdam Analysis Center Technical Workshop

At the Wuhan Workshop, it was decided to return to a biennial community workshop plan, and to hold smaller, more focused workshops in the years in between workshops.

Communications, Advocacy, and Outreach

The IGS is represented in a variety of roles throughout the geodetic community. IGS GB and AMs served on the Coordinating Board, EC, Consortium, and Science Panel of the IAG's GGOS.

GB members continue to be actively involved in communications, advocacy, and outreach through presentations at international meetings and articles in geospatial magazines.

Social media has been actively maintained by CB staff and has grown significantly since 2017, due in part by increasing 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 at IGS/presents, will continue.

New 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.

IGS Components and Working Groups

A.1 Analysis Center Coordinator

Analysis Center Coordinator: Loukis Agrotis (Germany)

Overview

The Real Time Service (RTS) was formally launched in April 2013. This consists of global GNSS data and products that are streamed from IGS DCs and are openly available to subscribed users with latencies of a few seconds.

The RTS expands the capacity of the IGS to support applications requiring real-time access. Analysis products include individual ACs as well as combination solutions. There is a large variety of potential applications for the service with a strong focus on scientific and educational applications.

Activities during the period 2015-2019

The RTS data network is shown in the Figure below. It originally provided only GPS or GPS+GLONASS data but it is rapidly transitioning to a truly multi-GNSS network, disseminating observation and broadcast ephemeris messages using the RTCM 3 standard and the Networked Transport of RTCM via Internet Protocol (NTRIP).

Figure A1.1 GNSS tracking stations in the IGS real-time network

The analysis infrastructure includes a number of individual ACs, which process the Real Time observations and compute epoch-wise orbit and clock products. These are formatted using RTCM SSR encoding software and transmitted to the NTRIP casters at the IGS DCs. Orbit products are available either with respect to the satellite center of mass (CoM) or the Antenna Phase Center (APC). The clock products are transmitted with an update interval of 5 seconds. The AC streams and NTRIP mountpoint designations are listed below.

Table A1.1 RTS AC Products

Center	Description	NTRIP Mountpoint
BKG	GPS and GPS+GLONASS orbits and clocks using IGU orbits (CoM/APC)	CLK00/10 CLK01/11
CNES	GPS+GLONASS orbits and clocks based on IGU orbits (CoM/APC) GPS+GLONASS+GAL+BEI orbits and clocks (CoM/APC)	CLK90/91 CLK92/93
DLR	GPS orbits and clocks based on IGU orbits (CoM/APC) GPS+GLONASS orbits and clocks	CLKC0/A0 CLKC1/A1
ESOC	GPS orbits and clocks using NRT batch orbits every hour which are based on IGS batch hourly files (CoM /APC) GPS orbits and clocks using NRT batch orbits every hour which are based on RINEX files generated from the RT streams (CoM /APC)	CLK50/51 CLK52/53
GFZ	GPS orbits and clocks and IGU orbits (CoM/APC)	CLK70/71
GMV	GPS+GLONASS orbits and clocks based on NRT orbit solution (CoM/APC)	CLK81/80
NRCan	GPS orbits and clocks using NRT batch orbits every hour (APC)	CLK22
WUHAN	GPS orbits and clocks based on IGU orbits (CoM/APC)	CLK15/16

The coordination of the AC activities is the responsibility of the RTACC. This role has been fulfilled by the European Space Operations Center of ESA, (ESOC) since the start of the Pilot Project in 2008. The RTACC is responsible for monitoring the individual AC streams and for generating and assessing the quality of combined real-time orbit and clock products. The currently available combination products are listed in the following table.

Table A1.2 RTS Combination Products

Center	Description	NTRIP Mountpoint
ESOC	RT GPS epoch combination from NRCan, BKG, CNES, DLR, ESOC, GMV and GFZ streams	IGS01 (APC) IGC01 (CoM)
BKG	RT GPS Kalman-generated combination from NRCan, BKG, CNES, DLR, ESOC, GMV, GFZ and WUHAN streams	IGS02 (APC) IGC02 (CoM)
BKG	RT GPS+GLONASS Kalman-generated combination from BKG, CNES, DLR and GMV streams	IGS03 (APC) IGC03 (CoM)

Fig. A.2 shows the orbit and clock performance of the IGC01 combination between 2010 and 2018. The plotted points represent single overall daily RMS values obtained from daily comparisons of the decoded orbit and clock products against the IGS Rapid solution. Outliers are generally due to a single poorly performing satellite, typically during the eclipse season.

Publications during the period 2015-2019

Rülke, A., Agrotis, L., Caissy, M., Söhne, W., Stürze, A., Weber, G., (2015), IGS Real-Time Service: An Open Service for Positioning, Navigation and Timing, 26th IUGG General Assembly, June 2015, Prague.

Rülke, A., Agrotis, L., (2017), The Real Time Service of the International GNSS Service: Products, Performance and Challenges, China Satellite Navigation Conference 2017, Shanghai, China.

Agrotis, L., Schoenemann, E., Enderle, W., Caissy, M., Rülke, A., (2017), The IGS Real Time Service, GNSS 2017 – Kompetenz für die Zukunft, Schriftenreihe des DVW Band 87/2017.

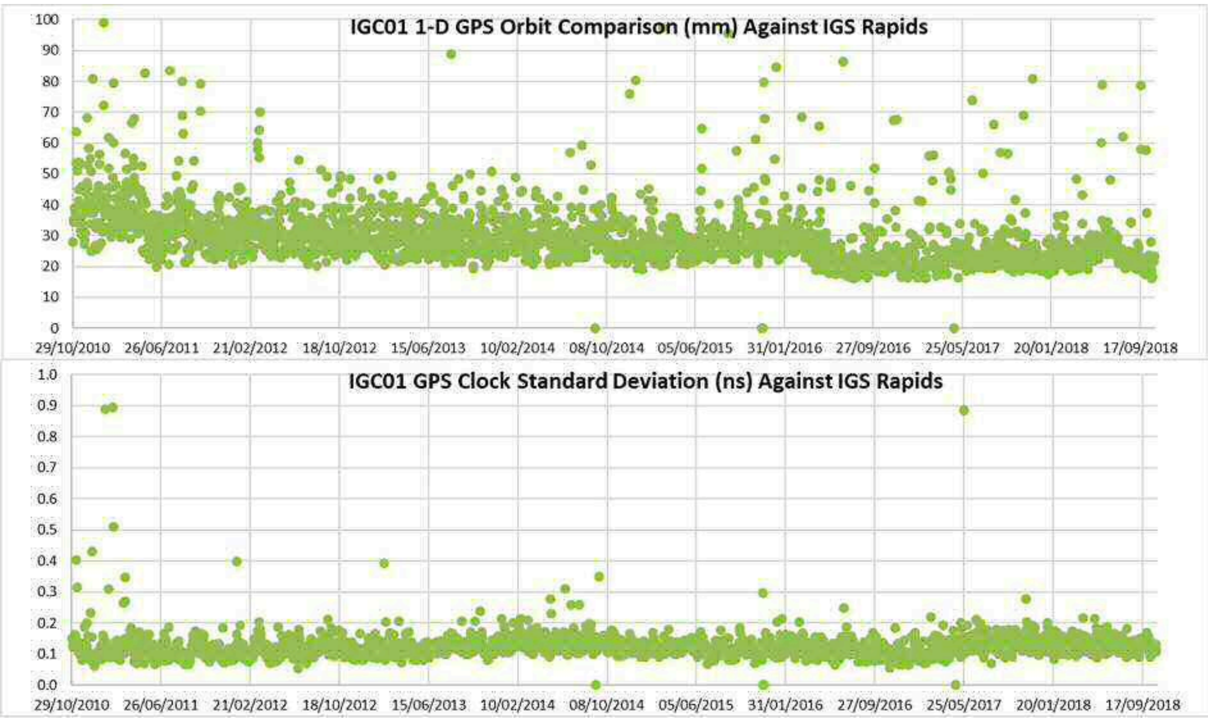

Figure A1.2 orbit and clock performance of the IGC01 combination between 2010 and 2018.

A.2 Antenna Working Group

Chair: Arturo Villiger (Switzerland)

Overview

The IGS Antenna WG establishes a contact point to users of IGS products, providing guidance for antenna calibration issues and for a consistent use of IGS products. It maintains the IGS files related to receiver and antenna information, namely the IGSANTEX file, including satellite antenna and receiver type-mean calibrations. Antenna phase center issues are related to topics such as reference frame, clock products, calibration and monumentation. The Antenna WG therefore closely cooperates with the respective WGs (Reference Frame WG, Clock Product WG, Bias and Calibration WG, Reanalysis WG), with antenna calibration groups, with the AC Coordinator and the ACs for analysis related issues, and with the Network Coordinator concerning maintenance of relevant files.

Activities and publications during the period 2015-2019

IGS adopted antenna calibration updates in igs14.atx, in alignment with the IGS14 Reference Frame release. As previously mentioned, these updates include robot calibrations for additional ground antenna types, increasing the percentage of ground stations in the IGS network with absolute calibrations to over 90%, which have translated in increased coordinate accuracy for stations equipped with these antennas.

A.3 Bias and Calibration Working Group

Chair: Stefan Schaer (Switzerland)

Overview

The IGS Bias and Calibration WG (BCWG) coordinates research in the field of GNSS bias retrieval and monitoring. It defines rules for appropriate, consistent handling of biases which are crucial for a "model-mixed" GNSS receiver network and satellite constellation, respectively. At present, we consider: P1-C1, P2-C2, and P1-P2 differential code biases (DCB). Potential quarter-cycle biases between different phase observables (specifically L2P and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, like the European Galileo and the Chinese Compass, an increasing number of types of biases is expected.

Activities and publications during the period 2015-2019

The Bias and Calibration WG continues coordinating research activities related to bias retrieval, analysis, and monitoring. Presently, the group is considering C1W–C1C, C2W–C2C, and C1W–C2W differential code biases (DCB). Potential quarter-cycle biases between different phase observables (specifically between GPS L2W and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, such as the European Galileo and the Chinese BeiDou, careful treatment of measurement biases in legacy and new signals becomes more and more crucial for combined analysis of multiple GNSS.

In 2016 and 2017, a GNSS bias reprocessing (for GPS/GLONASS) using the recently implemented observable-specific signal bias (OSB) parameterization was carried out at the Center for Orbit Determination in Europe (CODE) for 1994-2016 RINEX data. The outcomes of this reprocessing effort are daily normal-equation (NEQ) files for GPS and GLONASS code bias parameters that are conform to both global ionosphere and clock analysis.

The combination of these daily bias results into a coherent long-term (1994-present) GPS/GLONASS bias product is another key achievement. Such a bias product is particularly useful for applications where calibration in the absolute sense are crucial (e.g., for GPS timing, or atomic clock comparisons). Additionally, CODE's classic GPS DCB product and the most resent GNSS bias results are made available using the Bias-SINEX Format Version 1.00.

A.4 Clock Products Working Group

Chair: *Michael Coleman (USA)*

Overview

The IGS Clock Product Coordinator forms the IGS timescales based on the clock solutions of IGS ACs. IGS Rapid and Final products are aligned to these timescales. The Clock Products WG is the result of a transition from the earlier IGS/BIPM Time Transfer Pilot Project to a more operational status. Principal products of this WG are the IGS Rapid and Final timescales as described on the project website.

A.5 Data Center Working Group

Chair: *Carey Noll (USA)*

Overview

The IGS DC WG (DCWG) was established in 2002. The DCWG tackles many of the problems facing the IGS DCs as well as develops new ideas to aid users both internal and external to the IGS. The direction of the IGS has changed since its start in 1992 and many new WGs, projects, data sets, and products have been created and incorporated into the service since that time. The DCWG was formed to revisit the requirements of DCs within the IGS and to address issues relevant to effective operation of all IGS DCs, operational, regional, and global.

Activities and publications during the period 2015-2019

The DCWG continued to work closely with the IGS IC on several topics, primarily the implementation of the RINEX Version 3 Transition Plan and the goal of "one network one archive". Starting with data from January 01, 2016, the IGS GDCs integrated RINEX V3 data following the V3 naming conventions into their main, operational directories; this data structure is now routine at the IGS DCs and the number of stations submitting data in RINEX V3 format continues to increase. The IGS ACs are now capable of utilizing data in RINEX V3 format and the IC continues to work with stations to submit their data in this format.

During the 2016-2018 timeframe, significant work was accomplished on this XML site log metadata activity, particularly work with colleagues implementing GeodesyML. IGS participants provided feedback on its use and incorporating existing site log metadata into the schema.

Many of the topics addressed by the IGS DCWG have synergies with the IC and thus recent DCWG splinter meetings during IGS workshops have been held in conjunction with the IC splinter meeting. Because of the overlap in responsibilities and actions, updates to the IGS Terms of Reference will move DCWG activities into the IC. A newly identified position, the IGS DC Coordinator, will work within the IC, and with other IGS WG, to address DC related items and recommendations.

A.6 GNSS Monitoring Group (IGMA)

Chair: Tim Springer (Germany)

Overview

The GNSS landscape is undergoing a fundamental transition with the development of new satellite navigation systems. Furthermore, existing systems are being modernized and new signals and frequencies becoming available. To optimally exploit the benefits of multi-GNSS, users require homogeneous common monitoring of the performance of individual constellation and signals, to verify service commitments are met and to ensure public confidence in GNSS service provision and interoperability. Based on this, the ICG recommended at the ICG-10 meeting in Boulder 2015 that the IGMA Task Force and IGS initiate a joint Trial Project to demonstrate a global GNSS monitoring and assessment capability, utilizing existing resources and infrastructure and avoiding duplications.

The Joint GNSS Monitoring WG was formed by the IGS GB at its meeting in December 2016 in San Francisco in order to install, operate and further develop the IGS GNSS Monitoring and Assessment Pilot Project jointly with the International GNSS Monitoring and Assessment (IGMA) Task Force of the United Nations Office of Outer Space Affairs, International Committee on GNSS (UNOOSA-ICG).

A.7 Ionosphere

Chair: Andrzej Krankowski (Poland)

Overview

The Ionosphere WG started the routine generation of the combine Ionosphere Vertical Total Electron Content (TEC) maps in June 1998. This has been the main activity so far performed by the four IGS Ionosphere Associate ACs (IAACs): CODE, ESOC, JPL, and UPC (Technical University of Catalonia, Barcelona, Spain). Independent computation of rapid and final TEC maps is used by each ACs: Each IAACs compute the rapid and final TEC maps independently and with different approaches including the additional usage of GLONASS data in the case of CODE.

A.8 Multi-GNSS

Chair: Oliver Montenbruck (Germany)

Overview

The main activity of the Multi-GNSS WG (MGWG) is MGEX; which aims at the integration of the evolving global and regional satellite navigation systems Galileo, BeiDou, QZSS, and NavIC into the IGS data archives and operational products. Multi-GNSS observation data are provided by a global tracking network that is fully integrated into the IGS network since 2016. The MGEX ACs use these observations to generate multi-GNSS products, in particular orbits and clocks.

Activities and publications during the period 2015-2019

MGEX started as the multi-GNSS experiment in 2011 and its status was changed to a pilot project in the beginning of 2016. A comprehensive overview of the organizations contributing to MGEX as well as the various products and their quality is given in Montenbruck et al. (2017). The MGEX ACs generating orbit and clock products are given in the table below.

Table A8.1 RTS Combination Products

Institution	Constellations
Centre National d'Etudes Spatiales, Collecte Localisation Satellites (CNES/CLS)	GPS+GLO+GAL
Center for Orbit Determination in Europe (CODE)	GPS+GLO+GAL+BDS2+QZS
Deutsches GeoForschungsZentrum (GFZ)	GPS+GLO+GAL+BDS2+QZS
Japan Aerospace Exploration Agency (JAXA)	GPS+GLO+QZS
Shanghai Observatory (SHAO)	GPS+GLO+GAL+BDS2
Technische Universität München (TUM)	GAL+BDS2+QZS
Wuhan University	GPS+GLO+GAL+BDS2+BDS3+QZS

Solar radiation pressure is the largest error source for orbit determination of GNSS satellites. Early analysis of Galileo orbits generated by the MGEX ACs revealed systematic orbit-periodic effects (Steigenberger et al. 2015). These errors could be significantly reduced by introducing an a priori model considering the elongated shape of the Galileo satellites (Montenbruck et al. 2015) or more sophisticated empirical orbit models (Prange et al. 2017).

Metadata like satellite mass, center-of-mass coordinates, and surface properties are important the generation of accurate GNSS products (Montenbruck 2017). Subsets of satellite metadata were recently released by the European GNSS Agency for Galileo (https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata) and Cabinet Office for QZSS (http://qzss.go.jp/en/technical/qzssinfo/index.html). The MGWG developed an extension of the SINEX format for satellite metadata and maintains a draft version of the IGS satellite metadata file (http://mgex.igs.org/IGS_MGEX_Metadata.php).

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Steigenberger P, Hugentobler U, Loyer S, Perosanz F, Prange L, Dach R, Uhlemann M, Gendt G, Montenbruck O, (2015) Galileo Orbit and Clock Quality of the IGS Multi-GNSS Experiment, Adv Space Res 55(1):269–281, DOI: 10.1016/j.asr.2014.06.030

Montenbruck O, Steigenberger P, Hugentobler U (2015) Enhanced Solar Radiation Pressure Modeling for Galileo Satellites, J Geod 89(3):283–297, DOI: 10.1007/s00190-014-0774-0

Montenbruck O, Steigenberger P, Prange L, Deng Z, Zhao Q, Perosanz F, Romero I, Noll C, Stürze A, Weber G, Schmid R, MacLeod K, Schaer S. (2017) The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, Prospects and Challenges, Adv Space Res 59(7):1671-1697, DOI: 10.1016/j.asr.2017.01.011

Montenbruck O (2017) IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products

A.9 Precise Point Positioning with Ambiguity Resolution

Chair: Simon Banville (Canada)

Overview

Precise satellite orbit and clock corrections produced by the IGS are used by many for the purpose of computing precise point positioning (PPP) solutions. For 24-hour solutions in static mode, PPP can provide millimeter-level accuracies for all components (latitude, longitude and height). Since PPP processes undifferenced observations, it also provides useful information on other error sources affecting GNSS observations such as receiver clocks, tropospheric delays and slant ionospheric delays.

For about a decade now, techniques were developed to fix undifferenced ambiguities in PPP. Similar to a network solution, ambiguity resolution provides improved estimates for user parameters. Studies have demonstrated a 30% improvement in the longitude component, enhanced receiver clock stability estimates, and reduced errors in PPP-derived atmospheric delays. PPP with ambiguity resolution (PPP-AR) can also significantly improve the accuracy of short observation sessions, which is especially beneficial for fieldwork in many industries.

With PPP-AR having matured sufficiently since its inception, and with more IGS ACs producing products enabling PPP-AR (currently: CNES, NRCan, Wuhan and CODE), the timing is right for the IGS to start investigating a combined version of these products. Different from standard clock products produced by the IGS, PPP-AR products only retain their consistency when considering simultaneously both the satellite clock and bias (code and phase) corrections. There is, however, no impact on the combined orbit products.

The PPP-AR WG will investigate the development of a modernized combination process taking into consideration both satellite clocks and biases. Improvements to the current clock combination process shall also be considered, such as: satellite attitude during eclipse periods, day boundary discontinuities, and the inclusion of multiple GNSS constellations. It should also be noted that all ACs can contribute to such a clock/bias combination, although the combined phase-bias products would be determined solely from ACs contributing PPP-AR products. The goal of the PPP-AR WG is, therefore, to analyze the feasibility and benefits of having the IGS adopt a modernized clock/bias combination process.

A.10 Real Time Service

Chair: André Hauschild *(Germany)*

Overview

The Real Time Service (RTS) expands the capacity of the IGS to support applications requiring real-time access. It utilizes a global receiver network and provides infrastructure for data and product dissemination. Analysis products include individual ACs as well as combination solutions. There is a large variety of potential applications for the service with a strong focus on scientific and educational applications.

A.11 Reference Frame

Chair: Paul Rebischung (France)

Overview

The collective effort of the WG participants is to generate the official IGS station coordinates and velocities, Earth Rotation Parameters (ERPs), geocenter estimates and other terrestrial frame-related parameters along with the appropriate covariance information. The estimated parameters are aligned to the ITRF. The group strives for consistency, reliability, accuracy and timeliness of the above products.
The WG also specifies and selects globally distributed sets of GNSS stations from the ITRF solutions to realize the successive IGS Reference Frames (RF). New RF realizations are issued at irregular intervals, usually synchronized to new ITRF releases. The reliability and consistency of individual RF stations are continuously monitored and occasional updates announced to users.

Activities and publications during the period 2015-2019

Besides a continuous quality monitoring of the operational IGS terrestrial frame combination products, the main achievements of the WG during the period 2015-2019 were the following:

IGS contribution to ITRF2014. The IGS contribution to ITRF2014 is based on the products from the second IGS reprocessing campaign (repro2). A total of 9 ACs contributed to the repro2 campaign and provided daily terrestrial frame (SINEX) solutions among other products. The individual AC contributions were combined into official IGS repro2 SINEX solutions, named "ig2", which constitute the IGS contribution to ITRF2014. A complete description of the repro2 SINEX combination methodology and results can be found in Rebischung et al. (2016; https://doi.org/10.1007/s00190-016-0897-6).

IGS14/igs14.atx framework. After the latest release of ITRF2014 (Altamimi et al., 2016; https://doi.org/10.1002/2016JB013098) was published in January 2016, the Reference Frame WG and the Antenna WG prepared the IGS realization of ITRF2014, IGS14, and the associated set of satellite and ground antenna calibrations, igs14.atx. This preparation included:

- the selection of the most suitable reference frame (RF) stations from the complete set of GNSS stations in ITRF2014, and the design of a well-distributed core network of RF stations for the purpose of aligning global GNSS solutions,
- updates of the ground antenna calibrations of various antenna types and assessment of the impact of these updates on station coordinates,
- the re-evaluation of the radial components of all GPS and GLONASS satellite antenna phase center offsets.

The operational IGS products were switched from the previous IGb08/igs08.atx to the new IGS14/igs14.atx framework on GPS week 1934 (29 January 2017). The switch was announced to the community in [IGSMAIL-7399], together with details about the elaboration of IGS14 and igs14.atx and their impact on user results.

Further details on the WG activities during the period 2015-2019 can be found in the yearly IGS technical reports.

A.12 RINEX

Chair: *Ken MacLeod (Canada) through May 2019.* Vacant as of May 2019

Overview

The IGS RINEX-WG was established in December of 2011 to update and maintain the RINEX format to meet the needs of the IGS and the GNSS Industry. Since the RINEX format is widely used by the GNSS industry it was decided that it should be jointly managed by the IGS and RTCM-SC104. As a result, the working group consists of both IGS and RTCM-SC104 industry members. Document approval will follow the IGS/RTCM-SC104 consensus-based approach and majority voting will be used if a consensus cannot be reached in a reasonable amount of time. RINEX documents will continue to be freely distributed both by the IGS and RTCM-SC104.
RINEX 2.1X is currently the primary archival format used within the IGS and the GNSS industry. However, since RINEX 2.1X was designed in the mid 1990s, primarily to support GPS, it has proven difficult to extend RINEX 2.1X to support new GNSS constellations and signals. As a result of the shortcomings of RINEX 2.1X, RINEX 3.0x was designed to provide generic and systematic support for GNSS constellations, signals and observations. Given the needs of both the IGS and GNSS communities and the strengths of RINEX 3.0X, the IGS plans to support RINEX 3.0X.

It is understood by the IGS that the transition from RINEX 2.1X to 3.0x has to be done in partnership with the GNSS community. One of the first steps in this transition occurred in 2009 when the IGS joined the RTCM-SC104. Since joining RTCM-SC104 the IGS has contributed to the development of an open, generic, high precision and multi-GNSS binary observation format called RTCM-Multiple Signal Messages (RTCM-MSM). The RTCM-MSM format supports the creation of fully defined, phase aligned RINEX 3.0x observations files. To support the transition to RINEX 3.0X the IGS/RTCM-SC104 RINEX WG is encouraging and supporting the development of open source software tools that will convert RTCM-MSM to RINEX 2.1X and 3.0X formats and provide data quality control measures.

A.13 Space Vehicle Orbit Dynamics

Chair: Tim Springer (Germany)

Overview

Several groups and individuals within the IGS community are working on topics related to spacecraft orbit dynamics and attitude modelling. Recent progress in these areas show there is scope to improve the accuracy of the orbits and observable modelling through these studies that will be of direct benefit to IGS products and users. Moreover, given the emergence of new constellations the IGS will need spacecraft specific force and attitude models in order to fully exploit the availability of the new signals. The Space Vehicle Orbit Dynamics WG formalizes and coordinates the efforts of the individual groups in this area.

A.14 Tide Gauge (TIGA)

Chair: Tilo Schöne (Germany)

Overview

The Tide Gauge Benchmark Monitoring WG (TIGA) of the IGS continues its support for climate and sea level related studies and organizations concerned herewith (e.g., GGOS, OSTST, UNESCO/IOC). The TIGA WG provides vertical geocentric positions, vertical motion and displacements of GNSS stations at or near a global network of tide gauges and works towards establishing local geodetic ties between the GNSS stations and tide gauges. To a large extend the TIGA WG uses the infrastructure and expertise of the IGS.

The main aims of the TIGA WG are:
1. Maintain a global virtual continuous GNSS Tide Gauge network
2. Compute precise coordinates and velocities of GNSS stations at or near tide gauges. Provide a combined solution as the IGS-TIGA official product.
3. Study the impacts of corrections and new models on the GNSS processing of the vertical coordinate. Encourage other groups to establish complementary sensors to improve the GNSS results, e.g., absolute gravity sites or DORIS.
4. Provide advice to new applications and installations.

Activities and publications during the period 2015-2019

Following aim #2 TIGA WG members continued with the reprocessing of the TIGA network. Nearly 800 GNSS@TG stations and IGS08b core sites are processed by the TIGA ACs (to end of 2015). Two of the TIGA centers significantly contributed to the IGS repro2.

The TIGA-WG carried forward the IOC/GLOSS-Task "Priorities for installation of continuous GNSS) near to tide gauges. Report to Global Sea Level Observing System (GLOSS)" by King, M.A. (2014) for the densification and extension of the TIGA Observing Network to GGOS. The response by the GGOS Coordinating Board was received early 2017 and the TIGA-WG is working on the implementation of the plan.

TIGA Network operator continued to work with Tide Gauge and GNSS station operators to make existing stations available to TIGA and the scientific community. A main (ongoing) task is to continuously update the current database of existing local ties between GNSS and tide gauge benchmarks. By the end of 2018 about 197 local ties information are available at http://www.sonel.org/-Stability-of-the-datums-.html?lang=en. The current number of GNSS@TG stations is 1103 (TIGA: 125 stations) stations (with 163 stations decommissioned). Still there are 166 stations where the GNSS data is not (yet) available for scientific research.

The TIGA-WG members actively participated in the UNESCO GLOSS Group of Expert Meetings and the World Climate Research Project (WCRP) conference in 2017).

http://ioc-unesco.org/index.php?option=com_oe&task=viewEventRecord&eventID=1534
http://ioc-unesco.org/index.php?option=com_oe&task=viewEventDocs&eventID=2367

Selected publications

Hunegnaw, A., FN Teferle, KE Abraha, A. Santamaría-Gómez, M. Gravelle, G. Wöppelman, T. Schöne, Z. Deng, R. Bingley, DN Hansen, L. Sanchez, M. Moore, and M. Jia: A New Global Vertical Land Movement Data Set from the TIGA Combined Solution, Geophysical Research Abstracts, Vol. XX, General Assembly European Geosciences Union (Vienna 2017), http://meetingorganizer.copernicus.org/EGU2017/EGU2017-18947.pdf

Hunegnaw, A., Teferle, F., Abraha, K., Santamaria-Gomez, A., Gravelle, M., Wöppelman, G., Schöne, T., Deng, Z., Bingley, R., Hansen, D., Sanchez, L., Moore, M. (2017): On the Scientific Applications of IGS Products: An Assessment of the Reprocessed TIGA Solutions and Combined Products, (IGS Workshop Booklet), IGS Workshop, http://www.igs.org/assets/pdf/W2017-PY02-02%20-%20Teferle.pdf

Hunegnaw, A.; Teferle, FN.; Abraha, KE.; Bingley, R.; Deng, Z.; Gravelle, M.; Hansen, DN; Moore, M; Sanchez, LM; Santamaria-Gomez, A; Schöne, T; Wöppelmann, G: A Global Vertical Land Movement Data Set from a Combination of Global Navigation Satellite System Solutions, Regional Sea Level Changes and Coastal Impacts, 10-14 07 2017, USA, http://www.sealevel2017.org/images/Documents/abstracts/posters/Poster_abstractbook.pdf

A.15 Troposphere:

Chair: *Sharyl Byram (USA)*

Overview

GNSS can make important contributions to meteorology, climatology and other environmental disciplines through its ability to estimate troposphere parameters. Along with the continued contributions made by the collection and analysis of ground-based receiver measurements, the past decade has also seen new contributions made by space-based GNSS receivers, e.g., those on the COSMIC/FORMOSAT. The goal of the IGS Troposphere WG is to improve the accuracy and usability of GNSS-derived troposphere estimates. It does this by coordinating (a) WG projects and (b) technical sessions at the IGS Analysis Workshops.

International Laser Ranging Service (ILRS)

https://ilrs.gsfc.nasa.gov

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[4] Center for Space Research, The University of Texas at Austin, Austin, TX 78712, USA
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[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] Leibniz Universität Hannover, Institut für Erdmessung, 30167 Hannover, Germany
[11] Observatoire de la Côte d'Azur, Nice, 06300 France
[12] 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 10–20 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

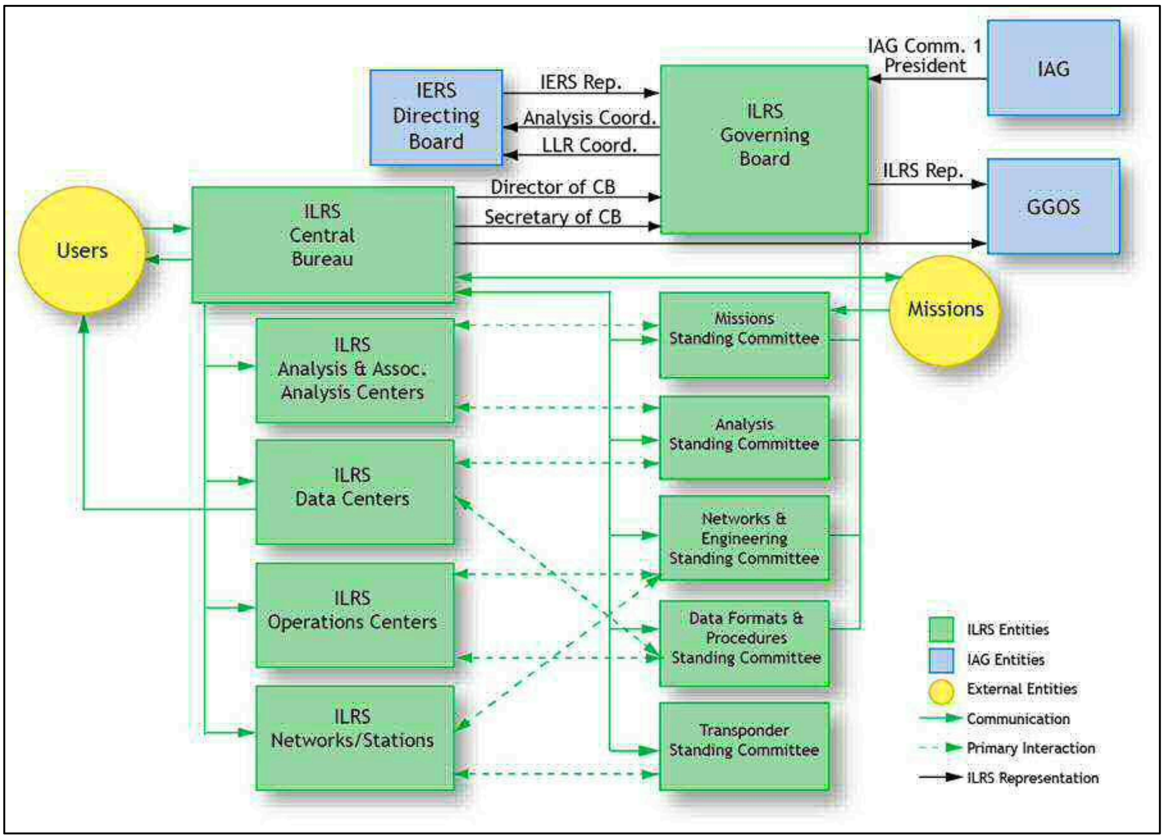

Figure 1. The organization of the International Laser Ranging Service (ILRS).

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.

Table 1. ILRS Governing Board (as of May 2019)

Name	Position	Country
James Bennett	Appointed, WPLTN Network	Australia
Giuseppe Bianco	Appointed, EUROLAS Network, Governing Board Chair (2015-2018)	Italy
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Georg Kirchner	Appointed, EUROLAS Network, Networks and Engineering Standing Committee Co-Chair	Austria
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Italy
Jan McGarry	Appointed, NASA Network	USA
Stephen Merkowitz	Appointed, NASA Network	USA
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	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
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 2015-2019		
Wu Bin	Appointed, WPLTN	China
Geoff Blewitt	Ex-Officio, Representative of IAG Commission 1	USA
Ludwig Combrinck	Elected, Lunar Representative	South Africa
David McCormick	Appointed, NASA Network	USA
Horst Müller	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Jürgen Müller	Elected, Lunar Representative	Germany
Andrey Sokolov	Appointed, At-Large	Russia

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.

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; 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 with 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 2017. Each official ILRS solution is obtained through the combination of solutions submitted by the 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
- GRGS, Observatoire de Cote d'Azur (participation suspended for two years)
- JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
- NSGF, NERC Space Geodesy Facility

Since 2016, the ILRS has released an additional operational product on a weekly basis following a pilot project period. These official products are precision orbits in standard SP3c formatted files for the four satellite targets (LAGEOS-1, -2, and Etalon-1, -2).

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:

ftp://cddis.nasa.gov/slr/products/pos+eop and
ftp://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 at:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

The main focus of the Analysis SC activities over the past two years was the improvement of modeling used in the reduction of the SLR data and generation of the official products for the development of ITRF2014, (Luceri et al., 2014). In particular, all ACs made major efforts to comply with the adopted analysis standards and the IERS Conventions 2010, the consistent modeling of low degree time-varying gravitation and the realistic modeling of the mean pole in computing the pole tide effects (Pavlis et al., 2014). Since the delivery of the preliminary and final versions of ITRF2014, the ASC has focused on evaluating them and providing feedback to ITRS for adjustments that led to the finally adopted version. The efforts to identify, quantify and contain systematic errors in the SLR data have continued with many new initiatives that ILRS feels necessary in order to improve data quality.

It is recognized that practices that will limit or mitigate the effect of systematic errors in the ILRS data, improve the final products through realistic description of geophysical processes, and strengthen the quality of the products include but are not limited to using LARES as an additional accurate target in developing the official products (Pavlis et al., 2015). In addition to that though, a new study group, the ILRS "Quality Control Board", with members from all areas of expertise within the service, has been established 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. More details on the initial results from this new initiative are given under the section for the ILRS ASC.

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. In that vein the LLR group proposed an Associate Analysis Center for LLR, which has been readily accepted by the ILRS.

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 Russian groups have advanced the idea of placing two SLR stations at critical locations to help address the tracking load. They have co-located a second station at Mendeleevo and an SLR station 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 2020 – 21 time frame, and have offered to co-locate new systems at stations currently operated by other organizations. The core Argentine-German Geodetic Observatory (AGGO), formally TIGO in Concepción, Chile, has been relocated to La Plata (Argentina); the SLR system is being upgraded and operations are expected to resume in late 2019. Work continues on the new station in Metsahövi (Finland) and the upgrade of the Chinese SLR station in San Juan (Argentina) both planned for operations in late 2019 or early 2020. Two new stations, are underway at Ponmundi and Mt. Abu (India) and planning is underway on a new in SLR station in Yebes (Spain). The NASA Space Geodesy Project (SGP) is building new SGSLR stations (as part of Core sites) at McDonald, TX, Haleakala, HI and NASA/GSFC. A fourth SGSLR system is being built in cooperation with the Norwegian Mapping Agency (NMA) for Ny Ålesund (Norway). Operations are projected for the 2021–2022 timeframe. Planning is underway for additional SLR systems as part of core sites at other current NASA partner sites and new locations to help fill some of the geographic gaps in the global space geodesy network.

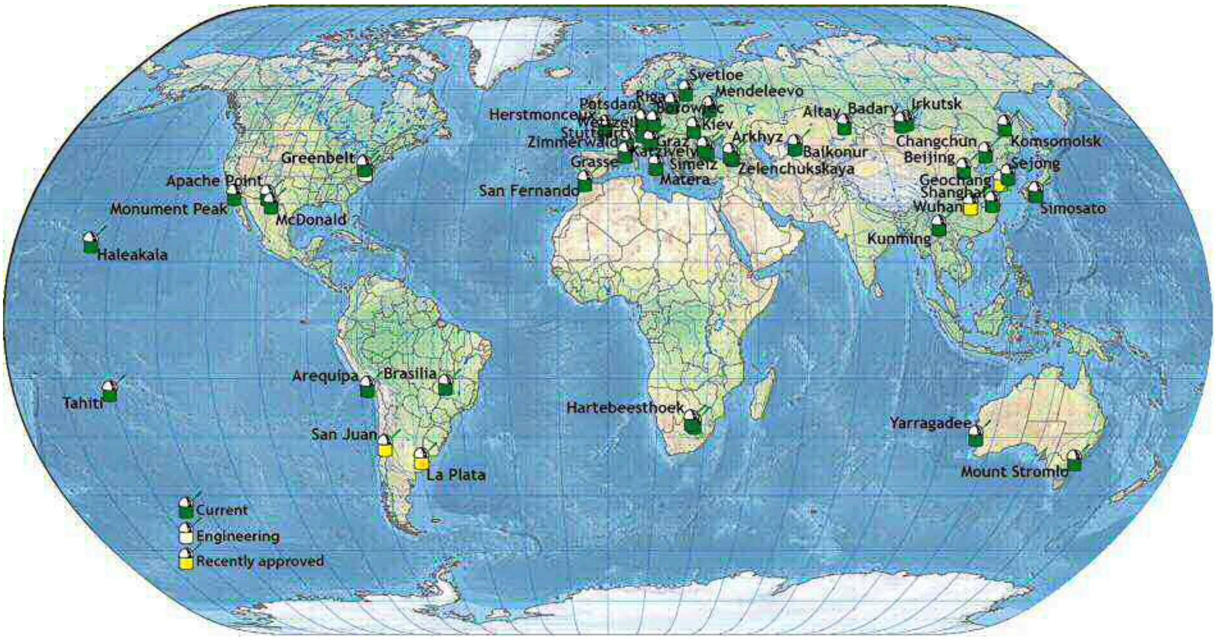

Figure 2. ILRS network (as of May 2019).

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 general stations continue to improve their performance; recent strong performers are shown in Figure 3. During the twelve-month period from May 2018 to April 2019, seventeen stations met the updated ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

As shown in Table 2, several stations are now operating with kHz lasers and fast detectors, 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 is increasing dramatically. Many others, particularly the Russian stations, are operating in the 100 to 300 Hz range. Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

Satellite Missions

The ILRS is currently tracking nearly 100 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). The large list of satellites is saturating some stations that are not fully manned and strategies are being examined to try 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.

Table 2. High-Repetition Rate ILRS Stations (as of May 2019)

Site Name	Station	Repetition
Altay	1879	300
Arkhyz	1886	300
Badary	1890	300
Baikonur	1887	300
Beijing	7249	1000
Brasilia	7407	300
Changchun	7237	1000
Graz	7839	2000
Hartebeesthoek	7503	300
Herstmonceux	7840	2000
Irkutsk	1891	300
Komsomolsk	1868	300
Kunming	7820	1000
La Plata	7405	100
Mendeleevo	1874	300
Mount Stromlo	7849	100
Potsdam	7841	2000
Sejong	7394	5000
Shanghai	7821	1000
Svetloe	1888	300
Wettzell (SOS)	7827	1000
Zelenchukskaya	1889	300
Zimmerwald	7810	110

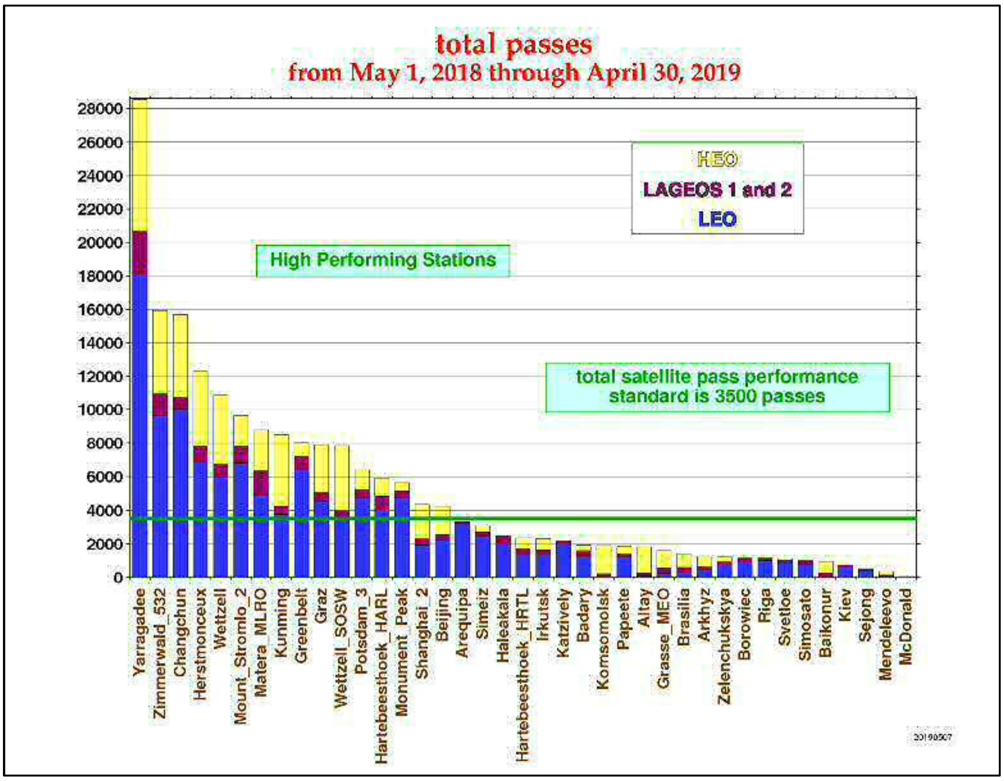

Figure 3. ILRS network performance (total passes), May 2018 through April 2019.

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).

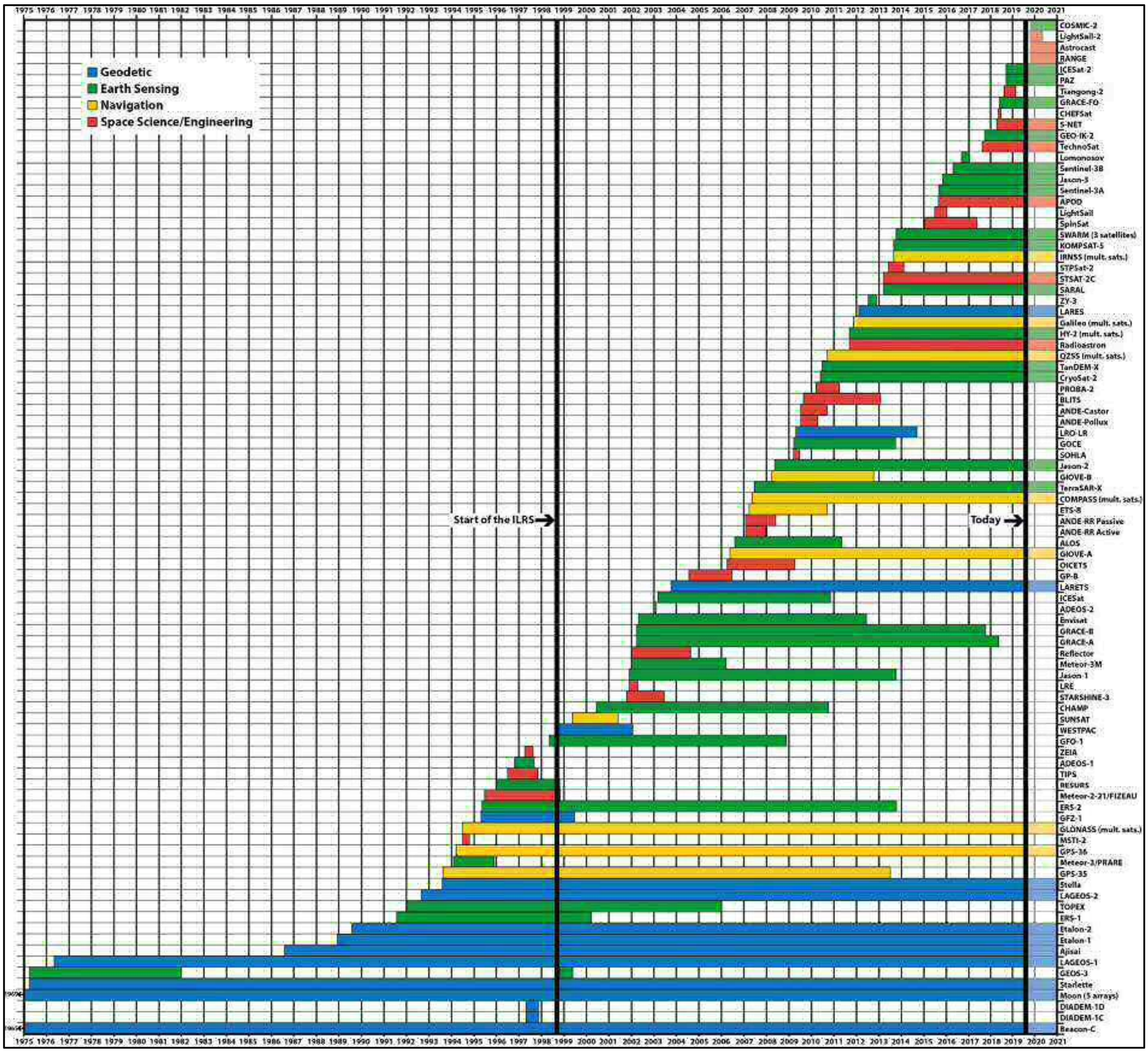

Figure 4. The past, current, and future ILRS satellite tracking list (as of May 2019).

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). Significant effort was spent by the ILRS CB on restricted tracking procedures for the Sentinel-3A and -3B, ICESat-2, and Lomonosov missions to ensure that only authorized stations ranged to the satellites and did so only during authorized time periods to avoid any damage to vulnerable onboard instrumentation. Some stations in the ILRS network continue to track several satellites (e.g., Envisat, TOPEX/Poseidon) considered “space debris” 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 form provides the ILRS with the following information: a description of the mission objectives, mission requirements including any tracking restrictions, responsible individuals and contact information, timeline, satellite subsystems, and details of the retroreflector array and its placement on the satellite; a mission concurrence section grants the ILRS stations permission to perform laser ranging to the satellite. This form also outlines the early stages of intensive support that may be required during the initial orbital acquisition and stabilization and spacecraft checkout phases. A list of 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 2019)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Compass/BeiDou (10 new, 16 total satellites)	Chinese Defense Ministry	Positioning, navigation, timing	2007- present
Galileo (21 new, 26 total satellites)	ESA	Positioning, navigation, timing	2011- present
GLONASS (5 new, 69 total satellites)	Russian Federation Ministry of Defense	Positioning, navigation, timing	1989-present
IRNSS (4 new, 7 total satellites)	ISRO	Positioning, navigation, timing	2013-2018
QZS (3 new, 4 total satellites)	Cabinet Office, Government of Japan	Positioning, navigation	2017
GRACE-FO-1, -2	NASA, GFZ	Gravity	May-2018
ICESat-2*	NASA	Ice sheet mass balance, sea level	Oct-2018
Jason-3	CNES, NASA, Eumetsat, NOAA	Oceanography	Jan-2016
Lomonosov*	Scobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University	Upper atmospheric research	Apr-2016
PN-1A	BACC	Precise orbit determination	Sep-2015
Sentinel-3A, -3B*	ESA, Eumetsat	Marine observation	Feb-2016
Approved by ILRS for Future SLR Tracking			
APOD/PN -1B, -1C, -1D	Beijing Aerospace Control Center	Engineering	2015
COSMIC-2	UCAR	Atmospheric research, validation of GNSS orbits	2017
LightSail-B	Planetary Society	Engineering	2017
NISAR	NASA	Earth sensing	2020
Future Satellites with Retroreflectors			
GPS-III	U.S. DoD, DoT	Positioning, navigation, timing	2019
HY-2B, -2C, -2D	CNES, CNSA	Earth observation	2017-2019
LARES-2	ASI, ESA	Relativity, geodesy	2020
Sentinel-6	ESA, Eumetsat, NASA, NOAA	Ocean altimetry	2020
SWOT	NASA, CNES	SAR altimeter	2020

*Note: * denotes restricted tracking mission; only authorized stations perform laser ranging to the satellite*

During this reporting period, over forty satellites from the GNSS, QZS, and IRNSS constellations were added to the ILRS priority list. In addition, and as shown in Table 3, eight other satellites, including four restricted tracking missions, were launched and supported by the ILRS network. As of May 2019, the ILRS priority list includes eight GLONASS satellites, eight Compass/BeiDou satellites, eight Galileo satellites, six IRNSS satellites, and four QZS satellite. Predictions are provided for additional GNSS satellites; stations can track these satellites on a non-interference basis with the ILRS priority list satellites.

New ILRS Tracking Strategy for GNSS

During the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand network support for GNSS satellites with retroreflector arrays (GLONASS, BeiDou (Compass), Galileo, and eventually GPS. The GLONASS constellation is fully populated. BeiDou and Galileo constellations are in process. GPS satellites with laser retroreflector arrays are now projected to begin deployment in the mid-2020's. There are presently 61 GNSS satellites; when completed, the full GNSS complex should reach over 100 satellites.

User tracking requirements for GNSS fall into two categories: intensive tracking on a small number of satellites in each constellation and sparse sampling on all of the other GNSS satellites. In addition, some users want to schedule focused campaigns for eclipse studies to better model the effects of solar radiation pressure. The ILRS and GGOS formed a joint study group, the LAser Ranging to GNSS s/c Experiment (LARGE) to define an operational tracking strategy to improve ILRS response to user needs. Based on experience from tracking campaigns (See Missions Campaigns below), the new tracking strategy will be:

- GNSS tracking will continued to be prioritized with the other ILRS satellites by the standard ILRS priority scheme (by altitude and inclination);
- Four GNSS satellites can be chosen for intensive tracking by each constellation; all of the remaining GNSS satellites will be relegated to a pool for sparse tracking on a random basis by the stations, with encouragement to support all of the constellations;
- Campaigns will be scheduled to support special requirements (e.g. eclipse coverage).

This new procedure will be announced once the current GNSS tracking campaign are over.

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.

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 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.

Lunar Laser Ranging (LLR)

LLR Stations

The LLR results are considered among the most important science return of the Apollo era; it certainly is the only experiment still supporting science. Of all the active ILRS observatories there are currently only four, which are technically in the position to track retro-reflector arrays on the surface of the Moon. These stations are APOLLO (USA), Grasse (France), Matera (Italy) and Wettzell (Germany). New stations are under development in China (Yunnan province), Russia and South Africa. The most active stations during this period (2015-2019) were the Observatoire de la Côte d' Azur, France and the APOLLO site in New Mexico, USA. Since late 2014, the Observatoire de la Côte d' Azur station has ranged primarily in the infrared (1064 nm); these data are available at (*http://www.geoazur.fr*). Unfortunately, the McDonald Observatory in Texas, USA is no longer operational, so its four decade-long time series has been interrupted. New stations are under development in China (Yunnan province), Russia and South Africa. The first LLR experiments were reported from the Yunnan Observatory December 2017 to March 2018. Current resolution is only at the meter level, but upgrading to a short pulse laser is currently planned. System improvements continue at the APOLLO station. Unfortunately, data yield is limited because the telescope is shared with other scientific applications. The station has introduced a novel timing concept to improve ranging stability. Technical improvements have been made at Matera and Wettzell, with noted improvement in performance. At the Altay site in Russia, hardware and software are being introduced, for LLR operation expected to start in the 2021-2022 timeframe.

Although data have been taken on the Apollo 11, 14, and 15, and the Lunokhod 1 and 2 reflectors, the bulk of the data has been from largest reflector on Apollo 15. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface.

Lunar Analysis Centers

LLR data analysis is carried out by a few major LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; Institute of Geodesy (IfE), University of Hannover, Germany. 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.). Some interest towards this end has also been shown by the Hartebeesthoek Radio Astronomy Observatory (South Africa) where an ex-Observatoire de la Côte d' Azur 1-m aperture telescope is being prepared for LLR use. In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

LLR Science

During the last few years, the strong increase in the annual LLR normal point rate was mainly due to the effort at the French station in Grasse (Courde C. et. al., 2017). The total data archive is still dominated by the Apollo 15 reflector, but its impact was reduced to 69%, and for the period between 2016 and 2018 (Figure 5) the contribution from the smaller reflectors has increased with the Apollo 15 share down to 39%. Data continues to be taken at the APOLLO station but have not been released since 2016; the data statistics for this station shown in Figure 5 were provided through private communication and not reflected in Figures 6-8.

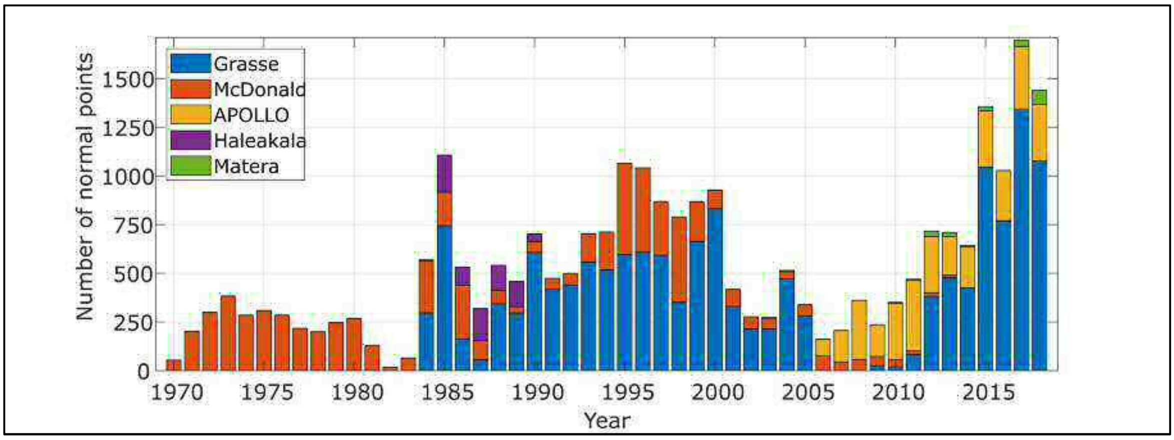

Figure 5. Distribution of LLR normal points taken by the major observatories over the years

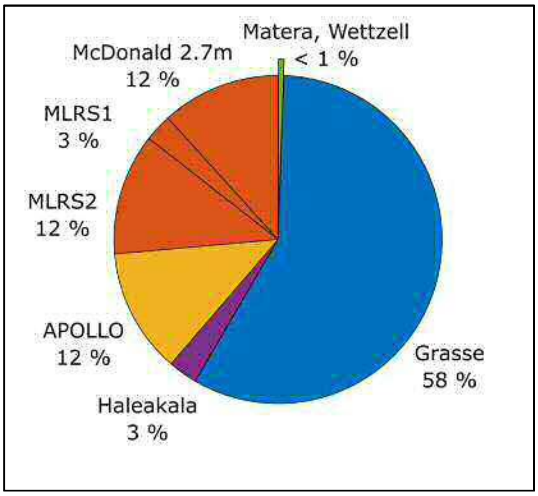

Figure 6. Measurement statistics (1970-2018) by station.

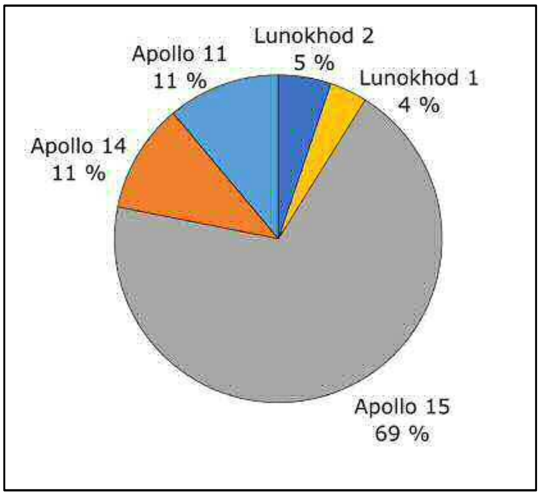

Figure 7. Measurement statistics (1970-2018) by reflector.

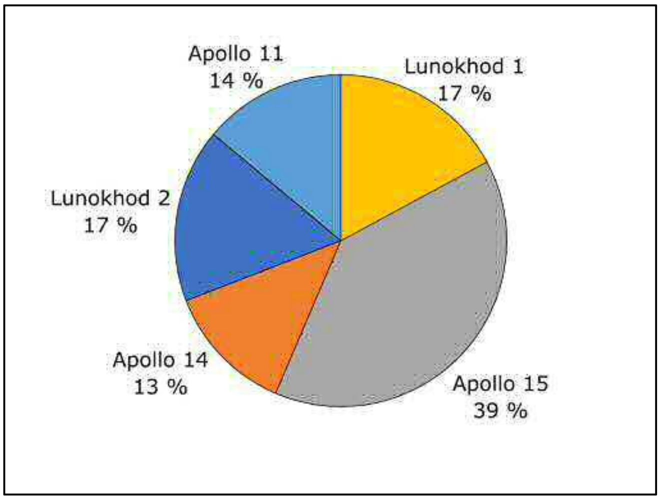

Figure 8. Measurement statistics (2016-2018) by reflector.

LLR is an important tool to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system. Current improvements in the estimation of relativistic parameters include, e.g., tests of the equivalence principle, possible time variability of the gravitational constant and Lorentz symmetry (Hofmann F. and Müller J., 2018). LLR based EOP results contribute to combined EOP solutions. With the larger LLR data set over time [9], the lunar tidal acceleration has been more accurately determined (Williams J.G. and

Boggs, D.H.,2016) as well as station coordinates and velocities. Through the studied of lunar tides, physical librations and the lunar orbit, LLR is been an important tool in improving our understanding of the physical properties and the interior of the Moon. Discrepancies between LLR and GRAIL derived results (Pavlov, D.A. et. al, and 2016) of elasticity parameters (Love numbers) and the degree 3 gravitational field which leads us to recognize that there is still very interesting and challenging science to address, especially in the modelling of dissipation and properties of the lunar interior.

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.

Recent 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 who will be appointed by the GB. Other changes addressed the addition of new SCs and clarifying terminology.

Standing Committee and Study Group Activities

All ILRS standing committees held meetings during ILRS workshops held during the reporting period (2015 ILRS Technical Workshop in Matera Italy and the 20th International Workshop on Laser Ranging in Potsdam Germany). The Analysis SC held additional meetings during the 2015, 2016, and 2017 EGU General Assemblies in Vienna Austria.

Analysis Standing Committee (ASC)

In addition to the production of the official ILRS ASC products, the ASC focused on two Pilot Projects (PP) during the reporting period: one was a continuation of the orbital product PP, which in early 2016 evolved into a bona fide official product as reported earlier under the "Data Products" section. The other PP was agreed at the ILRS Tech. Workshop in Matera, Italy, and the purpose of that effort was to develop a robust and efficient analysis procedure that will monitor the long-term performance of systematic errors at stations. A test period of four years (2005 to end of 2008) was selected for the validation of the procedure and the products of the contributing ACs. Of the eight ACs, six contributed to the PP. In the initial phase a combination of all available contributions was performed and the comparison of the individual estimates to the combined result was used to validate the contributing series. In the next phase of the PP the ACs reanalyzed all LAGEOS, LAGEOS-2 and Etalon-1 and -2 SLR data from 1993 to end of 2018 and generated a complete series of weekly estimates of biases for all systems. In the final step we will examine these biases on a system by system basis and aggregate them in groups that show a stable mean over time. These biases will be adopted as "a bias to be applied a priori" in the future reanalysis for the ITRF. The procedure will be implemented as the standard in our operations and the ASC will develop guidelines for identifying likely errors and notify the affected stations. This step is expected to be completed before the end of 2019. 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 2019.

Based on simulation studies that indicated the role that increased Etalon 1 & 2 data could play in the enhancement of ILRS EOP products (Andritsch, in press), 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 will further evaluate the effect of these additional data on the EOP products and make appropriate recommendations to the ILRS CB.

The co-chairs of the ASC are acting as guest-editors the publication of a special issue of the Journal of Geodesy, dedicated on Laser Ranging. The call-for-submissions resulted in over forty proposed contributions. As of this writing there are twelve articles accepted and another twelve still under the review process.

Data Formats and Procedures Standing Committee (DFPSC)

The DFPSC, especially the “Data Format Update” study group, worked on the review and update of the ILRS standard CRD (data) and CPF (prediction) formats. This was necessary in order to fulfill the needs of the European Laser Timing Experiment (ELT) but also for debris tracking. Additionally, the extension of the CRD and CPF formats was also required in order to provide additional information about meteorology, software, camera, calibration, predictions, etc. within the data. The DFPSC worked on the automation of the station history log and site log management in order to improve and clarify the update process. This was realized by the site log manager which allows stations to update their log online on the EDC website. A similar manager was created for the station history log. Both are now in operation, and the ILRS website has been updated with information on the new procedures.

The inconsistent handling of the leap second in the prediction files and at the station let to difficulties in acquiring data during the time around leap seconds. Therefore, the DFPSC formulated a new procedure which proposed to stop tracking during leap seconds.

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. Work is nearly complete on this task, which includes a detailed check of the CRD data fields for reasonable values.

Missions Standing Committee (MSC)

The MSC, working with the ILRS CB, completed a revision to the ILRS Missions Support Request form. This form is the vehicle used by mission sponsors to provide information required by the ILRS to enable the ILRS to determine if future laser ranging to the satellite is warranted. The form provides key contacts and parameters to allow the ILRS to use the SLR data in the development of science data products and to provide the missions with SLR data that supports their goals. The MSC also reviewed submitted request forms and provided recommendations and feedback to the CB and GB for future mission support. The ILRS now requests the form should be submitted at least 6 months prior to launch or from when missions expect tracking support to begin. Missions approved during the reporting period include: COSMIC-2, LightSail-B, Lomonosov, NISAR, Sentinel-3A/-3B, TechnoSat, ICESat-2, S-NET, GRACE Follow-On, GEO-IK-2, RANGE, CHEFSat, Tiangong-2, HY-2B, QZS, Beidou, PAZ and Astrocast Precursor.

Networks and Engineering Standing Committee (NESC)

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.

Transponders Standing Committee (TSC)

Currently, the main focus for the TSC is on highly accurate time transfer, particularly ELT for ACES (expected launch in 2018) on the International Space Station. The SC is working with stations to implement requirements for the mission. During its meetings, the SC also discussed common view time transfer and cross system ranging via space debris targets for the direct detection of the laser return and diffusely scattered signal from the partner station. Experiments are underway.

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.

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.

Mission Campaigns

LARGE

Several GNSS tracking campaigns have been held since 2014, testing different combinations of satellite selections and priorities. Some improvement has been seen, but it may also have been the result of stations becoming more familiar with GNSS tracking procedures. Details on early campaigns can be found in a poster presented at the 2015 ILRS Technical Workshop in Matera (Noll et al., 2015).

In 2018, the ILRS conducted two LARGE tracking campaigns to examine how the service might strike a balance between the GNSS user needs and still maintain the priorities of lower altitude satellites. In each campaign, a short list of GNSS satellites was identified by the GNSS constellations for high intensity tracking (3 segments per pass), higher priority tracking in the current GNSS priority band. A larger pool of lower priority GNSS satellites was identified for sparse tracking (1 segment per pass) by the stations on an "as time available" basis. The campaigns demonstrated that the network could support this kind of strategy, with the intensive coverage hopefully increasing over time. Results from the 2018 LARGE campaigns can be found in the monthly reports section available on the ILRS website. Based on the results from the campaigns and discussions with the IGS, a new tracking strategy is being implemented (see Section on *New GNSS Tracking Strategy* above).

In the meantime, a three-week (May 15 through June 5, 2019) high intensive tracking campaign has been undertaken with many of the high performing network stations to monitor the orbits of Galileo-102 and -220 as they go through a series of eclipse conditions over Europe.

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.

In addition to the LARGE and GREAT efforts, the ILRS has supported several other tracking campaigns, including the IRNSS constellation at geosynchronous orbits.

ILRS Meetings

The ILRS organizes yearly workshops, the biannual International Workshop on Laser Ranging and then ILRS Technical Workshops, oriented toward SLR practitioners, on the years between. Meetings of the Governing Board and standing committees are typically held in conjunction with these ILRS workshops. 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).

The ILRS also conducts meetings of the Central Bureau on a monthly basis. These meetings review network station operation and performance, as well as coordinate support of upcoming missions, monitoring and managing the ILRS infrastructure, and future directions and activities.

In May 2016, the ILRS celebrated forty years of supporting LAGEOS; the satellite was launched on May 04, 1976. To acknowledge the anniversary, the NASA Space Geodesy Program sponsored a symposium at NASA GSFC with several talks from speakers involved in the program over the last forty years. Links to information about the symposium as well as general information about LAGEOS, is available at the website: https://lageos.cddis.eosdis.nasa.gov/Celebrating_40_years_of_LAGEOS.html. Similarly, 30 years of Ajisai tracking was celebrated on August 13, 1986.

Table 4. Recent ILRS Meetings (as of May 2019)

Timeframe	Location	Meeting
April 2015	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2015	Matera, Italy	2015 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings
October 2016	Potsdam, Germany	20th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee meetings
April 2016	Vienna, Austria	ILRS Analysis Standing Committee meeting
April 2017	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2017	Riga, Latvia	2017 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings
April 2018	Vienna, Austria	ILRS Analysis Standing Committee meeting
November 2018	Canberra, Australia	21st International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee/Study Group meetings
April 2019	Vienna, Austria	ILRS Analysis Standing Committee meeting

The ILRS co-sponsored several workshops over the last five years. These workshops include the bi-annual International Workshop on Laser Ranging which covers 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 to focus on a few timely topics that impact the quality of ILRS data products and service operations. These workshops are held in intervening years between the full International Workshops on Laser Ranging and are intended to provide time to articulate the issues carefully, allow for in-depth discussion, and formulate a path forward.

The 2015 ILRS Technical Workshop was held in October 2015 in Matera Italy; the theme of the focused workshop was “Network Performance and Future Expectations for ILRS Support of GNSS, Time Transfer, and Space Debris Tracking” and address the topics that impact the quality of the data products and operations. Abstracts, presentations, posters, and papers from the workshop are online at the workshop’s website: https://cddis.nasa.gov/2015_Technical_Workshop/.

In October 2016, the Helmholz Center Potsdam of the GFZ German Research Centre for Geosciences organized and hosted the 20th International Workshop on Laser Ranging in Potsdam, Germany. Over 170 attendees participated in the workshop. The theme for this workshop, "The Path Toward the Next Generation Laser Ranging Network" allowed attendees to present ideas for future advances in SLR technology and science; workshop materials, abstracts, presentations, posters, and papers, are available at the meeting’s website https://cddis.nasa.gov/lw20. This workshop continued the “station clinic” session concept to address station operations topics; ILRS experts met in small groups of station engineers and operators to provide solutions to common station problems, information to maintain station stability, and guidelines for interacting with the analysts in determining station biases.

The 2017 ILRS Technical Workshop, sponsored by the Institute of Astronomy at the University of Latvia and the ILRS, was held in Riga, Latvia, October 2-5, with the theme "Improving ILRS Performance to Meet Future GGOS Requirements". Over 120 people from 21 countries participated in the meeting. The program included over 50 oral presentations, as well as many relevant posters.

The Space Environment Research Centre (SERC) and the ILRS hosted the 21st International Workshop on Laser Ranging at the John Curtin School of Medical Research, Australian National University in Canberra, Australia during the week of November 05-08, 2018. The theme of the workshop "Laser Ranging for Sustainable Millimeter Geoscience" afforded presentations on a wide range of topics highlighting SLR contributions to research. The four-day workshop program was organized into nine oral sessions, and two poster sessions focused on the oral session topics. The last day of the week was devoted to a separate event, the International Workshop on Space Debris Management, which has synergy with new ILRS applications. Over 175 registrants from 23 countries participated in the laser ranging workshop; 20 additional attendees, mainly from Australia, participated in the one-day space debris workshop. The workshop program included 80 oral presentations and over 60 posters; 25 oral presentations and 15 posters were given at the Space Debris Workshop; these presentations, posters, and resulting papers are available on the proceedings website at *https://cddis.nasa.gov/lw21*.

Publications

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 latest volume is the eighth published report for the ILRS and concentrated on achievements and work in progress rather than ILRS organizational elements. However, this report, the 2009-2010 ILRS Report, published in late 2012, was the last edition produced by the ILRS due to the extensive amount of work required to generate these documents. The ILRS CB is currently working with the ILRS components to prepare the next service report to cover 2016-2018.

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.

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 is implementing 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 incipient data bias sources, particularly in calibration area.

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https://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Axel Nothnagel (Germany)
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 2015−2019. The IVS Directing Board developed a Strategic Plan for the Period 2016–2025 based on a Retreat held in October 2015. An IVS Outreach and Communications Office was created at the MIT Haystack Observatory at the end of 2018. Axel Nothnagel was re-elected as IVS Chair for a second four-year term. Two VLBI Training Schools were organized. ICRF3 became the new celestial reference frame on 01 January 2019. Work continued to make the VGOS an operational system.

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.

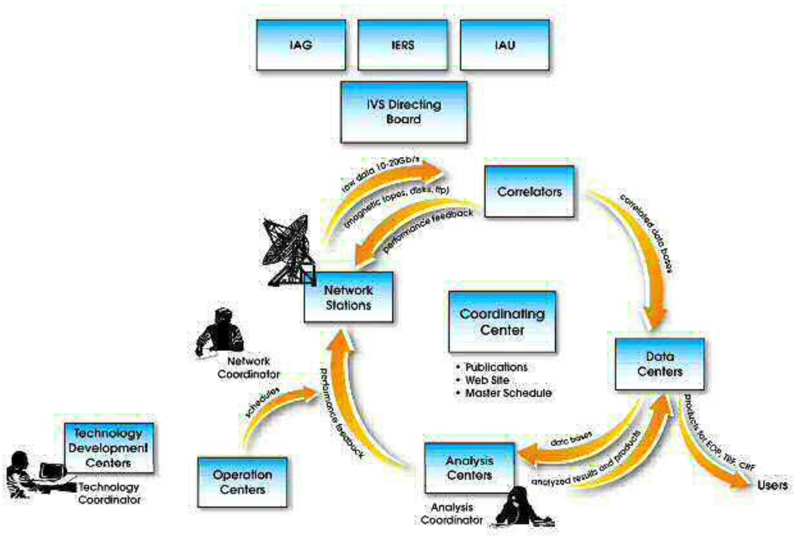

Figure 1. Organizational diagram of the IVS.

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 (2015−2019).

Time	Meeting	Location
7–8 October 2015	IVS Retreat	Penticton, BC, Canada
23–26 November 2015	4th International VLBI Technology Workshop	Auckland, New Zealand
9–12 March 2016	2nd VLBI Training School	Hartebeesthoek, South Africa
13–17 March 2016	9th IVS General Meeting	Johannesburg, South Africa
18 March 2016	17th IVS Analysis Workshop	Johannesburg, South Africa
5–6 October 2016	1st International Workshop on VLBI Observations of Near-field Targets	Bonn, Germany
12–14 October 2016	5th International VLBI Technology Workshop	Westford, MA, USA
30 April – 4 May 2017	9th IVS Technical Operations Workshop	Westford, MA, USA
17 May 2017	18th IVS Analysis Workshop	Gothenburg, Sweden
9–11 October 2017	6th International VLBI Technology Workshop	Bologna, Italy
3–7 June 2018	10th IVS General Meeting	Longyearbyen, Norway
8 June 2018	19th IVS Analysis Workshop	Longyearbyen, Norway
12–15 November 2018	7th International VLBI Technology Workshop	Krabi, Thailand
14–16 March 2019	3rd VLBI Training School	Las Palmas, Spain
20 March 2019	20th IVS Analysis Workshop	Las Palmas, Spain
5–9 May 2019	10th IVS Technical Operations Workshop	Westford, MA, USA

Noteworthy among the list of meetings are the IVS Retreat and the two VLBI Training Schools. At the retreat, the IVS Directing Board plus six invited guests discussed the current and future challenges of developing the IVS to meet the needs and take advantage of the opportunities of the next decade. In a series of SWOT analyses (Strength, Weaknesses, Opportunities, and Threats) the current state was evaluated. It was concluded that the relationships of the IVS with some of the space agencies, research institutions and surveying and mapping agencies should be improved. A business plan was discussed indicating that if the IVS were to be established from scratch it would cost an initial investment of $200 million for a network of 30 observatories plus $70 million per year operating costs for daily UT1−UTC determinations. The findings of the retreat were used as the basis for preparing the Strategic Plan of the IVS for the Period 2016–2025 (see below).

The 2nd and 3rd VLBI Training Schools were organized at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa and at the Universidad de Las Palmas de Gran Canaria in Spain, respectively. The purpose of the Schools was to help prepare the next generation of researchers to understand VLBI systems and inspire them in their future careers. Both events attracted some 50 participants from all over the world. The South African School included a large group of students from different countries in Africa with the aim to develop expertise in geodesy and especially VLBI as part of an effort to build new stations in Africa and integrate them into the global VLBI network.

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 (2015−2019).

a) ***Current Board members (May 2019)***

Directing Board Member	Institution, Country	Functions	Recent Term
James Anderson	GFZ Potsdam	Analysis and Data Centers Representative	Feb 2019 − Feb 2023
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
Francisco Colomer	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2017 − Feb 2021
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	IERS Representative	—
Hayo Hase	BKG & AGGO, Argentina	Networks Representative	Feb 2019 − Feb 2023
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Nancy Kotary	Haystack Observatory, USA	Office for Outreach and Communications	—
Laura La Porta	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2019 − Feb 2023
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	IGG, University of Bonn, Germany	Analysis and Data Centers Representative, Chair	Feb 2017 − Feb 2021
Chet Ruszczyk	Haystack Observatory, USA	Technology Development Centers Representative	Feb 2019 − Feb 2023
Oleg Titov	Geoscience Australia, Australia	IAG Representative	—
Gino Tuccari	IRA/INAF, Italy	Technology Coordinator	—
Alet de Witt	Hartebeesthoek Radio Astronomy Observatory, South Africa	At Large Member	Feb 2019 − Feb 2021

b) *Previous Board members in 2015−2019*			
Alessandra Bertarini	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2015 − Sep 2017
Ludwig Combrinck	Hartebeesthoek Radio Astronomy Observatory, South Africa	IAG Representative	—
Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2013 − Feb 2017
David Hall	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Sep 2017 − Feb 2019
Thomas Hobiger	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2017 − Feb 2019
Alexander Ipatov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2015 − Feb 2017
Ryoji Kawabata	Geospatial Information Authority, Japan	At Large Member	Feb 2015 − Feb 2017
Jim Lovell	University of Tasmania, Hobart, Australia	Networks Representative	Feb 2013 − Feb 2017
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2015 − Feb 2019
Bill Petrachenko	Natural Resources Canada	Technology Coordinator	—
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 − Feb 2019
Takahiro Wakasugi	Geospatial Information Authority, Japan	At Large Member	Feb 2017 − Feb 2019
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2017 − Feb 2019

During the report period two Directing Board elections were held. Following the elections from December 2016 to February 2017, the Board re-elected Axel Nothnagel of the University of Bonn for a second four-year term as chair of the IVS (until spring 2021). In March 2016, Gino Tuccari of the Italian Istituto di Radioastronomia (IRA/INAF) took over the position of IVS Technology Coordinator from Bill Petrachenko of Natural Resources Canada.

Following a call for proposals in July 2018, the Board approved the creation of an IVS Office for Outreach and Communications (OOC) at the MIT Haystack Observatory (lead: Nancy Kotary) at the end of 2018. The OOC will promote awareness and understanding of geodesy's unique and vital role in science and society to the larger scientific community, decision makers, and the general public. Activities will include the creation of a dedicated Web site, of social media accounts, and of extensive educational materials. It is anticipated that the OOC will improve collaboration across institutions, sponsor organizations, and scientific associations on education and outreach work.

IVS Strategic Plan for the Period 2016–2025

Based on the discussions at the IVS Retreat, the IVS Directing Board developed a Strategic Plan for the Period 2016–2025. 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. In the period 2016 to 2025 the IVS will enter the era of the VLBI Global Observing System (VGOS), which will be composed of a transition period and subsequent full VGOS operations.

The strategic plan was developed on the basis of the current composition and framework of the IVS' operations. The IVS acts as a truly international entity consisting of hardware distributed all over the world, a global organizational structure, and the associated personnel for organizing and administering the IVS. The IVS is not a formal global institution but a collaboration, which operates on a best-effort basis. The full potential of geodetic and astrometric VLBI can only be exploited if baselines beyond a length of about 6000 km are employed for Earth orientation parameter (EOP) and celestial reference frame (CRF) determinations. The same also applies to any terrestrial reference frame (TRF) application. Because of this it would be difficult for the IVS to be replaced by a single country running its own VLBI network, operating its own telescopes, correlating and analyzing the results, and producing the final VLBI products. The IVS is essential for the monitoring of the Earth orientation parameters and for the maintenance of the celestial and terrestrial reference frames. However, the IVS is little known for its products beyond the geodetic and astrometric communities. For this reason, the organizational relationships of the IVS, external as well as internal, and the administration of the IVS must be developed further. In this context the IVS may benefit from the GGOS and UN-GGIM initiatives (Global Geodetic Observing System, UN-Global Geospatial Information Management), which will help to raise awareness in political circles of the needs for geodetic products.

Another challenge of the future is that many experienced colleagues have reached or are close to retirement age. Hence, an active recruiting and staff structure development is needed to replace them. An increased awareness of this issue is needed within the IVS components up to the highest level of their administrations.

On the product side, several separate requirements compete: accuracy, resolution, and timeliness. These need to be balanced for an optimum satisfaction of the product users. There may arise conflicts between what is actually feasible given the current economic and organizational circumstances and the users' desires for higher accuracy, resolution, and timeliness.

Working Groups

Working Group 7 on Satellite Observations with VLBI. This WG was established by the IVS Directing Board in May 2015. WG7 studies possibilities to observe Earth satellites with the VLBI ground network affiliated with the IVS. In particular the development of corresponding observing schedules, of the necessary technology at the observing stations, data correlation, and data analysis are looked into. Experts from the various fields, who are able to perform one or more of the different tasks, were brought together to enable observations of Earth satellites by VLBI.

Working Group 8 on Galactic Aberration. This WG was established by the IVS Directing Board in October 2015. WG8 investigated the issues related to incorporating the effect of galactic aberration in the analysis of the IVS. The aberration effect is not negligible in terms of future microarcsecond astrometry. The WG prepared a final report, recommending a galactic aberration model, and was then officially closed in March 2019. The recommended value of the aberration constant is $A_G = 5.8 \pm 0.3$ µas/yr.

Observing Program and Special Campaigns

Observing Program

The observing program for 2015–2019 with the legacy S/X system (production system) included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 9–12 stations, depending on station availability. These networks were designed with the goal of having comparable x_p and y_p results. Data bases are available no later than 15 days after each session. Daily 1-hour UT1 Intensive measurements on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Tsukuba (Japan).
- 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.
- Triennial ~two-week continuous VLBI observing campaigns to produce continuous VLBI time series and to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy. During the report period the continuous campaign CONT17 was organized (see below).

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.

With the VGOS broadband system (future system under development to be operational in the early 2020ies) a network of 3–7 stations observed a VGOS Test (VT) session roughly every other week for about 26 sessions per year. While in 2015 and early 2016 the lengths of the sessions were limited to one, two, or six hours, from mid-2016 onward the test sessions were extended to the full 24-hour duration. The test sessions were used to shake out problems with the new system and establish standard operational procedures. From 2019 onward, the results of the VT sessions are made available through the IVS Data Centers for general analysis. The network size is typically six stations; the network size is expected to grow gradually to 10–12 stations in the later part of 2019 and in 2020.

CONT17

The IVS organized a continuous VLBI campaign (CONT17) during the period from November 28 to December 12, 2017. The campaign consisted of three separate networks: two legacy S/X networks observing for 15 consecutive days and one VGOS broadband network observing for five consecutive days in the middle of the CONT17 period. The use of the two legacy networks allows to study the accuracy of VLBI estimates of EOP and to investigate possible network biases. A special issue on CONT17 is planned to be published in Journal of Geodesy.

Analysis

ITRF2014

In 2013, the IERS requested the geometric services (IDS, IGS, ILRS, and IVS) to contribute to the determination of the next International Terrestrial Reference Frame (ITRF). Initially it was anticipated to include data through 31 December 2013, with the various techniques providing their solutions in early 2014. Then the data coverage period was changed to include all available data through 2014, with a firm deadline for submissions to the IERS of 28 February 2015. Ten IVS Analysis Centers submitted solutions to the IVS Combination Center. The software and the number of ACs using it are, in order of popularity: (a) Calc/Solve (five), (b) VieVS (two), (c) Geosat (one), (d) Occam (one), and (e) Quasar (one). For the first time, all analysis centers applied thermal expansion modeling for the majority of telescopes involved. The IVS Combination Center compared the input from the various ACs and produced a combined solution for use by the IERS Combination Centers (DGFI, IGN, and JPL). In the process of comparing the input from different ACs numerous issues were uncovered, most of which were subsequently fixed. Two of the submissions had such serious problems that they were not used in the IVS combination solution.

ITRF2014 differs from previous ITRFs in that it includes models for post-seismic deformation (PSD) at sites that had earthquakes. These models were derived by using data from GPS receivers located at these sites. Previously, PSD was handled on an ad-hoc basis by different VLBI analysis packages. For example, Calc/Solve estimated splines for sites. Several IVS ACs compared the use of ITRF2014 vs. ITRF2008, and the general consensus was that ITRF2014 was a better a priori model.

In December 2016, the IERS Directing Board requested that the geometric services begin using ITRF2014 in their analysis as soon as possible. In order to have a smooth transition the IVS Analysis Coordinator requested that the IVS ACs submit two sets of SINEX files: one using ITRF2008 and the other ITRF2014 until a sufficient number of ACs had made the transition. GSFC began doing so in October 2016, and GFZ in January 2017. Several ACs indicated that they would switch over to ITRF2014 in the beginning of 2017.

ICRF3

Several IVS Analysis Centers (ACs) in cooperation with the International Astronomical Union (IAU) Working Group on the third realization of the International Celestial Reference Frame (ICRF3) prepared CRF solutions as input to ICRF3. The new frame was adopted at the IAU General Assembly in Vienna, Austria on August 30, 2018 under Resolution B2. ICRF3 contains positions of more than 4000 extragalactic radio sources at three frequencies and became the Fundamental Astrometric Reference Frame on 01 January 2019.

Transition to Multi-tone Phase Calibration

In VLBI measurements the measured delays are corrupted by unknown and unstable phase shifts in the signal as it travels down the signal path from the front end to the sampler. Many of these effects can be removed through the use of phase calibration. The most common approach is to inject a calibration signal near the front of the signal chain. The calibration signal consisting of a set of tones (‘phase-cal tones’) equally spaced in frequency and derived from the station frequency standard. These signals are extracted during the correlation process and used to adjust the phases prior to fringe-fitting. Since the spurious phase shifts are frequency dependent, each frequency channel is calibrated independently. Historically, only a single phase-cal tone was used in each frequency channel.

Due to the ever-broader channel bandwidth and advances in correlator software, for the past several years the correlators have been able to use multiple phase-cal tones in each channel. This latter approach is called multi-tone phase-cal. Naively, the use of multiple phase-cal tones should reduce the noise. A verification by correlating the CONT14 data set with both multi-tone and single-tone phase calibration revealed that multi-tone was generally slightly better than single-tone. On average, the multi-tone sessions had ~1% more observations. The session fit was slightly better, again on the ~1% level, indicating that the data within a session was less noisy and more consistent. Lastly, the RMS baseline scatter across all of the CONT14 sessions was generally lower. All of these are arguments for using multi-tone phase-cal. However, it also turned out that for Zelenchukskaya there was a difference of 8 mm in the vertical position (3-sigma level) depending on whether you used multi-tone or single-tone phase-cal. There are differences for other stations, but none of these are greater than 1-sigma. These issues were discussed publicly within the IVS at a few occasions (e.g., IVS Analysis Workshop in Ponta Delgada, a special meeting devoted to this subject held at MIT Haystack Observatory in October 2016). Following a recommendation coming out of these discussions, the IVS Directing Board decided to switch over to multi-toned phase-cal for all sessions observed on or after 1 January 2017. It is expected that this will yield an improvement in the quality of the data; but it may also introduce a discontinuity in some station positions.

Gravitational Deformations of Radio Telescopes

With the advent of powerful and affordable terrestrial laser scanners (TLS), the issue of path delay variations and position changes due to gravitational deformations of the radio telescopes surfaced again around the year 2010. From these investigations, it became clear that gravitational deformations have a direct effect on the delay observables. As a consequence, these delay effects then change the vertical position of the telescope in a global frame by several millimeters. Within the reporting period, a few more telescopes were investigated by TLS measurements and subsequent data analysis. From these, empirical correction models were developed, which can now be applied in VLBI data analysis. For a full positive impact on the scale of the ITRF, more telescopes need to be measured and modeled. The IVS has called for increased endeavors in this respect. However, this is costly and sophisticated work which will need considerable time and efforts.

Technology Development

The main focus of the IVS technology development was placed on the build-out of the next-generation VLBI system (VLBI Global Observing System, VGOS) network and achieving operational readiness with the various installations of the signal chain realizations. Over the next several years a number of new VGOS stations will come online. Operational readiness for the existing VGOS stations was worked on in a series of test sessions of initially 1-, 2-, and 6-hour lengths in 2015/16 and then extended to 24-hour sessions from the second half of 2016 onward. These tests uncovered a number of smaller and larger issues of high-level, low-level, and transient nature that were successively ironed out or identified and actively being worked on. Since 01 January 2019 the currently available six-station VGOS network was operating in a stable way, so that the session results could be made available on the IVS Data Center for general use. Aside from increasing the VGOS network size in the next couple of years, the focus of the VGOS effort will be on the data transport and correlation parts of the processing chain. Here the use of cloud services and distributed correlation to deal with the large amount of data are aspects that will be investigated.

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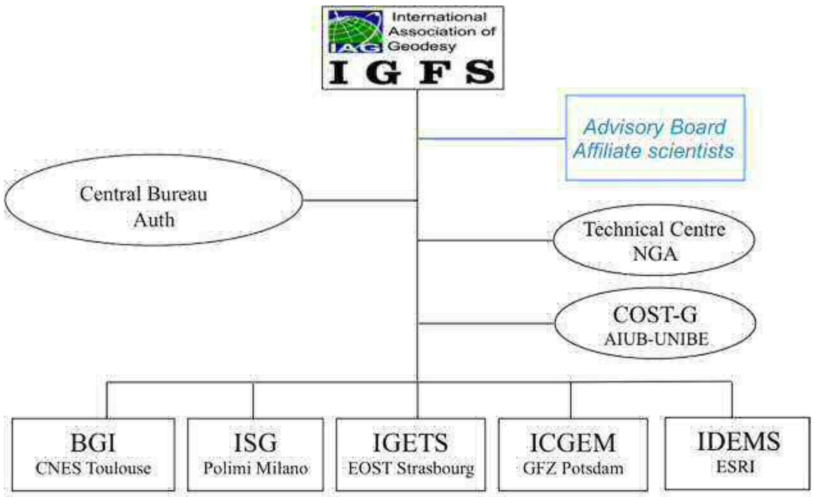
International Gravity Field Service - IGFS

http://igfs.topo.auth.gr/

Chairman: Riccardo Barzaghi (Italy)
Director of the Central Bureau: George Vergos (Greece)

The IGFS structure

The present day IGFS structure is summarized in the following chart



BGI (Bureau Gravimetrique International), Toulouse, France
ISG (International Service for the Geoid), Politecnico di Milano, Milano, Italy
IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg,France
ICGEM (International Center for Global Earth Models), GFZ, Potsdam, Germany
IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA, USA
COST-G (International Combination Center for Time-Variable Gravity Field Solutions), University of Bern, Bern, Switzerland
Auth (Aristotle University of Thessaloniki), Thessaloniki, Greece
NGA (National Geospatial-Intelligence Agency), USA

IGFS coordinates the activities of the Gravity Services (BGI, ISG, IGETS, ICGEM, IDEMS, COST-G) via its Central Bureau at the Aristotle University of Thessaloniki (Greece), the Advisory Board and the Technical Centre at NGA (USA).
The members of the IGFS Advisory Board are:

- S. C. Kenyon (USA)
- J.-P. Barriot (French Polynesia)
- S. Bonvalot (France)
- F. Barthelmes (Germany)
- U. Marti (Switzerland)
- R. Pail (Germany)
- S. Bettadpur (USA)
- H. Denker (Germany)
- Y. Wang (USA)
- L. Sanchez (Germany/Colombia)
- L. Vitushkin (Russia)
- M. G. Sideris (Canada)
- J. Huang (Canada)
- A. Eicker (Germany)
- R. Forsberg (Denmark)
- T. Gruber (Germany)
- M. Reguzzoni (Italy)
- I. N. Tziavos (Greece)
- K. Kelly (USA)
- H. Abd-Elmotaal (Egypt)
- Y. Fukuda (Japan)

Through this structure, the interaction between the Gravity Services proved to be effective and able to provide users with the required gravity products. Another important task of IGFS is to be an interface between the Gravity Services and GGOS. Particularly, in this respect, the IGFS actions have been performed in strict contact with the GGOS Bureau of Products and Standards, the Bureau of Network and Observations and GGOS Focus Area on "Unified Height Systems". Finally, IGFS is cooperating with IAG Commissions and Inter-Commission Committee on Theory through Joint Working and Study Groups, namely:

- JSG 3.1: Intercomparison of Gravity and Height Changes (joint with Commissions 1, 2 and 3)
- JWG 0.1.2: Strategy for the Realization of the International Height Reference System (joint with GGOS, Commission 1, ICCT)
- JWG 2.1.1: Establishment of a global absolute gravity reference system (joint with Commission 2)
- JWG 2.2.1: Integration and validation of local geoid estimates (joint with Commission 2)

Overview

In the period 2015-2019, IGFS activities were mainly addressed on one side to improve the internal organization and, on the other side, to strength the connections with GGOS and IAG Commission 2. Parallel to that, standard activities have been also performed, i.e. actions related to: coordinate collection, validation, archiving and testing of gravity field related data; coordinate exchange of software of relevance for gravity field activities; coordinate courses on gravity field estimation; distribute information materials related to the earth's gravity field. Although most of these activities have been performed in a direct way by the related Gravity Services, they have been supervised and harmonized by IGFS.

The internal structure has been revised. A new Central Bureau has been established since, after IAG/IUGG in Prague, OGS decided to end this activity. The call for the IGFS CB was sent out at the beginning of 2016 and on April 1st, 2106 the new CB, hosted at the Aristotle University of Thessaloniki (Greece), started its activity. Furthermore, in 2016, the ICET Service evolved in the new International Geodynamics and Earth Tides Service (IGETS) aiming at extending and integrating the activities of the International Centre for Earth Tides (ICETS) and of the Global Geodynamics Project. Also, in 2016, the International Digital Elevation Model Service (IDEMS) was moved from De Montfort University (UK) to ESRI Company (USA), which is now in charge for distributing data and metadata on DEMs.

All this reorganization procedures were managed and carried out by IGFS in cooperation with its Advisory Board and in agreement with the IAG EC.

Furthermore, during 2018, a new service has been added to the IGFS structure. This is the International Combination Service for Time-variable Gravity Field Solutions (COST-G), the continuation within the framework of IGFS of the H2020 European Gravity Service for Improved Emergency Management project (EGSIEM). One of the main objectives of EGSIEM was to unify the knowledge of the GRACE community in order to come to a standardisation of gravity-derived products describing mass transport in the system Earth. The key role of this data is widely known in the geodetic community and it is thus of extreme importance to have this new service under the IGFS umbrella. COST-G will provide monthly global gravity models in terms of spherical harmonic coefficients and derived grids. This will be done by combining solutions from different analysis centers based on GRACE/GRACE-FO data.

As mentioned, external actions were mainly performed in connection with GGOS activities. IGFS representatives attended the GGOS Days Meetings held in Frankfurt, Germany (October 21st-23rd, 2015), Cambridge, USA (October 24th-27th, 2016) and Vienna, Austria (October 11st-

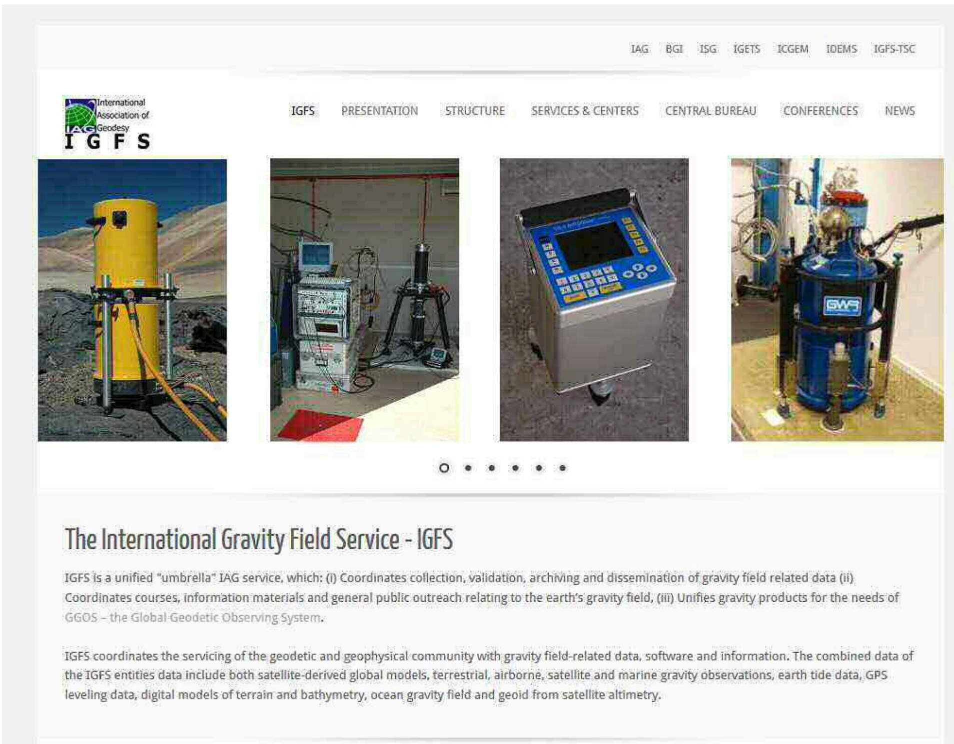
November 2nd, 2017). IGFS representatives have been also involved in the GGOS Bureaus meetings held in San Francisco (during AGU 2015, 2016) and Vienna (during EGU 2016, 2017, 2018, 2019). Through these activities, a closer cooperation between the Gravity Filed Services and the Geometric Services of IAG was reached. Furthermore, standards on gravity metadata were developed (based on the GGOS Bureau of Products and Standards recommendations) and implemented in the new IGFS web page. IGFS actions in GGOS were also performed within the framework of the Focus Area on "Unified Height Systems". In this respect, IGFS actively participated to the definition of the International Height Reference System/Frame (IHRS/IHRF).

Cooperation with IAG Commission 2 is based on the activities of several Joint Working and Study Groups that have been established at the last IAG/IUGG Assembly in Prague. Also, on September 19th-23rd, 2016, IGFS and Commission 2 co-organized the 1st Joint Commission 2 and IGFS Meeting in Thessaloniki, named "International Symposium on Gravity, Geoid and Height Systems 2016". A second conference of this series has been then held in Copenhagen. On September 17th-21st, 2018, IGFS and Commission 2 co-organized there the 2nd Joint Commission 2 and IGFS Meeting

Finally, IGFS is managing the Geomed2 project, an ESA supported project, for the computation of the geoid and the DOT in the Mediterranean area. This project involves most of the Gravity Services related to IGFS.

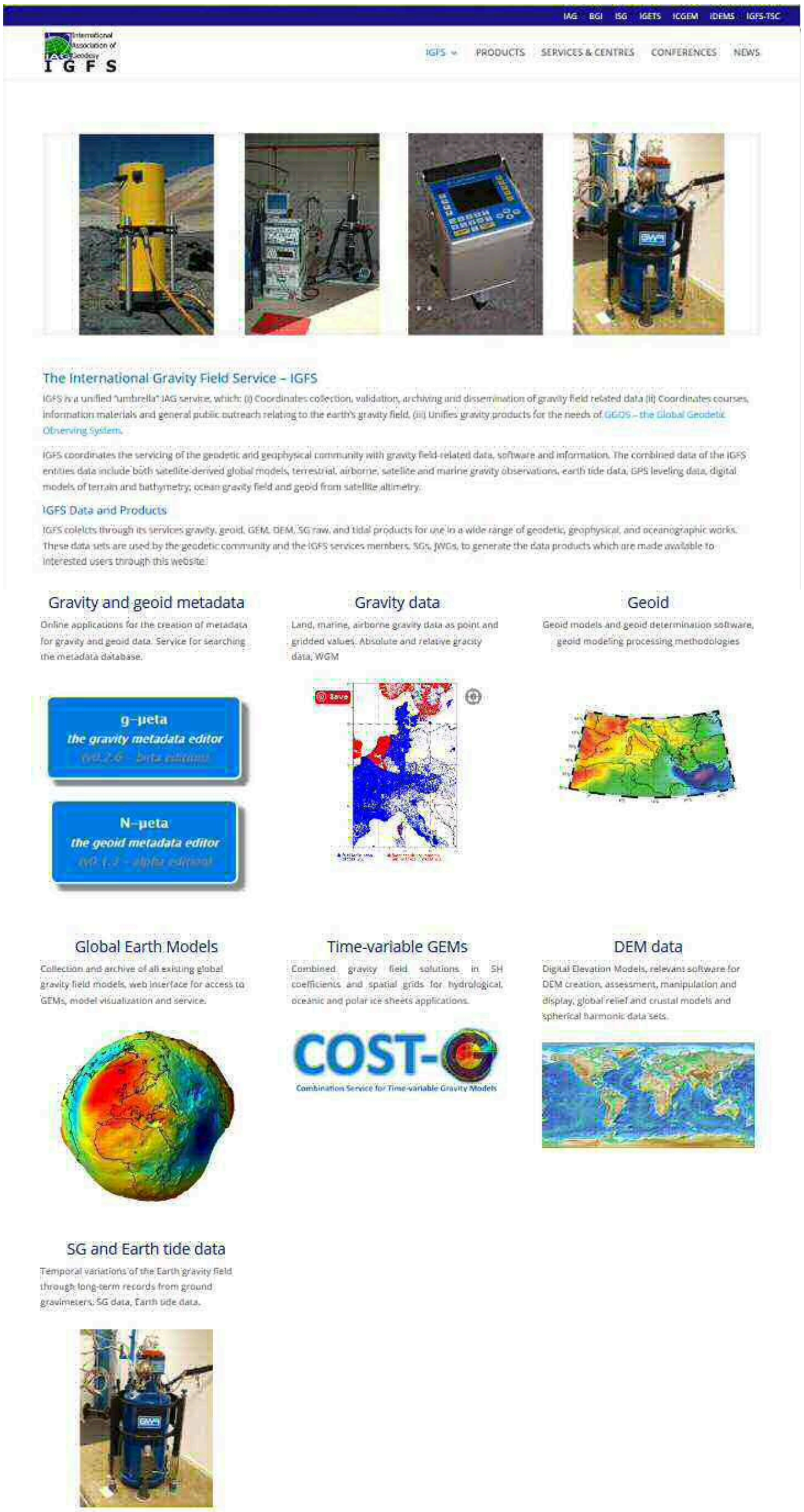
The IGFS Central Bureau and the IGFS web page

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, 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, a first webpage has been created presenting mostly administrative information for IGFS and its services in order to guarantee its presence online.



The first update of the IGFS webpage online since April 2016

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, 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, online since October 2016

Finally, 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.

IGFS and GGOS

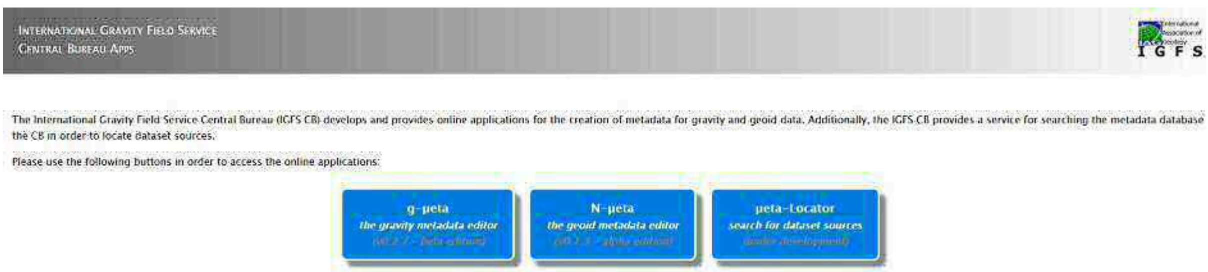
- Gravity metadata structure g-μeta

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.

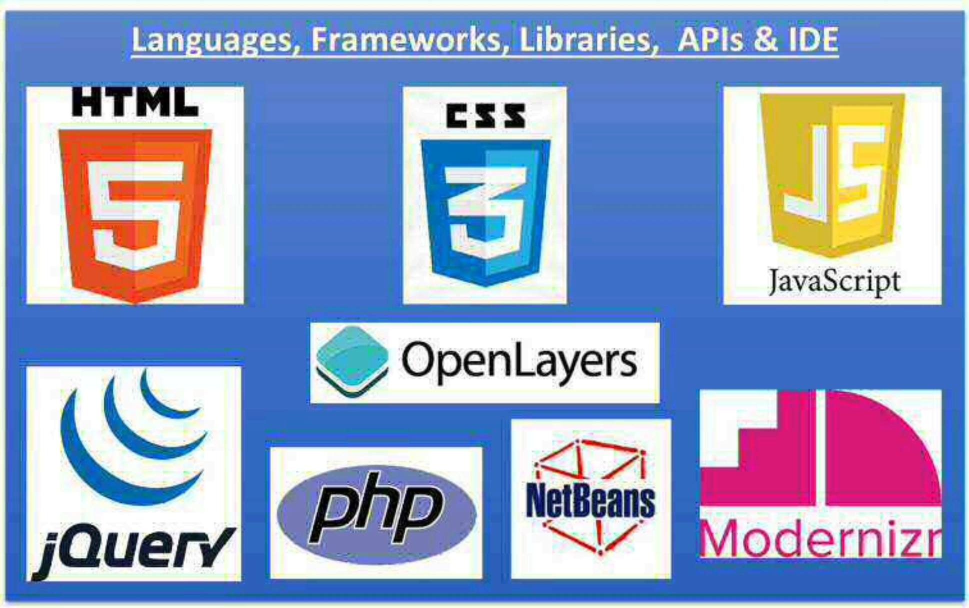
The rest refers to metadata for geoid models as well as a geodatabase and geolocator for the visualization of all products offered by IGFS and its services.

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.

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.



The IGFS applications front-end (g-μeta, N-μeta and μeta-Locator)



Technologies and modules used for the development of the IGFS metadata

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. The proper estimation and modelling of global phenomena of the system Earth requires the definition of a reliable reference system/frame. This system/frame must be theoretically defined and established at a given level of precision and accuracy related to the studied phenomena. 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. At the moment, a corresponding physical reference system/frame for the reliable description of changes in the Earth's gravity field is still missing. IGFS has been actively involved in the definition of such a system since the IHRS/IHRF is basically related to the gravity field and its estimation. As a matter of facts, the aim of this project is to study the methodology for defining the IHRS and to realize it as global frame of points where the W(P) values are estimated. IGFS strictly co-operated with GGOS focus area on "Unified Height Systems" and Commission 2 on such topic and contributed to the paper by Ihde at al. (2017) that has been published on this subject on Survey in Geophysiscs. At the same time, IGFS is also 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.

References

J. Ihde1, L. Sanchez, R. Barzaghi, H. Drewes, Christoph Foerste, Thomas Gruber, Gunter Liebsch, Urs Marti, Roland Pail, Michael Sideris, Definition and Proposed Realization of the International Height Reference System (IHRS), Surv Geophys, 2017, DOI 10.1007/s10712-017-9409-3.

Recent IGFS activities

- *1st Joint IGFS and Commission 2 meeting "Gravity, Geoid and Height Systems 2016"*

Thessaloniki, Aristotle University. 1st Joint Symposium of IAG Commission 2 and IGFS

The GGHS2016 "Gravity, Geoid and Height Systems 2016" Meeting was the first Joint Commission 2 and IGFS Symposium co-organized with GGOS Focus Area 1 "Unified Height System". It took place in Thessaloniki, Greece between September 19-23, 2016 at the premises of the Aristotle University of Thessaloniki (Main Ceremony Hall of the Aristotle University of Thessaloniki). Its main focus was on methods for observing, estimating and interpreting the Earth gravity field as well as its applications.

GGHS2016 continued the long history of IAG's Commission 2 Symposia, GGG2000 (Banff, Canada), GG2002 (Thessaloniki, Greece), GGSM2004 (Porto, Portugal), GGEO2008 (Chania, Greece), GGHS2012 (Venice, Italy), with those of IGFS, 1st IGFS Meeting 2006 (Istanbul Turkey), 2nd IGFS Meeting 2010 (Fairbanks, Alaska, USA), 3rd IGFS Meeting 2014 (Shanghai, China) under a unified umbrella, the latter being decided during the XXVI IUGG General Assembly in Prague.

GGHS2016 was composed by 6 sessions spanning the entire 5 days of the program.

For GGHS2016, 211 abstracts have been received, out of which 94 have been scheduled as oral presentations and 117 as posters. 204 participants from 36 countries participated in the conference. It should be particularly emphasized that this symposium was able to attract also the young generation of scientists, since 35% of the total number of participants were either MSc Students or PhD candidates.

The scientific program of GGHS2016 was of outstanding quality and showed significant scientific advancements in several fields of gravity field research. The Symposium was organized in Sessions on the following topics:

- Session 1: Current and future satellite gravity missions
  (Convenors: T.Gruber and D.Wiese)
- Session 2: Global gravity Field Modelling
  (Convenors: N. Pavlis and S. Jin)
- Session 3: Local/regional geoid determination methods and models
  (Convenors: U. Marti and H. Abd-Elmotaal)
- Session 4: Absolute and Relative gravity: observations and methods
  (Convenors: L. Vituskin and J. Flury)
- Session 5: Height systems and vertical datum unification
  (Convenors: M. Sideris and L. Sanchez)
- Session 6: Satellite altimetry and climate-relevant processes
  (Convenors: O. Andersen and A. Eicker)

35 of the abstracts accepted and presented at the GGHS2016 conference (either oral or poster) have been submitted as papers for publication in the official peer-reviewed IAG Symposia Series at Springer Publisher.

- 2nd Joint IGFS and Commission 2 meeting: "Gravity, Geoid and Height Systems 2018"

The GGHS2018 "Gravity, Geoid and height Systems 2018", the second Joint Symposium of IAG Commission 2 and IGFS, was held in Copenhagen, Denmark, between September 17-21, 2018 at the "Black Diamond", which is part of the Royal Library of Copenhagen. The Local Organizing Committee was managed by the DTU-Space. The topics discussed in the Symposium were organized in seven sessions covering the following topics:

Copenhagen, “Black Diamond”. 2nd Joint Symposium of IAG Commission 2 and IGFS

- Session 1: Current and future satellite gravity missions
  (Convenors: T.Gruber and D.Wiese)
- Session 2: Global gravity Field Modelling
  (Convenors: D. Roman and S. Jin)
- Session 3: Local/regional gravity field modelling
  (Convenors: J.Agren and H. Abd-Elmotaal)
- Session 4: Absolute, Relative and Airborne Gravity: observations/methods
  (Convenors: L. Vituskin and R: Forsberg)
- Session 5: Height systems and vertical datum unification
  (Convenors: M. Sideris and L. Sanchez)
- Session 6: Satellite altimetry and applications
  (Convenors: O. Andersen and X. Deng)
- Session 7: Mass transport and climate-relevant processes
  (Convenors: C. Boening and A. Eicker)

87 oral presentations were given in the seven sessions during the 5 Symposium days while the 76 posters were displayed during the entire Symposium.
Papers from oral and poster presentations have been submitted to the Journal of Geodetic Science for a special issue that will be available by the end of 2019.

- *The 12th Geoid School*

IGFS has been involved, together with ISG, in the organization of the 12th International Geoid School that was planned during the IAG/IUGG in Prague (June 2015). The school was held on June, 6th-10th, 2016, at Campus 5, Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia. The Local Organizing Committee was set up by the Mongolian University of Science and Technology (MUST), MonMap Engineering Services Co., Ltd, as a local hosting organizations, and the Mongolian Association of Geodesy, Photogrammetry and Cartography (MAGPC). 30 people attended this Geoid school. 15 students were from Mongolia and the remaining were from 9 different countries, namely: Bhutan, China, India, Latvia, Mongolia, Philippines, Poland, Russia and Sri Lanka.

The participants to the 12th International Geoid School, Ulaanbaatar, Mongolia

During the four lesson days the following topics were discussed:

- General Theory on Gravity Field (F. Sansò)
- The Height Datum Unification (M. Sideris)
- Terrain Effect Computation and Remove/Restore (R. Forsberg)
- Residual Geoid Estimation (R. Barzaghi)
- Global Geopotential Models (S. Holmes)

Future geoid schools are foreseen in Iran and/or Argentina: contacts are ongoing with the Local Organizing Committees.

- *The Geomed2 Project*

IGFS has proposed and managed the GEOMED2 Project that started in 2015 and will end in 2019.

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 and GOCE/GRACE based Global Geopotential Models. 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. Within a pre-processing step, all available gravity observations for the wider Mediterranean basin has been collected, validated, homogenized and unified in terms of their horizontal and gravity system, so as to derive a gravity data base that is used for the determination of the geoid. The so-determined geoid model will form the basis for height-system unification within the Mediterranean Sea and will allow to derive high-resolution models of the Mean Dynamic Topography (MDT) to be used in estimating the circulation in the Mediterranean Sea.

The Mediterranean Sea has always been of economic and ecological importance to its surrounding countries. So, a better understanding of its currents is necessary for the management of fishery resources, potential pollution, and maritime security. In the context of this project, currents will be derived from the Mean Dynamic sea surface Topography (MDT), which will be calculated by subtracting the estimated geoid from the available high resolution Mean Sea Surface (MSS) models based on the combination of ERS-1/2, Envisat, TOPEX/Poseidon, Jason-1/2 and Cryosat-2 altimeter data.

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

Since the beginning of this project, which is financially supported by ESA, IGFS has organized four meetings in which the scientific problems related to the project topics were analysed and discussed. Presentations on GEOMED2 were given at EGU2016, EGU2017 and EGU2018 in Vienna. Furthermore at IAG/IASPEI 2017 Conference in Kobe (Japan), four abstracts on the project have been accepted accepted as oral/poster presentations.

International Centre for Global Earth Models (ICGEM)

http://icgem.gfz-potsdam.de/home

Elmas Sinem Ince, Sven Reißland, Franz Barthelmes (Germany)

Overview

The ICGEM service continues its activities with additional new features introduced in 2017 and 2018. The new features include calculation of the gravity field functionals at user-defined points, a separate collection of the topographic gravity field models, as well as the journal paper which has been published recently as an extensive reference to the ICGEM related activities. ICGEM continues to make the global gravity field models publicly available with a possibility of assigning a DOI number. Although the service was established to collect and provide access to static gravity field models, increasing interest in the temporal gravity field models as well as the topographic and other celestial body gravity field models through the years encouraged the ICGEM team to allocate some effort for archiving and making also these models publicly available. In the following months, new temporal gravity field models developed under the new IAG Service COST-G will be made available via ICGEM. Therefore, some extensions will be applied to the temporal gravity field page.

During the recent years, ICGEM and its products have been used extensively. With the increasing attention to the good scientific practice, copyright and usage restrictions, user inquires regarding referencing the service activities made us reconsider our documentation records. Downloading a model, using a figure published in one of the ICGEM documents or calculation results performed via the calculation service eventually require the user to refer to the service, but our existing reference list was very technical for such purpose. It was not obvious to the reader how to refer to the different activities of the ICGEM. Thinking that a journal paper would be a complementary reference, we prepared an extensive document that is published in Earth System Science Data. Therefore, beside Barthelmes and Koehler 2016 and Barthelmes 2013, the user can now refer to Ince et al., 2019 (https://www.earth-syst-sci-data.net/11/647/2019/) for all ICGEM related activities. This paper will also make the ICGEM Service more visible in international platforms.

Finally, the long-time ICGEM service developer and director Franz Barthelmes retired end of 2017. He did invaluable contribution to science and the gravity community. He started and brought such a platform like ICGEM to its current stage. We therefore would like to acknowledge Franz Barthelmes' contributions to gravity field community and GFZ family. The ICGEM will continue its activities with its current two staff given with their time allowance. ICGEM Service can be more informative with the active use of the reshaped discussion forum. The new forum welcomes the users to join the discussion to both ask and answer questions. The forum can be more informative with the contributions from different scientists all over the world.

Activities and publications during the period 2015-2019

1- The new ICGEM Server

The ICGEM Service has been renewed from technical, administration and presentation perspectives which was a very important step to develop a new flexible platform for future applications and plans also applicable to GRACE-FO mission. The programs used in the calculation service have not been changed. Therefore, the calculations in the new platform are identical to the calculations of previous service settings. Following up the launch of GRACE-FO, new products are planned to be made available under the same environment.

The ICGEM Service is actively used for different purposes, e.g. download model, calculate gravity field functionals. The distribution of the visitor statistics of the new service between May 2018 and April 2019 is presented in Fig.1.

Figure 1: ICGEM Visitor Statistics between May 2018 and April 2019 (EU: Europe, AS: Asia, NA: North America, SA: South America, AF: Africa, OC: Oceania).

As of May 2019, apart from the 169 static gravity field models, we have received Release 6 GRACE models from the three analysing centres and solutions from other groups. The growing interest in the topographical gravity field models also increased the number of the models submitted to ICGEM which is 9 at the moment. Finally, models concerning the other celestial bodies are also of interest to different groups and we received 5 Moon models in 2017 and 2018. Similar to the previous ones, all recently submitted models are provided in the standardised format (Barthelmes and Foerste, 2011) and in the form of spherical harmonic coefficients with possible DOI number assignment via GFZ Library and Information Services (Ince et al., 2019).

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. User can access any reference related to the model that was provided to ICGEM on the same page in column 6 and access to the links to download the model coefficients in column 7, calculate the gravity functionals in column 8 and also to visualise the geoid and gravity anomalies using the link provided in column 9 corresponding the model.

Our evaluations for the static gravity field models are still valid in both spectral domain and wrt 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 wrt 6 different dataset corresponding to different countries and continents (USA, Canada, Europe, Australia, Japan, and Brazil) are provided in "GNNS/Levelling" (http://icgem.gfz-potsdam.de/tom_gpslev). The columns can be re-ordered by simply clicking on the title of the column.

2- Calculation of gravity field functionals at user-defined points

In December 2018, the ICGEM Service introduced the calculation of gravity field functionals at the user-defined list of points. Before, it was only possible to do calculations at grid points that are defined at a spatial resolution of users' request. Now, the user can upload a set of points that are prepared in one of the allowed formats and the gravity field functionals are computed at these points directly. The results are provided on the same page once the computation is finalised.

For the point calculations, after the user uploads the text file of the set of data points in a predefined format (see Fig. 2), the points are displayed on the map. The example in Fig. 2 shows the GNSS/levelling benchmark points in Europe which also are used in the geoid comparisons in the model evaluations. Figure 3 shows the results for the first few points corresponding to the given example in Fig. 2. Different heights for different points can be introduced in the point calculation which is different to the grid calculation where the height is assumed same for all the grid points and consequently delivers results faster. The point calculation was a request from the users, it has been actively used since it has been established.

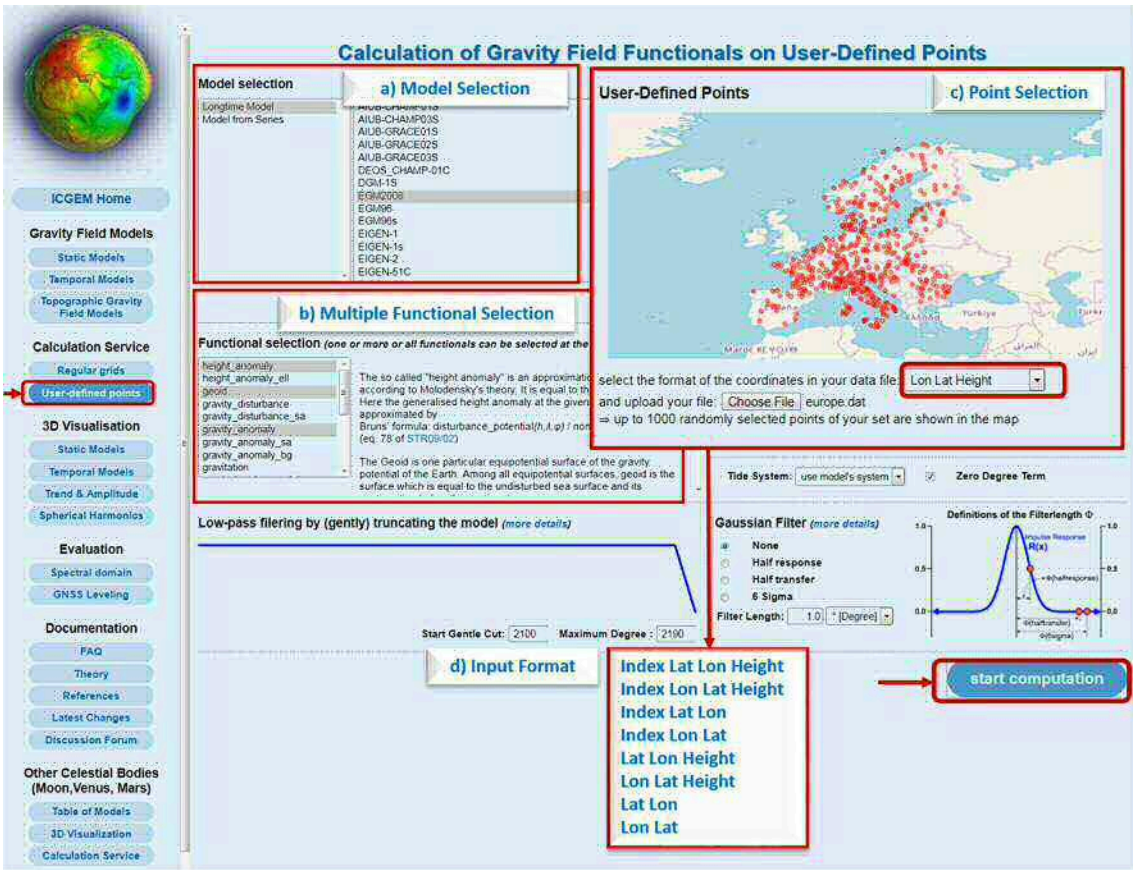
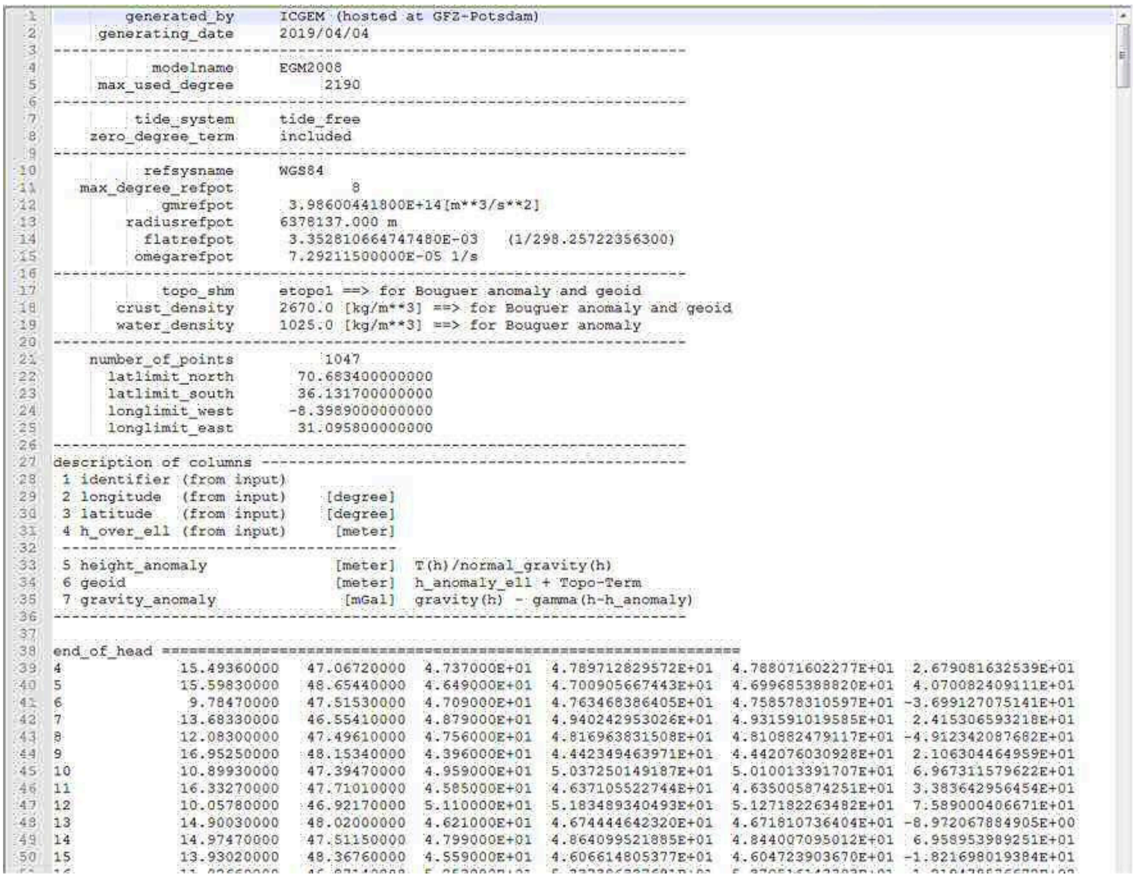


Figure 2: ICGEM Calculation Service – Calculation of Gravity Field Functionals at User-defined Points



```
        generated_by     ICGEM (hosted at GFZ-Potsdam)
     generating_date     2019/04/04
---------------------------------------------------------------------
           modelname     EGM2008
     max_used_degree         2190
---------------------------------------------------------------------
         tide_system     tide_free
   zero_degree_term     included
---------------------------------------------------------------------
          refsysname     WGS84
   max_degree_refpot             8
            gmrefpot      3.98600441800E+14[m**3/s**2]
        radiusrefpot     6378137.000 m
          flatrefpot      3.35281066474748OE-03    (1/298.25722356300)
        omegarefpot      7.29211500000E-05 1/s
---------------------------------------------------------------------
            topo_shm     etopol ==> for Bouguer anomaly and geoid
       crust_density     2670.0 [kg/m**3] ==> for Bouguer anomaly and geoid
       water_density     1025.0 [kg/m**3] ==> for Bouguer anomaly
---------------------------------------------------------------------
    number_of_points         1047
      latlimit_north       70.683400000000
      latlimit_south       36.131700000000
      longlimit_west      -8.398900000000
      longlimit_east       31.095800000000
---------------------------------------------------------------------
description of columns ---------------------------------------------
 1 identifier (from input)
 2 longitude  (from input)     [degree]
 3 latitude   (from input)     [degree]
 4 h_over_ell (from input)      [meter]
 ------------------------------------
 5 height_anomaly               [meter]  T(h)/normal_gravity(h)
 6 geoid                        [meter]  h_anomaly_ell + Topo-Term
 7 gravity_anomaly               [mGal]  gravity(h) - gamma(h-h_anomaly)
---------------------------------------------------------------------

end_of_head ==========================================================
4             15.49360000   47.06720000  4.737000E+01  4.789712829572E+01  4.788071602277E+01  2.679081632539E+01
5             15.59830000   48.65440000  4.649000E+01  4.700905667443E+01  4.699685388820E+01  4.070082409111E+01
6              9.78470000   47.51530000  4.709000E+01  4.763468386405E+01  4.758578310597E+01 -3.699127075141E+01
7             13.68330000   46.55410000  4.879000E+01  4.940242953026E+01  4.931591019585E+01  2.415306593218E+01
8             12.08300000   47.49610000  4.756000E+01  4.816963831508E+01  4.810882479117E+01 -4.912342087682E+01
9             16.95250000   48.15340000  4.396000E+01  4.442349463971E+01  4.442076030928E+01  2.106304464959E+01
10            10.89930000   47.39470000  4.959000E+01  5.037250149187E+01  5.010013391707E+01  6.967311579622E+01
11            16.33270000   47.71010000  4.585000E+01  4.637105522744E+01  4.635005874251E+01  3.383642956454E+01
12            10.05780000   46.92170000  5.110000E+01  5.183489340493E+01  5.127182263482E+01  7.589000406671E+01
13            14.90030000   48.02000000  4.621000E+01  4.674444642320E+01  4.671810736404E+01 -8.972067884905E+00
14            14.97470000   47.51150000  4.799000E+01  4.864099521885E+01  4.844007095012E+01  6.958953989251E+01
15            13.93020000   48.36760000  4.559000E+01  4.606614805377E+01  4.604723903670E+01 -1.821698019384E+01
```

Figure 3: A screenshot of the Calculation Service Point Value Calculation Output as a response to the entry in Figure 2.

3- Documentation

The new 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 discussion forum. The ICGEM team responds to users' questions as soon as possible in the discussion forum. During the last few years, there were common questions from advanced users, researchers and students that are fundamental to do thorough analyses in different application areas. The ICGEM team has collected frequently asked questions (FAQs) and provided this collection with answers as a pdf document. The questions are answered to meet the needs of both users from different scientific disciplines and experts in the field of physical geodesy. The FAQs list is updated when new questions accumulate. The last version of the FAQs can be accessed via http://icgem.gfz-potsdam.de/faq.

Although the theory of the global gravity field modelling and the calculations of gravity field functionals are technical to be included in this progress report, it is most fundamental to the development of the ICGEM Service. A detailed documentation is reported in Barthelmes, 2013 which includes the potential theory and approximations that are used in the global gravity field modelling.

ICGEM does not only collect gravitational models, but also pays attention on the full documentation of the models. New model releases, new documentation, conference and symposium presentations can be found in the ICGEM Home page and in the list of latest changes. Moreover, 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.

Since the interaction between the users and ICGEM team members involves extensive communications via the service and as well as e-mails, the definition of the guest book was redefined in the last reporting period. The old guest book was modified into a gravity field discussion forum (http://icgem.gfz-potsdam.de/guestbook), which provides users with a platform to communicate with the ICGEM team and other scientists working on similar topics. Apart from fulfilling the requirements of the service, this platform has also been used as a tool for educational purposes in which undergraduate or graduate students communicate with the ICGEM team directly. Anyone without any registration requirement are able to write comments in the forum. However, an approval from the ICGEM team is required in order the comment to be available on the website.

In the following reporting period, this platform should be advertised in the gravity field community to support the ICGEM team and the users. The professionals are also welcome to exchange ideas and answer questions.

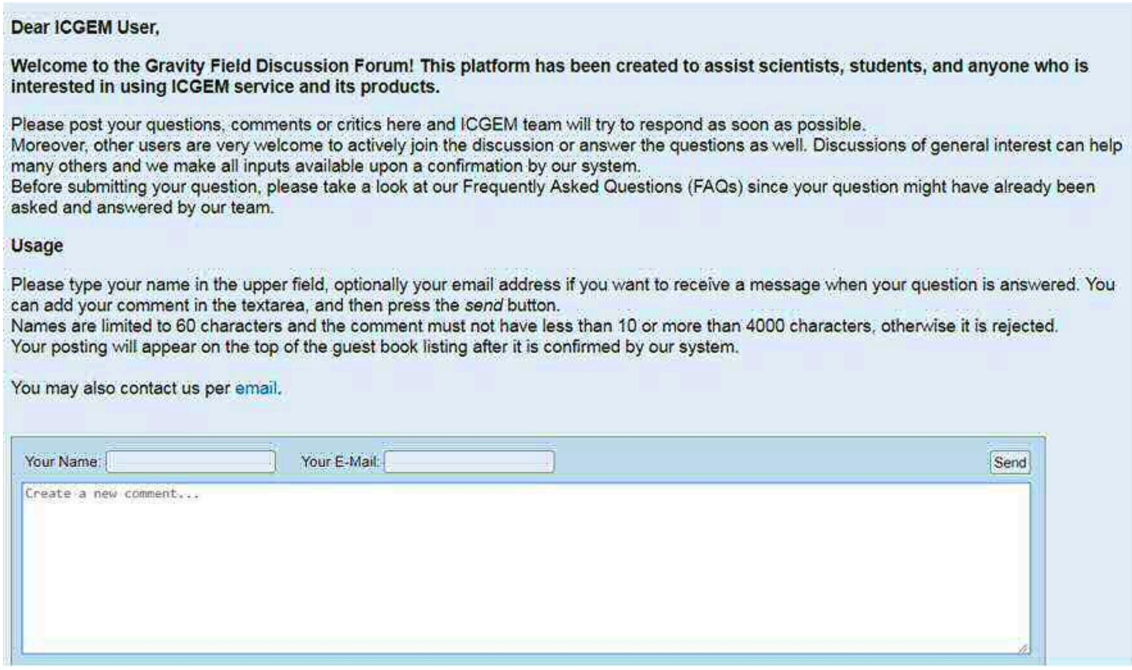


Figure 4: Discussion Forum

4- Presentations and Papers

Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., and Schuh, H.: 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, 2019.

EGU poster contribution: New Features and Future Plans of the International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/Ince_et_al_EGU2019_15513_poster.pdf

GGHS2018 poster contribution: New and Long-term Features of the International Centre for Global Earth Models

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

Elmas Sinem Ince (since August 2016)
Sven Reißland (since 2016)
Franz Barthelmes (until December 2017)

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International Digital Elevation Model Service (IDEMS)

https://idems.maps.arcgis.com/home/index.html

Director, Mr Kevin M. Kelly (USA)

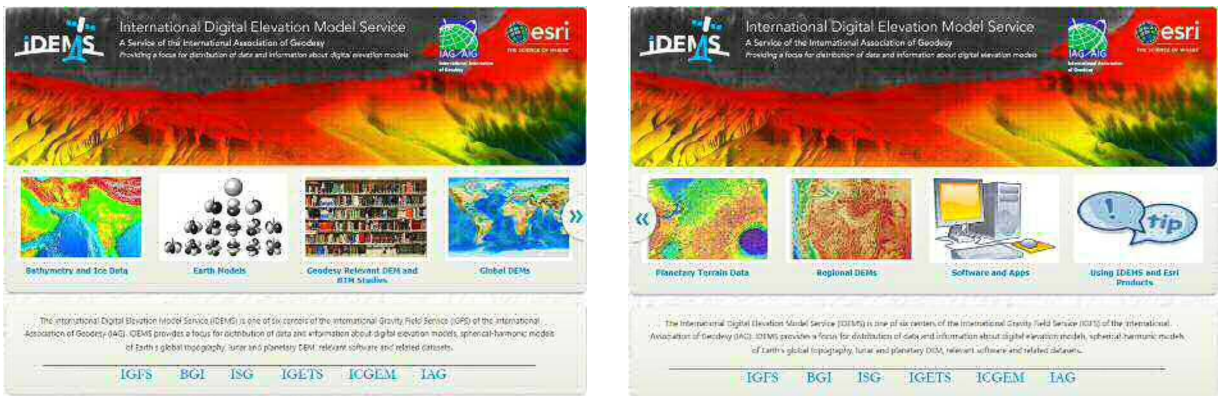
Structure

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 Jianbin Duan
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 31 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.arcgis.com/home/item.html?id=7863485b217241cbb67d98d7e361cac5) which is fully integrated with the ArcGIS platform for accessing, sharing, and publishing maps and data.

Over the last 3 years, the IDEMS website has been continually updated with new DEM datasets, both terrestrial and planetary. Table 1 lists the current content available from the IDEMS website.

Table 1. DEM and Related Data Sources Hosted on IDEMS

Bathymetry and Ice Data (12)	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)
	Polar Geospatial Center
	Randolph Glacier Inventory (RGI 6.0)
	SRTM30_PLUS (30 arc-sec grid), 2014
	Svalbard time-lapse terrain data
Global DEMs (14)	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)
	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 (4)	Earth2014 (60 arc-sec), 2014
	ICE-6G GIA Model
	Preliminary Reference Earth Model (PREM)
	Topographic Earth Models (LMU Munich)

IDEMS Website Usage

Table 2 below shows IDEMS activity from 2016 to 2019. Over the past three years the site has received reasonably good use for the small community it serves. Among the 10 most popular IDEMS content, these items collectively received a total of 6,433 views. Among all IDEMS content, 895 DEM or DEM related descriptions/metadata were downloaded.

Table 2. IDEMS activity by number of views of most popular content and number of downloads of all content since April,2016

Data Type	**No. of item views**	**No. of downloads of DEM descriptions / metadata**
ALOS/PRISM AW3D30		42
Antarctica CryoSat-2 DEM		6
ArcGIS Earth (Esri)		20
Arctic DEM Explorer		15
ASTER GDEM v2	161	140
BedMap2		28
BOEM Northern Gulf of Mexico Bathymetry		5
DEM and BTM Research Papers	102	
Earth2014 (60 arcsec), 2014	74	73
Elevation Coverage Map (Esri)	411	
Esri Elevation Layers		41
ETOPO1 (60 arc-sec grid), 2009		13
Getting Started with IDEMS	73	
Global bathymetry (Esri)	762	
Global Geospatial Data from Earth Observation (2016)		19
Global Terrain DEM (Esri)	4,684	
Global Water Body Map (G3WBM)		9
IAU Cartographic Coordinates and Rotational Elements (WGCCRE)		13
Ice, Cloud, and Land Elevation (ICESat / GLAS Data)		11
ICE-6G GIA Model		3
MERIT DEM (SRTM-based Bare-Earth model), 2017		9
MH370 Bathymetry		2
NASA Planetary Data System (PDS) Geosciences Node		10
NASADEM (reprocessed SRTM model), 2017		19
OpenTopography		4
Planetary topography data archive		22
Polar Geospatial Center		11
Preliminary Reference Earth Model (PREM)		46
Randolph Glacier Inventory (RGI 6.0)		8
SRTM v3 (NASA)	111	99
SRTM v4.1 (CGIAR-CSI)	74	59
SRTM30_PLUS (30 arc-sec grid), 2014		39
Svalbard Time-Lapse Terrain Model		8
TanDEM-X DEM	81	72
Topographic Earth Models		34
USGS Astrogeology Science Center		15
Total	**6,433**	**895**

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. Foerste, H.-P. Sun, B. Meurers, D. Crossley, J. Hinderer, 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), established at the 2015 IUGG General Assembly in Prague (Czech Republic), 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 to provide support to geodetic and geophysical research activities using superconducting gravimeter data within the context of an international network. IGETS also continues the activities of the International Center for Earth Tides, in particular, in collecting, archiving and distributing Earth tide records from long series of gravimeters, tiltmeters, strainmeters and other geodynamic sensors.

Superconducting Gravimeter data are still the major source of data available at IGETS, and different product levels are derived from gravity and pressure data:

- Raw gravity and local air pressure records sampled at 1 or 2 seconds, in addition to the same records decimated at 1-minute samples (Level 1 products).
- Gravity and air pressure data corrected for instrumental perturbations, ready for tidal analysis (Level 2 products).
- Gravity residuals after geophysical corrections (Level 3 products).

Status of the Analysis Centers

The two IGETS Analysis Centers, located at the University of French Polynesia (Tahiti) and at EOST (Strasbourg, France) provide the different Level-2 and Level-3 products. The two centers have been processing the Level 2 data from the raw Level 1 data, i.e. gravity and pressure data corrected for all major disturbances. The EOST center has produced the Level 3 data, i.e. gravity residuals after correction of all major geophysical signals.

IGETS preprocessing Centre at University of French Polynesia (UPF), Tahiti

Raw minute data (IGETS-SG-MIN) are preprocessed and validated at IGETS preprocessing Centre Tahiti. In total, 776 months of data have been processed. Hourly data are also generated as one-year blocks (IGETS-SG-HOUR, code h2) for these sites. Table 1 summarizes the status, where data processed in 2018 are highlighted in red.

New stations (shaded in Table 1) have been preprocessed for the first time: Djougou, La Plata, Lhasa and Lijiang. For these new stations a report was sent to the data owners providing a comparison between the observed tidal gravity factors and those modelled from a theoretical body tide model (Dehant et al., 1999) and ocean tide loading, which allows to assess an upper limit of the calibration error of the instrument.

Table 1: Status of IGETS data preprocessed and analyzed by UPF on April 1st 2019
n: number of preprocessed months in 2018 N: number of days analyzed
STD: standard deviation of the tidal analysis (ETERNA)

Code	Location	SG Instr.	Code	RAW	Corrected	n (months)	N (days)	STD (nm/s²)
AP	Apache Point, USA	SG046	00466090	180800	180822	17	2873	1.142
BA*	Bandung, Indonesia	T008	00084100	030600	030622		1104	2.938
BE*	Brussels, Belgium	T003	07790200	000900	000901		¶6692	1.641
BF	Black Forest, Germany	CD056_L	01560716	190100	180122	21	2651	0.576
		CD056_H	02560716	190100	180122		2698	0.629
BG	Borowa Gora, Poland	iGRAV027	00270908	170100	170212 ••			
BH	Bad Homburg, Germany	(T001)					¶1005	0.950
		CD030_L	01300734	070400	070422 *		2222	0.783
		CD030_U	02300734	070400	070422 *		2218	0.835
		SG044	00440734	170300	170322 *		3619	0.521
BO*	Boulder, USA	C024	00246085	031000	031022		1850	1.109
BR*	Brasimone, Italy	T015	00150515	991200	991222		1428	2.954
CA	Cantley, Canada	T012	00126824	190200	170422		6084	1.539
							¶7755	1.613
CB	Canberra, Australia	C031	00314204	161200	161222	12	6809	0.778
CI	Cibinong	CT022	00224102	120500	120522		872	1.970
CO	Conrad, Austria	C025	00250699	170300	170322	25	2880	0.609
DJ	Djougou, Bénin	C060	00603335	190100	180222	90	2522	0.769
ES*	Esashi, Japan	T007	00072849	081200	081222	→20040225	2274	1.491
HS	Hsinchu, Taiwan	T048	00482695	120800	090622 ••		898	2.249
KA*	Kamioka, Japan	T016	00162828	130700	130722		3006	1.229
KY*	Kyoto, Japan	T009	00092823	030600	030622	→20020731	1533	3.691
LP	La Plata, Arg..	RT038	00387800	180200	171222	24	729	1.277
LH	Lhasa	OSG057	00572650	170600	170622	91	2391	0.503
LI	Lijiang	0SG066	00662651	130400	170622	51	1378	0.811
MA*	Matsushiro, Japan	T011	00112834	080600	080622		3954	1.008
MB	Membach, Belgium	C021	00210243	120900	120922 ••		5907	0.705
MC	Medicina,Italy	C023	00230506	180300	170622		6990	0.891
ME	Metsahovi, Finland	T020	00200892	160900	150422 *		5409	1.167
							¶5935	1.159
		iGRAV013	00130892	180300				
		iOSG022	00220892	180300				
		OSG073_N6	01730892	150100	150122		356	0.683
		OSG073_N7	02730892	150400	150422		381	0.608
MO	Moxa, Germany	CD034_L	01340770	181200	181222	35	6600	0.535
		CD034_U	02340770	181200	181222	35	6672	0.548
NY*	Ny Alesund, Norway	C039	00390005	120100	120122		3776	2.687
OS	Onsala, Sweden	OSG54	00540875	181200	180122	22	3113	1.217
PE	Pecny, CZ	OSG050	00500930	181000	181022	27	4065	0.628
PO*	Potsdam, Germany	T018	00180765	980900	980912		2250	0.856
ST	Strasbourg, France	(T005)					3272	2.265
		C026	00260306	181000	161122	19	6775	0.630
SU	Sutherland, South Africa	CD037_L	01373806	181200	181222	32	5850	0.802
		CD037_U	02373806	181200	181222	32	5373	0.769
		SG052	00523806	170900	170922	17	2845	0.721
SY	Syowa, Antarctic	T016	00169960	030100	030122 *	→20001231	1279	1.387
TC	Tigo, Concepcion, Chile	RT038	00387621	150400	150422 *		3544	1.071
VI*	Vienna, Austria	C025	00250698	061200	061222		3402	0.525
							¶4278	0.463
WE	Wettzell, Germany	(SG103)	01030731	980900	980921 *		¶726	2.639
		CD029_L	01290731	1803001	180322	68	6294	0.583
		CD029_U	02290731	80300	180322	68	6260	0.584
		CD030_L	01300731	180300	180322	16	2776	0.604
		CD030_U	02300731	180300	180322	16	2791	0.576
		iGRAV006	00060731	170300	170322	24	672	1.004
WU	Wuhan, China	T004	00322647	120700	120712 *		3844	0.937
		C065	00652647	170600	170600 ••			
YS	Yebes, Spain	OSG64	00640435	190200	180222	24	2228	0.723
					TOTAL	776		

Legend: * instrument or station stopped ( ) not included in IGETS
••preprocessed only by data owner ¶ with data before 1997/07 → end of analysis

IGETS processing at EOST, University of Strasbourg, France

EOST has produced Level 2 and 3 data from 37 records, from 31 instruments located at 27 different sites, with its own processing strategy.

Raw 1-minute gravity and pressure (Level 1 data) are first calibrated using the available calibration files. We start processing the air pressure data, removing interpolated hourly surface pressure from MERRA2 (Gelaro et al., 2017) reanalysis model. We correct manually these residuals for eventual offsets, and fill any gaps with a linear interpolation. The de-gapped series is then corrected for the remaining perturbations (spikes) using a threshold on its derivative, following Crossley et al. (1993) procedure. The full air pressure is then restored by adding back the MERRA2 pressure. For gravity, the methodology is similar: calibrated gravity is corrected for a local tidal model, including polar motion, and local air pressure effects. Offsets are manually corrected, gaps are filled with a linear interpolation, and remaining perturbations (spikes, earthquakes) are corrected using a threshold on the derivative of the gravity residuals. The full gravity is then restored by adding back the modeled tidal signal and air pressure effects.

1-min. gravity residuals are computed after subtracting to the Level 2 data: Solid Earth tides and ocean tide loading, atmospheric loading, polar motion and length-of-day induced gravity changes, and an instrumental drift.
Tidal gravity variations are computed differently for the long-period tides and for the diurnal and sub-diurnal bands:

- At high frequency, a local tidal model, adjusted by least-squares, is used.
- At frequencies below diurnal tides, we model the tidal signal using the DDW99 gravimetric factor (Dehant et al., 1999) and HW95 tidal potential (Hartmann and Wenzel, 1995) for the Solid Earth tides, and FES2014b (Carrère et al., 2016) for the ocean tidal loading.

This hybrid methodology allows us to remove most of the short-period tides, and to keep all other long-period variations, including, for example, the seasonal hydrological contributions (Boy and Hinderer, 2006).

Atmospheric loading is computed according to Boy et al. (2002), using MERRA2 (Gelaro et al., 2017) hourly surface pressure, and assuming an inverted barometer ocean response to pressure. MERRA2 pressure is replaced by the 1-minute local pressure record for angular distance less than 0.10° to the station.

The polar motion and length-of-day induced gravity variations are modelled using the IERS EOPC04 daily series (http://hpiers.obspm.fr/iers/eop/eopc04/) (Wahr, 1985), and assuming a δ_2 factor of 1.16. We also model ocean pole tide as a self-consistent equilibrium response (Agnew and Farrell, 1978; Chen et al., 2008).

Depending on the sensor, the instrumental drift is generally modelled as a polynomial or an exponential function (Van Camp and Francis, 2007). When available, we use time series from absolute gravimeters for the adjustment.

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Status of the Data Center

The IGETS data sets are stored on a FTP server and are freely available after user registration. The number of IGETS users has been rapidly increasing since the launch in summer 2016 (see Fig. 1) and reached the number of 400 in Feb 2019. The data base server is hosted by GFZ Potsdam (Germany) and is accessible via http://igets.gfz-potsdam.de.

Currently Level 1 data from 42 stations and 60 sensors are available, globally distributed (see Fig. 2), provided by 28 producers covering a time span of up to 30 years (see Fig. 3). Records from superconducting gravimeters made by GWR of compact (CT) and observatory (OSG) type are predominant. However, data from four transportable GWR iGrav superconducting gravimeters and one LaCoste & Romberg spring gravimeter were added. The Level 2 data are processed on a regular basis by the University of French Polynesia (see Table 2). These cover all stations and sensors with Level 1 data with the exception of the very recently added sensors. Level 3 data are provided by EOST since Mar 2019 for 27 stations and 37 sensors (see. Fig. 4). 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 in large part from the Global Geodynamics Project (GGP) were updated and extended for IGETS.

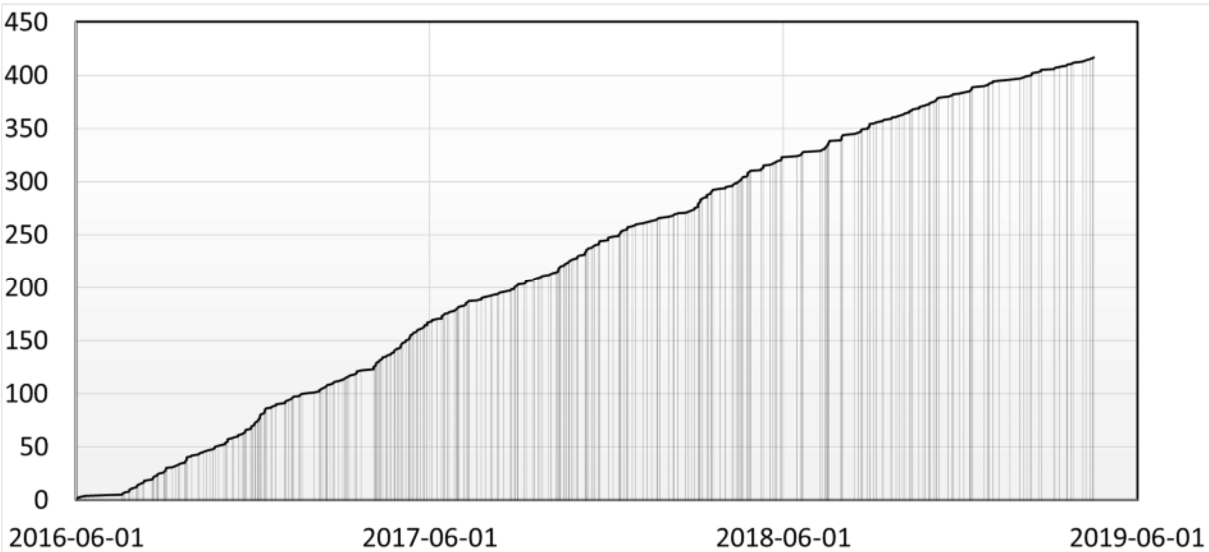

Fig. 1 Number of IGETS data base users since the launch in summer 2016 (status from 18 Apr 2019)

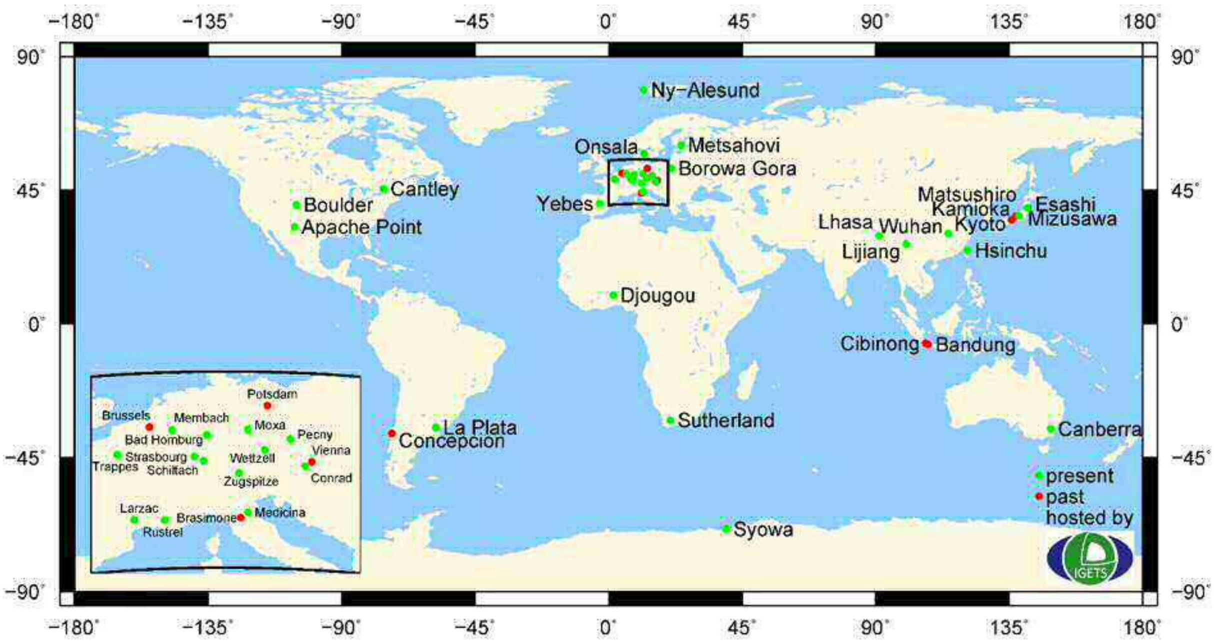

Fig. 2 Present and past stations included in the IGETS data base

References

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

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. For level 2 data contributed by station operators, a DOI can be assigned individually for each station.

Station	Sensor	1989	90	91	92	93	94	95	96	97	98	99	2000	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Apache Point	ap046																					■	■	■	■	■	■	■	■	■	■	
Bad Homburg	bh030-1													■	■	■	■	■	■	■												
Bad Homburg	bh030-2													■	■	■	■	■	■	■												
Bad Homburg	bh044																			■	■	■	■	■	■	■	■	■	■	■		
Bandung	ba009									■	■	■	■	■	■	■																
Borowa Gora	bg027																												■	■		
Borowa Gora	bg1036																												■			
Boulder	bo024							■	■	■	■	■	■	■	■	■																
Brasimone	br015							■	■	■	■	■	■																			
Brussels	be003									■	■	■	■																			
Canberra	cb031									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Cantley	ca012	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Cibinong	ci022																				■	■	■	■	■							
Concepcion	tc038														■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Conrad	co025																			■	■	■	■	■	■	■	■	■	■	■		
Djougou	dj060																						■	■	■	■	■	■	■	■	■	■
Esashi	es007									■	■	■	■	■	■	■	■	■	■	■	■											
Hsinchu	hs048																		■	■	■	■	■	■	■				■			
Kamioka	ka016																■	■	■	■	■	■	■	■	■	■						
Kyoto	ky009									■	■	■	■	■	■	■																
Larzac	la002																							■	■	■	■	■	■	■	■	■
La Plata	lp038																												■	■	■	■
Lhasa	lh057																					■	■	■	■	■	■	■	■	■		
Lijiang	li066																									■	■	■	■	■		
Matsushiro	ma011									■	■	■	■	■	■	■	■	■	■	■	■											
Medicina	mc023										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Membach	mb021							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
Metsahovi	me013																												■	■	■	■
Metsahovi	me020						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Metsahovi	me022																													■	■	■
Metsahovi	me073-1																										■	■				
Metsahovi	me073-2																										■	■				
Mizusawa	mi007																					■	■	■	■	■	■	■	■	■		
Moxa	mo034-1												■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Moxa	mo034-2												■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Ny-Alesund	ny039											■	■	■	■	■	■	■	■	■	■	■	■	■	■							
Onsala	os054																					■	■	■	■	■	■	■	■	■	■	
Pecny	pe050																			■	■	■	■	■	■	■	■	■	■	■	■	
Potsdam	po018				■	■	■	■	■	■	■																					
Rustrel	ru024																											■	■	■	■	
Schiltach	bf056-1																					■	■	■	■	■	■	■	■	■	■	■
Schiltach	bf056-2																					■	■	■	■	■	■	■	■	■	■	■
Strasbourg	st023																												■	■	■	■
Strasbourg	st026									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Sutherland	su037-1												■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■
Sutherland	su037-2												■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■
Sutherland	su052																				■	■	■	■	■	■	■	■	■	■		
Syowa	sy016									■	■	■	■	■	■	■																
Trappes	tr005																									■	■	■	■	■	■	■
Vienna	vi025									■	■	■	■	■	■	■	■	■	■													
Wettzell	we006																											■	■	■		
Wettzell	we029-1										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Wettzell	we029-2										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Wettzell	we030-1																						■	■	■	■	■	■	■	■	■	
Wettzell	we030-2																						■	■	■	■	■	■	■	■	■	
Wettzell	we103								■	■	■																					
Wuhan	wu004									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
Wuhan	wu065																									■	■	■	■	■		
Yebes	ys064																							■	■	■	■	■	■	■	■	■
Zugspitze	zu052																														■	

Fig. 3 Temporal coverage of the Level 1 data provided by the station operators to the IGETS data base (status of 18 April 2019)

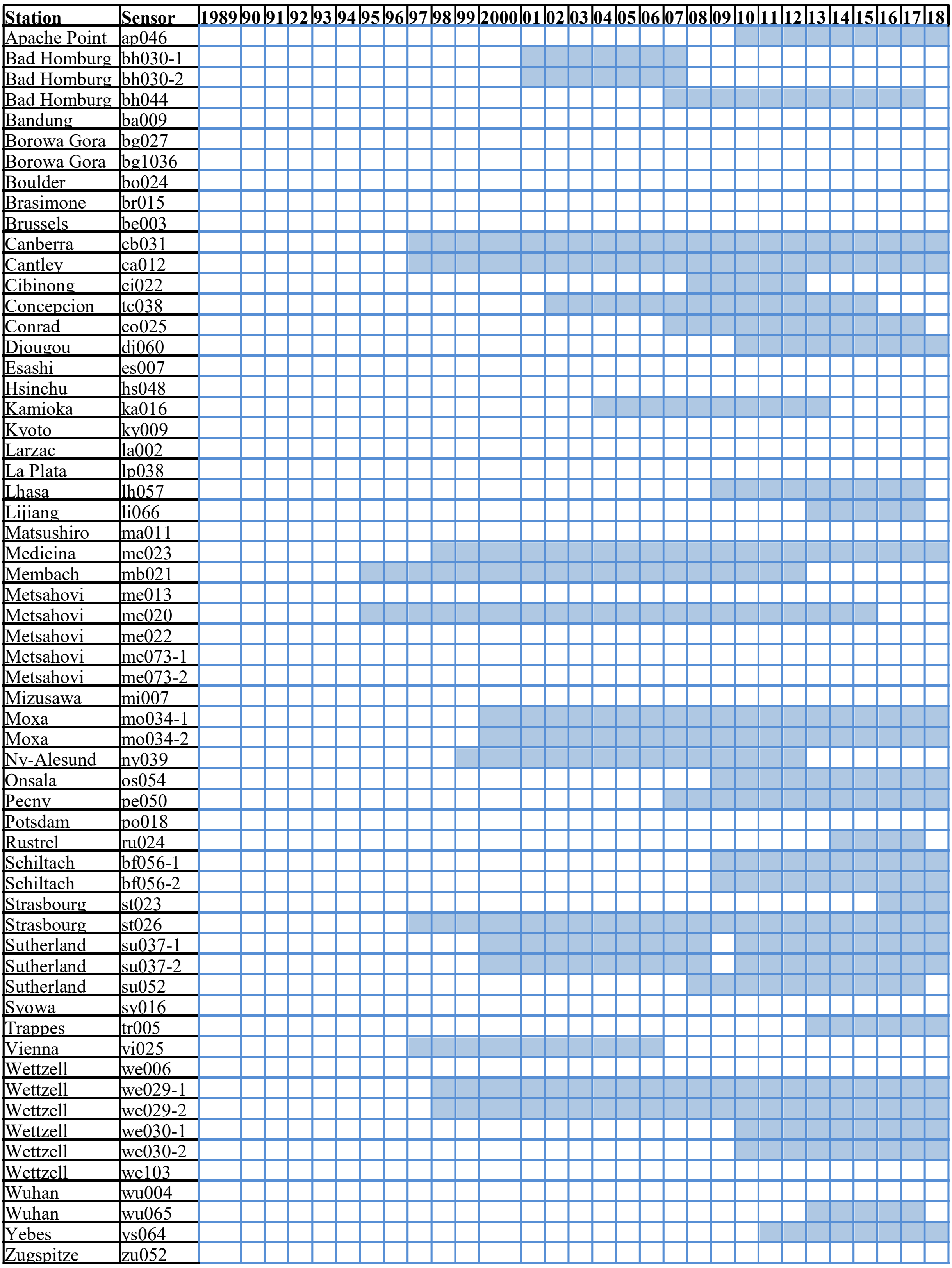

Fig. 4 Temporal coverage of the Level 3 data provided by EOST to the IGETS data base (status of 18 April 2019)

Meetings

A first meeting was held in Trieste during the 18th International Symposium on Geodynamics and Earth Tides. An introduction to the database updates was given by C. Voigt and aspects of the documentation of instrumental parameters by the calibration file were discussed. At the symposium, the progress during the first year was presented by J.-P. Boy and a status update of the Analysis Centre Tahiti (former ICET) was given by J-P. Barriot.

A second meeting was held in April 2017 during the EGU General Assembly in Vienna with station reports, a report about the IGETS database and a discussion about the current status of the different product levels. The IGETS database was presented with a poster.
A third meeting was held in August 2017 at the IAG-IASPEI Joint Scientific Assembly in Kobe, Japan. The status report for Japan given by Y. Tamura was of special interest. Further details on Level 2 and 3 data processing were discussed.

The last meeting was held in April 2019 during the EGU General Assembly in Vienna with station reports, a report about the IGETS database and a presentation of Level 3 products, including a discussion about the current status of the different product levels, analysis software and data formats.

Meeting reports are provided at the IGETS homepage http://igets.u-strasbg.fr/stations.php

A first IGETS Workshop with 35 participants from 12 countries was organized in Potsdam (Germany) from the 16th to the 18th of June 2018, covering various topics: Station reports, data products and scientific applications. The program and the presentations can be found on http://igets.u-strasbg.fr/workshop.php.

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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.

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.

Publications

A list of publications related to IGETS can be found at: http://igets.u-strasbg.fr/biblio.php

International Gravimetric Bureau (Bureau Gravimétrique International, BGI)

http://bgi.obs-mip.fr

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, 2016", H. Drewes, Eds. (International Association of Geodesy). Journal of Geodesy, *Journal of Geodesy* DOI:10.1007/s00190-016-0948-z
- BGI website : http://bgi.obs-mip.fr/

Overview

During the 2015-2019 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 2015-2019 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) 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 relational database (AGrav) 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.).

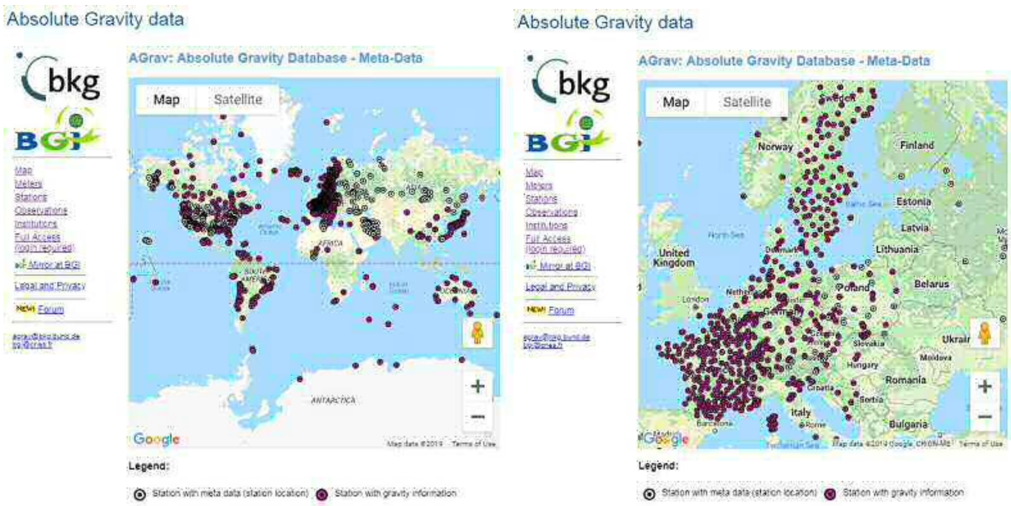

Figure 1: WEB interface of the Absolute Gravity database (BGI-BKG)
Current status (07/2019): 1256 stations / 4714 observations / 78 instruments / 63 institutions

An improved version of the database has been also initiated (development in progress) in order to support the project of realization of the international absolute gravity reference system (IAG/IGFS/GGOS initiative) and to provide a better link between observations provided by both absolute and superconducting gravity meters. This new version (see presentations at EGU2018 and IAG/GGHS 2018) keeps a similar structure but will provide new functionalities as for instance: interactive maps, plot of time series, link to superconducting gravity times series, etc.

1.3. Regional or global gravity anomaly grids

The BGI provided new 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)

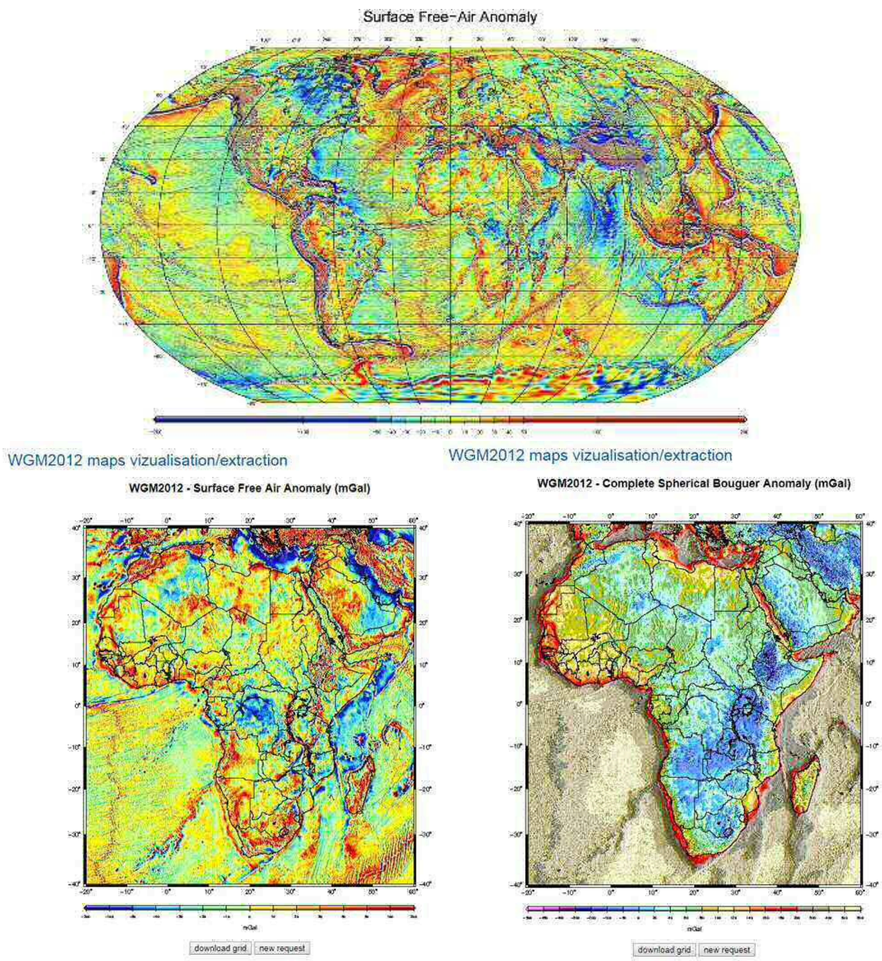

Figure 2: Examples of grid extraction from the global WGM2012 gravity model (http://bgi.obs-mip.fr/data-products/Grids-and-models/wgm2012)

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 GEOMED2 project will be finalized in 2019-2020 with the release of digital grids. See for details : Barzaghi et al. (2018, 2017), Lequentrec-Lalancette et al. (2016). 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).

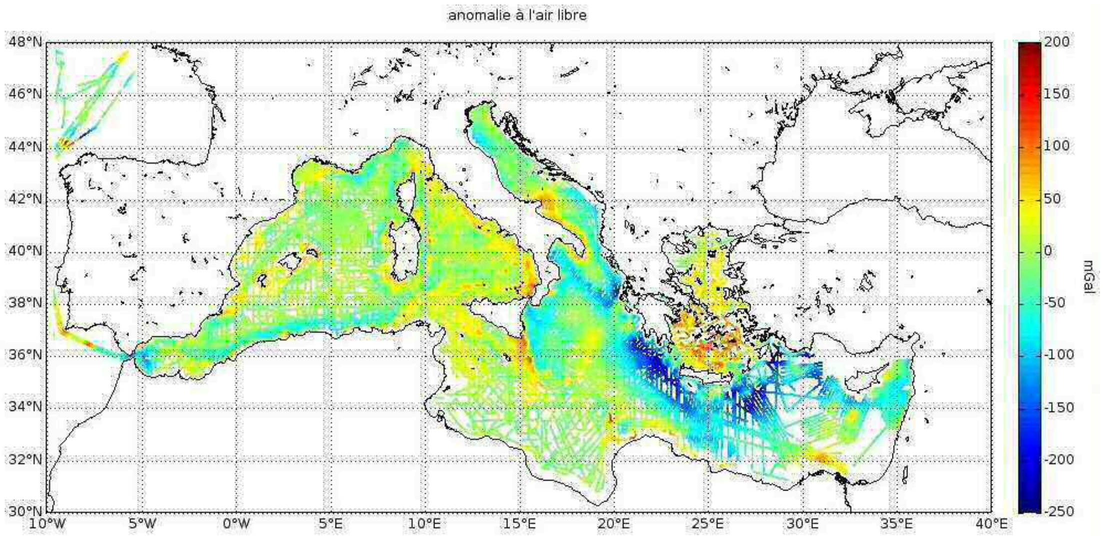

Fig. 3: Free air gravity anomalies over Mediterranean Sea from marine data analysed at BGI for the GEOMED2. (see Lequentrec-Lalancette et al., *IAG Symposia Series*. 2016).

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 other 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 and Peru).

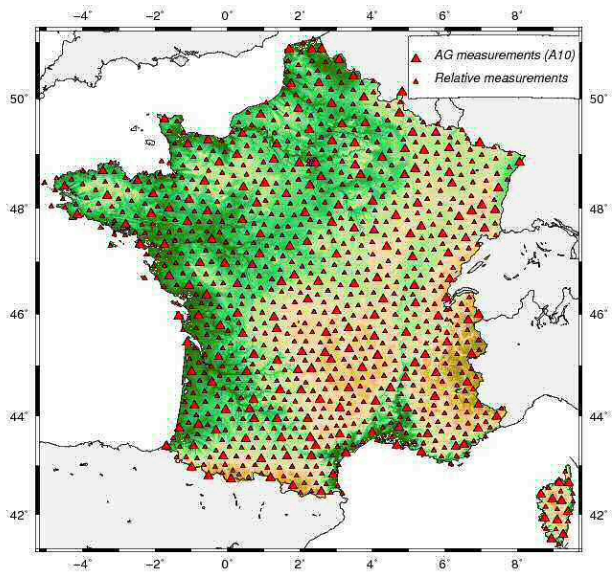

Figure 4: Example of hybrid (absolute and relative) reference gravity network in France (IGN France).

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 main objectives and realization of this future network have been discussed in dedicated splinter meeting during EGU meetings and are presented in Wziontek et al. (2019) and Wilmes et al. (2016).

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 (Menoret et al., 2018 ; Pereira and Bonvalot, 2016 ; Le Moigne et al., 2019). 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 spring 2019 (Collab. BGI, ONERA, DTU, SHOM, CNES, SAFIRE).

Figure 5a: Absolute Quantum Gravimeter (AQG) model A from MUQUANS.

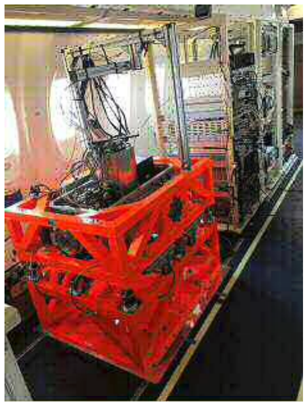

Figure 5b: GIRAFE-2 cold-atom gravimeter (ONERA) during airborne survey in spring 2019.

Scientific events

International meetings

- 07/2019 : IUGG General Assembly 2019 ; Montreal, CA
- 04/2019 : EGU General Assembly 2018 ; Vienna, AU
- 12/2018 : AGU General Assembly 2016 ; San Francisco, USA
- 09/2018 : IAG/GGHS Workshop, Copenhagen, DK
- 04/2018 : EGU General Assembly 2018 ; Vienna, AU
- 08/2017 : IAG/IASPEI Joint Assembly 2017 ; Kobe, JPN
- 04/2017 : EGU General Assembly 2017 ; Vienna, AU
- 12/2016 : AGU General Assembly 2016 ; San Francisco, USA
- 09/2016 : GGHS - Joint IAG / IGFS Meeting, Thessaloniki, GR (as Scientific Com.)
- 05/2016 : ESA Living Planet Symposium ; Pragua, CSR,
- 04/2016 : 4th IAG Symposium on Terr. Gravimetry. St. Petersburg, RU (as Scientific Com.)
- 04/2016 : EGU General Assembly 2016 ; Vienna, AU
- 04/2015 : EGU General Assembly 2015 ; Vienna, AU

BGI was also involved in co-organizations or participations to splinter meetings and International project workshops carried out during these main scientific events.

Participation to IAG structure & working groups

- IAG Sub-commission 2.1: « Gravimetry and gravity networks » (Chair. L. Vitushkin, Russia)
- 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)
- Advisory Board of IGFS - http://igfs.topo.auth.gr/structure.html/
- Consortium member of GGOS - 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

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Rülke A., S. Bonvalot, H. Wziontek, and R. Falk. The Upgraded International Database for Absolute Gravity Measurements (AGrav). EGU, Vienne, 8-13 avril 2018. EGU2018-14758 | Posters

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Note for BGI users & contributors / Attribution of DOI

The contribution to the BGI databases of worldwide scientists, agencies or institutions involved in relative or absolute gravity data acquisition is crucial for improving the global knowledge of the Earth gravity field and providing the best service to the IAG/GGOS community. It is reminded that any dataset or metadata derived from land, marine or airborne surveys or from compilation works (point data or grids) can be deposited as public or proprietary information. This enables BGI to ensure a long term archiving of the data and to validate the incoming gravity observations in a global reference frame and restore them (public data only) in standard and unified formats useful for various users.

In order to better reference and acknowledge these contributions, a **DOI (Digital Object Identifier)** will be provided to any gravity dataset or product deposited at BGI. This new service will ensure a proper reference to authors and institutions who have acquired or compiled gravity data and a better traceability of improvements provided by these local or regional surveys to the global gravity data coverage.

Contacts for updating BGI databases or obtaining DOI for data, products or software:
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F. Reinquin	J.-D. Bernard
L. Seoane	N. Le Moigne
H. Wziontek	C. Salaun
V. Palinkas	D. Roussel
M. Diament	J. Hinderer
T. Gattacceca	U. Marti (IAG Representative)

International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it/

President: Mirko Reguzzoni (Italy)
Director: Daniela Carrion (Italy)

Structure

The Service is currently provided by two centers, one at the Politecnico di Milano (Italy) and the other at NGA (USA).

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 and L. Rossi) 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)
- U. Marti (Switzerland)
- H. Denker (Germany)
- L. Sánchez (Germany)
- I. Tziavos (Greece)
- W. Kearsley (Australia)
- D. Blitzkow (Brazil)

In the period 2015-2019, ISG has been involved in the Joint Working Groups JWG 2.2.1 of Sub-commission 2.2 "Integration and validation of local geoid estimates".

Overview

The service governance was changed on 13th April, 2018, nominating Daniela Carrion as director of the service. The service rendered by Giovanna Sona as previous director is warmly thanked.
In the period 2015-2019, the main scientific activities of ISG have been related to the following research lines:

- local/regional geoid estimation;
- merging of local geoid estimates, defining a unified height datum;
- school organization and scientific support to researchers on geoid estimation;
- ISG geoid repository and website update.

As for the geoid estimation, the main effort has been devoted to the GEOMED-II project. The goal of this project is the computation of a high-accuracy and high-resolution geoid model for the Mediterranean Sea employing land and marine gravity data and GOCE/GRACE based global models. Moreover, the Italian geoid model has been recomputed, after validating the existing gravity database. Finally ISG took part in the so-called Colorado experiment organized by NOAA's National Geodetic Survey.

As for the local geoid merging, this activity has been performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2. The output will represent a new product of ISG and aims to be a contribution in the frame of GGOS for the establishment of an International Height Reference System (IHRS).

According to tradition, during this four-year period ISG organized an international school on geoid determination and height datum definition. The school was held at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia, from 6th to 10th June, 2016. The total number of participants was 30, half of them coming from abroad.

Last but not least, to maintain the main ISG purpose of collecting, analysing and redistributing local and regional models, the ISG geoid repository has been continuously updated and the ISG website has been modified accordingly. In particular, the webpage of each model has been "standardized" in the sense of providing the same type of information. Moreover, all public models are redistributed with a unique ASCII format.

Local/regional geoid estimation

In the last four years, the activities on local/regional geoid estimation have been focused on the GEOMED-II project and the ITALGEO model update, as well as the participation to the Colorado experiment. The former is dedicated to the computation of a geoid model for the Mediterranean Sea. It is sponsored by the European Space Agency (ESA) and by all the participating Institutions. Apart from the IGFS, BGI and ISG services, the project partners are:

- Politecnico di Milano (Italy),
- GET, SHOM and OCA/Geoazur (France),
- Aristotle University of Thessaloniki (Greece),
- DTU Space (Denmark),
- General Command of Mapping (Turkey),
- University of Zagreb (Croatia),
- University of Jaén (Spain).

The processing methodology is based on the well-known remove-compute-restore approach using both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data.

The input data come from the BGI database and from the project partners, in particular classified gravimetric data from Italy, Greece, Croatia and Turkey were used. All the available gravity observations for the wider Mediterranean basin have been homogenized in terms of their horizontal system and are being validated and homogenized in terms of gravity system. An outlier rejection has been performed and some biases have been identified. These biases have a negative impact on the covariance function estimation and, of course, on the geoid estimation. In particular, a track by track de-biasing with respect to EIGEN-6C4 has improved the results, in terms of the stochastic behaviour of the gravity residuals.

The geoid grids have been computed by the collocation method using the GRAVSOFT software. Stokes and FFT-based geoid models have been also determined and compared with the collocation-based ones. The accuracy of the estimated geoids has been assessed through comparisons to GPS/levelling and altimeter data.

At first, preliminary computations have been performed to test the processing chain. In particular, a test of the collocation method and a test of the FFT-based method have been performed. The test consisted in first estimating the EGM2008 undulation residuals starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$) and then comparing the estimates to the actual EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$, see Figure 1). This allowed to check the procedure and to choose the best FFT kernel modification for the GEOMED-II computation.

A lot of effort has been dedicated to investigate and properly determine topographic effects over both land and marine areas to efficiently reduce land and marine gravity data towards geoid determination. In fact, over land areas, the latest SRTM-based DTMs offer high-accuracy and high-resolution information on the topographic variations, in the sense that they properly model the high-frequency contributions of the topographic masses. Over marine regions, the situation is quite different, since the resolution of the available DBMs is not always capable to remove the high frequencies that are present in shipborne marine gravity data. On the other hand, marine gravity data do not often have the necessary spatial resolution to rigorously model the high frequencies depicted in the DBM. Aliasing effects on the estimated topographic effects will be also investigated and the corresponding errors introduced in gravity anomalies and geoid heights will be taken into account.

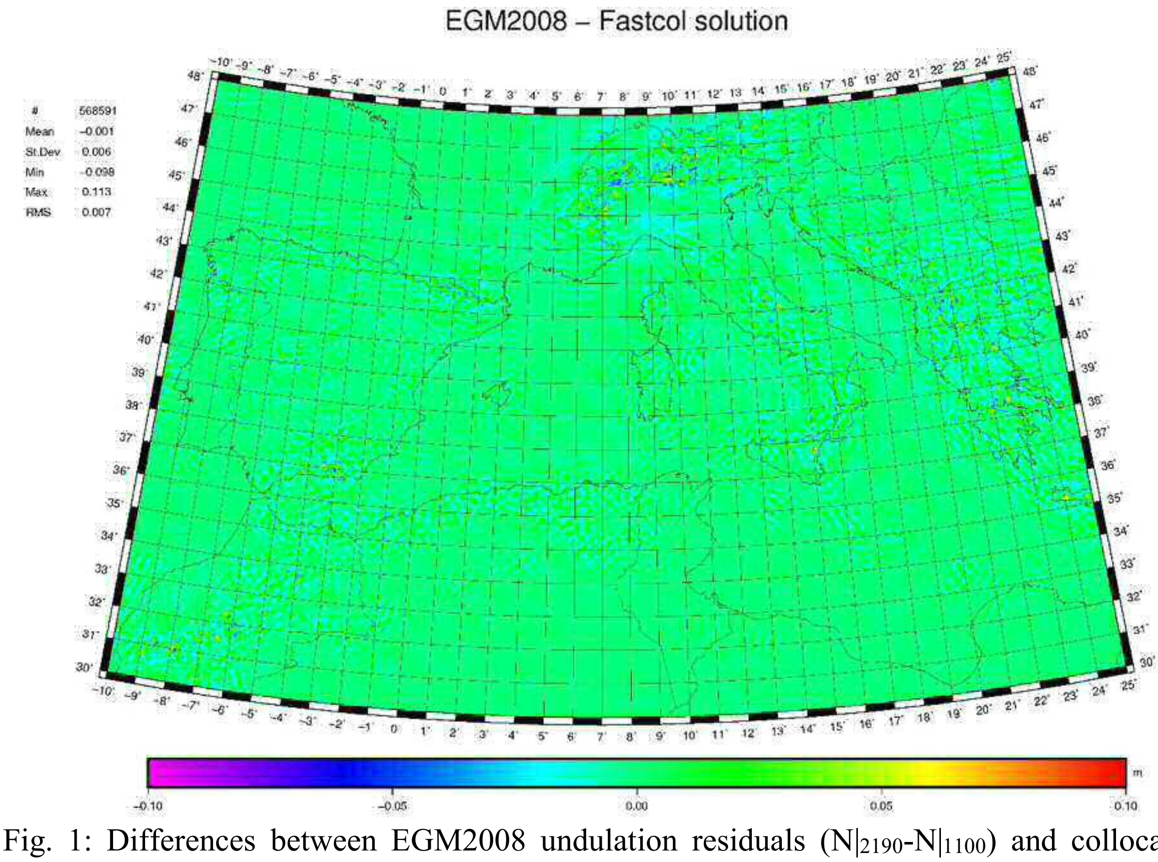


Fig. 1: Differences between EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$) and collocation estimates starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$).

Improvements in the performance of the data reduction over sea have been obtained using the Hirt & Kuhn approach. In addition, to fill gaps in land gravity data or to avoid the propagation over sea of the effect of unreliable land gravity data, in selected critical areas, the gravity residuals have been substituted using simulated data reflecting the global stochastic behaviour of the gravity residuals. In Figure 2, the gridded gravity residuals obtained with Hirt & Kuhn approach for RTM reduction and after having substituted portions of land with simulated data are shown.

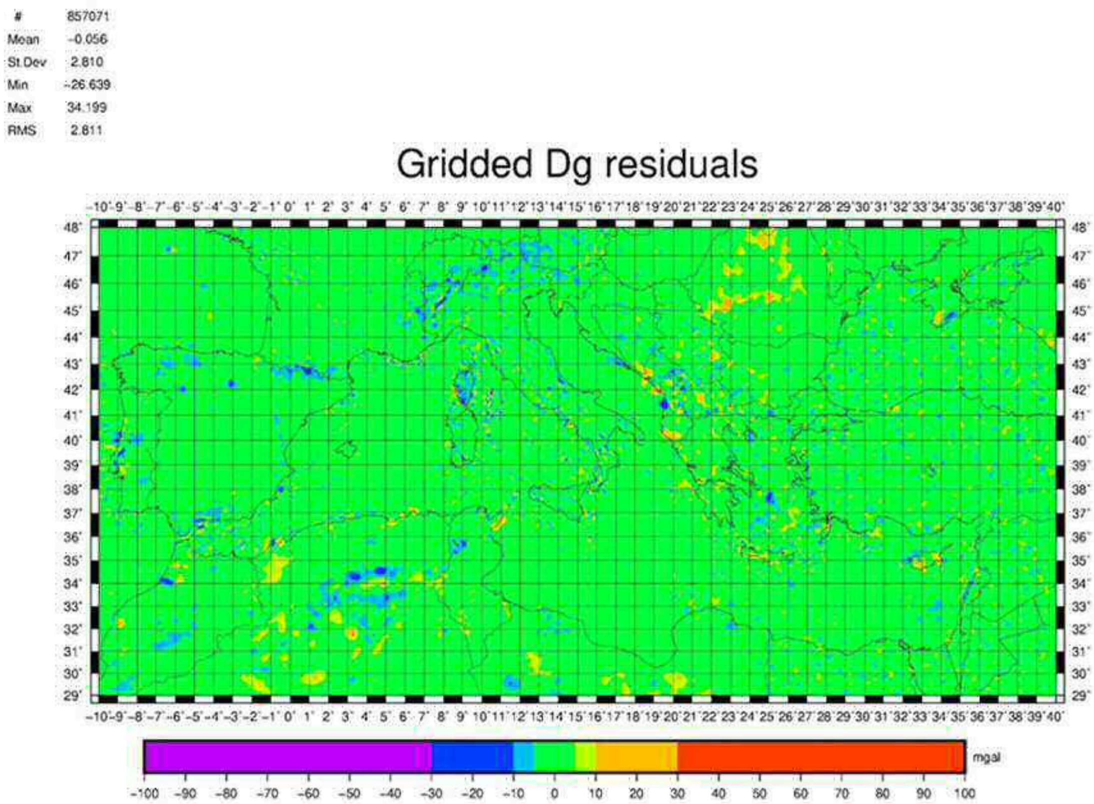


Fig. 2: Gridded gravity residuals for the remove-restore computation of the geoid of the Mediterranean Sea.

Geoid solutions of the Mediterranean Sea have already been computed and are being assessed. In particular:

- One solution has been produced at Politecnico di Milano with Fast-collocation algorithm.
- One solution has been produced at Aristotle University of Thessaloniki with a tapered version of the Wong-Gore modification of Stokes' kernel function (truncated at degree 1000), through the SPFOUR software of the GRAVSOFT package.
- One solution has been produced at the General Command of Mapping (Ankara, Turkey) with KTH method based on the least-squares modification of Stokes' formula.
- One solution has been produced at University of Zagreb with RCR approach with Stokes integration, using Heck & Grűninger kernel, with modification degree 300. Two additional corrections on geoid undulations were applied: tide free to mean tide geoid undulation and topographic bias.

The computed solutions have been compared with GPS/levelling data over Italy and Greece, see Tables 1 and 2 respectively, showing a substantial agreement. At present, solutions inter-comparisons are being performed as well as inter-comparisons with respect to altimetry models such as DTU15 (Figure 3).

	Collocation (POLIMI)	Stokes-WG (AUTH)	KTH (GCM)	KTH (UZG)
#	977	977	977	977
Mean [m]	0.000	0.000	0.000	0.000
St. Dev. [m]	0.090	0.097	0.093	0.096
Min [m]	-0.229	-0.217	-0.462	-0.409
Max [m]	0.382	0.463	0.282	0.325

Table 1: Statistics on the differences between geoid estimates and GPS/levelling over Italy (after bias and tilt removal).

	Collocation (POLIMI)	Stokes-WG (AUTH)	KTH (GCM)	KTH (UZG)
#	1542	1542	1542	1542
Mean [m]	0.057	0.068	-0.838	0.166
St. Dev. [m]	0.128	0.128	0.127	0.135
Min [m]	-0.497	-0.448	-1.286	-0.326
Max [m]	0.574	0.507	-0.365	0.560
RMS [m]	0.140	0.145	0.838	0.214

Table 2: Statistics on the differences between geoid estimates and GPS/levelling over Greece.

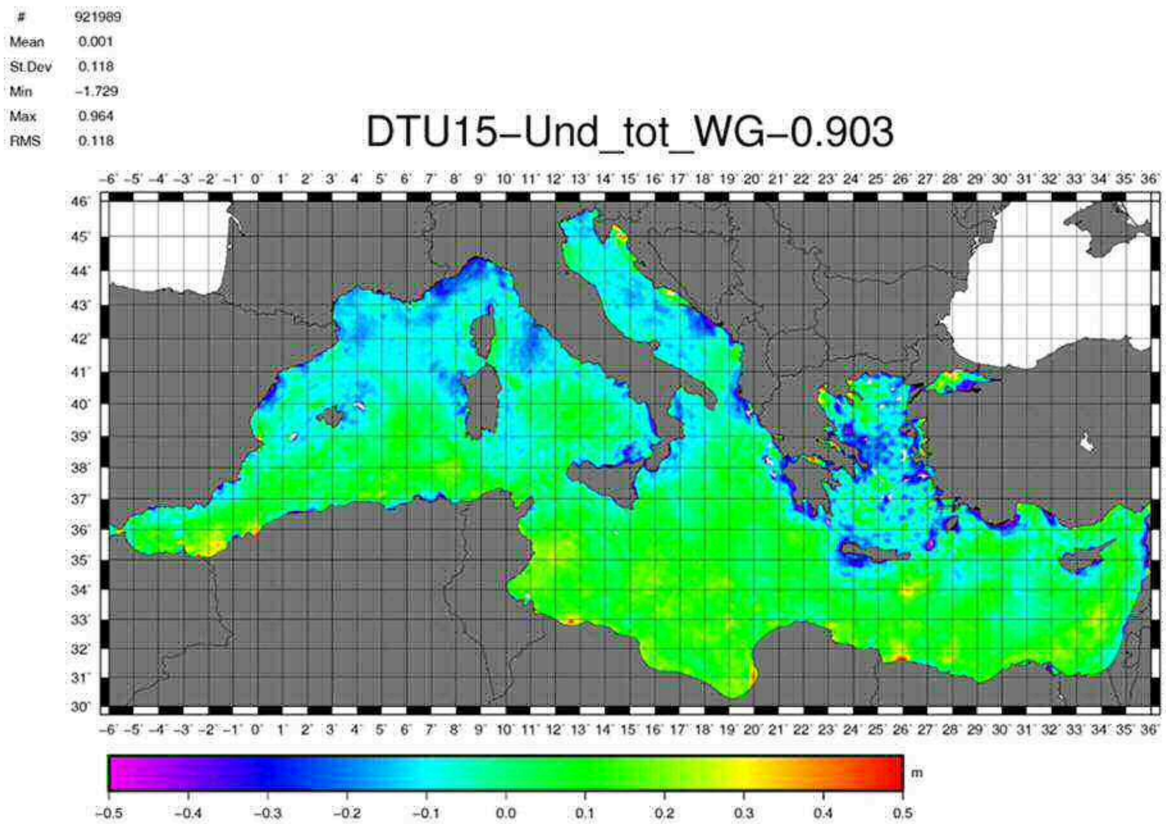


Fig. 3: Map of the differences between DTU15 and the solution obtained with the Wong-Gore modification of Stokes's kernel function (0.903 bias has been subtracted).

The new Italian gravimetric geoid (ITALGEO15) has been computed after a thorough revision of the available gravity database. The database has been homogenized in terms of horizontal and gravity reference systems and an outlier rejection has been performed mainly through local consistency checks.

This resulted in an improvement in the differences of the geoid with respect to the GPS/levelling data, after reference system adjustment, see Figure 4. The standard deviation of the differences decreases of two centimetres with respect to the previous release of the Italian geoid (ITALGEO05), see Table 3.

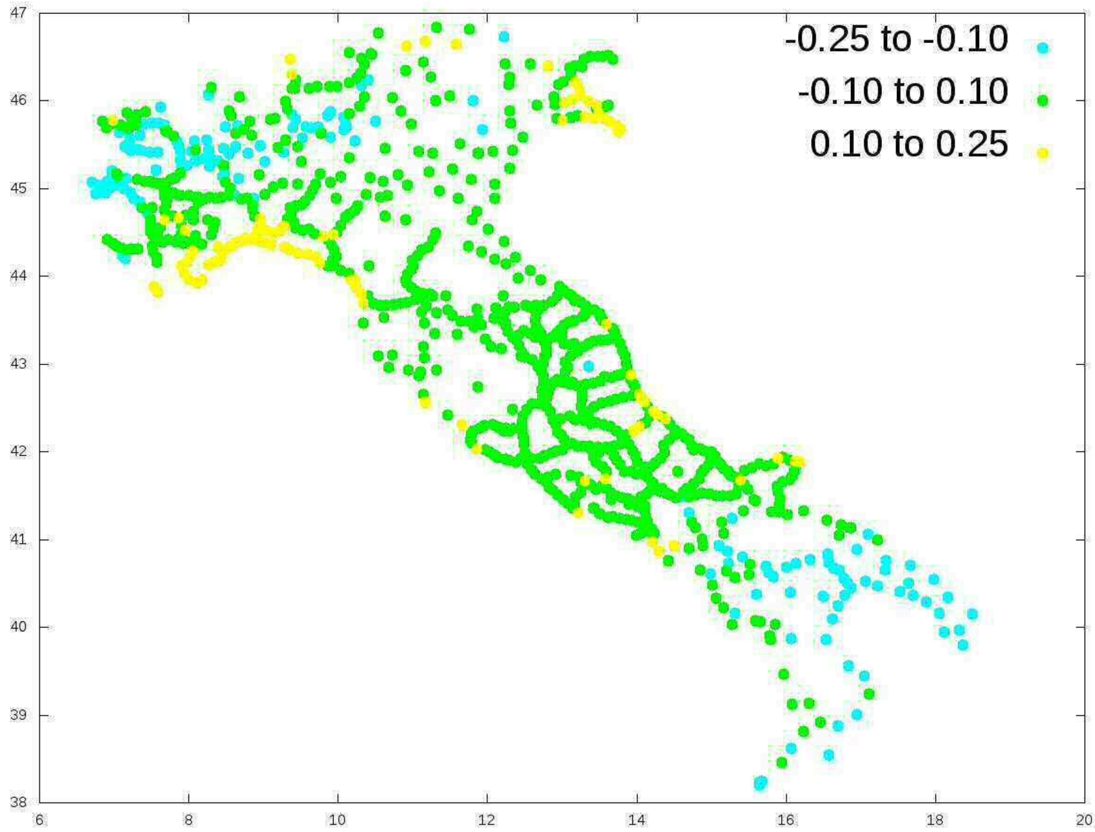


Fig. 4: Differences between GPS/levelling and ITALGEO15 gravimetric geoid after reference system adjustment (units in m).

	ITALGEO05	ITALGEO15
# Values	956	956
Mean [m]	0	0
St. Dev. [m]	0.114	0.090
Min [m]	-0.292	-0.235
Max [m]	0.294	0.235

Table 3: Statistics of the differences of ITALGEO05 and ITALGEO15 gravimetric geoids with respect to the GPS/levelling over the continental territory.

NOAA's National Geodetic Surveying is leading a geoid computation experiment over a test area in Colorado (USA). They have provided the participants with gravity data, both terrestrial and airborne, together with the DTM and GPS/levelling data. Fourteen research groups are contributing with their solutions. The performance of the computation can be assessed by every participant with respect to the GPS/levelling data and by NGS on a specific line with benchmarks which have not been distributed to the test participants.

One solution has been submitted to the test board, using the remove-restore approach, with collocation. As usual, some pre-processing has been performed to remove outliers or duplicates from the input data. For the time being, terrestrial data only have been considered. The gravity residuals have been obtained by removing the XGM2016 model up to degree and order 1000 and the residual terrain correction (Figure 5).

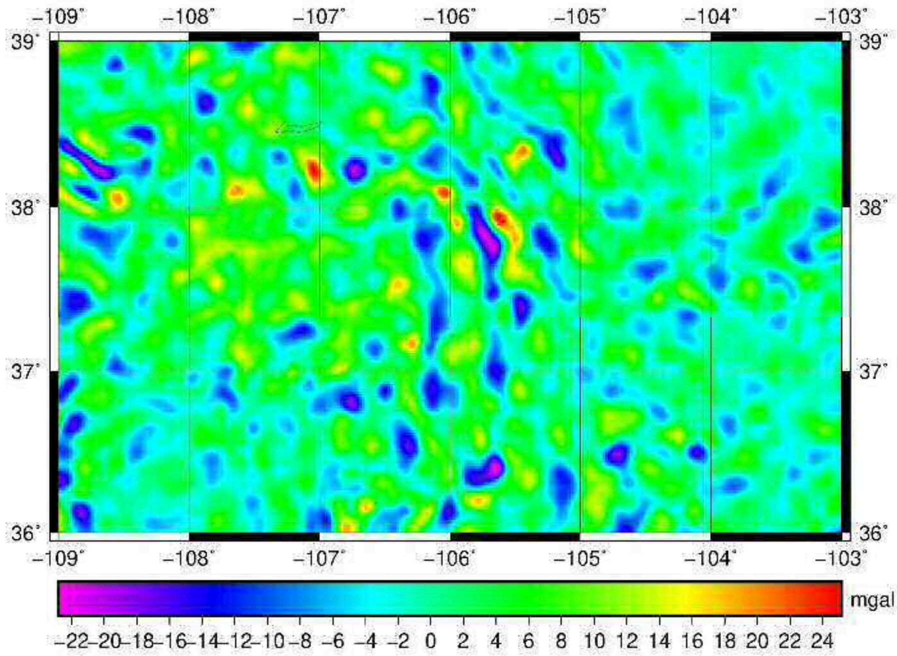


Fig. 5: Gravity residuals for NGS Colorado geoid computation experiment.

Applying collocation for geoid computation, the best performance has been obtained with a local approach, considering a moving window over the computation area and selecting only the data within a cap where the covariance function shows a significant data correlation.
Table 4 reports the statistics of the obtained geoid with respect to the GPS/levelling data which were provided to the participants. The results are consistent with the outcomes of the other participants, as well as for the benchmarks which NGS only could compute.

	Colorado
# Values	223
Mean [m]	0.187
St. Dev. [m]	0.094
Min [m]	0.004
Max [m]	0.336

Table 4: Statistics of the differences between the geoid heights computed by collocation and the ones from GPS/levelling data.

Merging of local geoid estimates

The large availability of local/regional geoid/quasigeoid models in the ISG archive fosters the study and the development of a merging strategy to produce unified models between neighbour countries. The proposed method consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining distortions along the national borders to better join the local geoid models. This investigation is performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2.

A preliminary test has been implemented on a subset of European models, including the following countries (the name of the used model in brackets):
- France (QGF98)
- Corsica (QGC02)
- Italy (ITALGEO05)
- Iberian Peninsula (IBERGEO2006)
- Belgium (BG03)
- Switzerland (CHGEO2004Q)
- Greece (GreekGeoid2010).

For each model, a subset of about 1000 points on land and inside the national borders has been selected for the bias and trend estimation. The digital terrain model (DTM) for each country has been derived from SRTM.

The reference geoid has been synthesized from the GOCO-05S satellite-only global model up to spherical harmonic degree and order 280 and has been then subtracted to the local solutions. Neither the contribution of global models at higher degrees, e.g. using EGM2008, nor a residual terrain correction (RTC) has been further subtracted to the geoid residuals.

The geoid commission error of the reference model has been modelled by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients, while the omission error above degree 280 has been modelled by using EGM2008 degree variances. A white noise with a standard deviation of 5 cm has been attributed to each local geoid model.

By using the computed geoid residuals and this stochastic modelling, a bias and a trend for each local model have been estimated by least-squares adjustment. The systematic effect *S* included into each local geoid has been modelled as follows:

$$S(\varphi,\lambda) = b_1 + b_2(\varphi - \varphi_0) + b_3 \cos\varphi(\lambda - \lambda_0)$$

where φ_0 and λ_0 are the mean latitude and longitude, respectively. The result of this adjustment is reported in Table 5. The estimated biases and trends are shown in Figure 6, while the residuals before and after the de-trending procedure are displayed in Figures 7 and 8.

	France	*Corsica*	*Italy*	*Iberia*	*Switzerland*	*Belgium*	*Greece*
$\hat{b}_1$	-1.067	0.344	0.246	-0.930	-0.617	-0.140	0.305
$\hat{b}_2$	1.466	21.090	-10.247	-1.826	-3.492	2.452	-0.733
$\hat{b}_3$	-4.753	-81.137	-0.873	-0.697	-2.379	-0.261	11.248
$\hat{\sigma}_{b_1}$	0.002	0.042	0.004	0.002	0.004	0.008	0.005
$\hat{\sigma}_{b_2}$	0.056	6.459	0.121	0.069	0.975	1.656	0.229
$\hat{\sigma}_{b_3}$	0.069	16.943	0.140	0.060	0.476	1.459	0.333

Table 5: Estimated biases and trends with their error standard deviations (units in m).

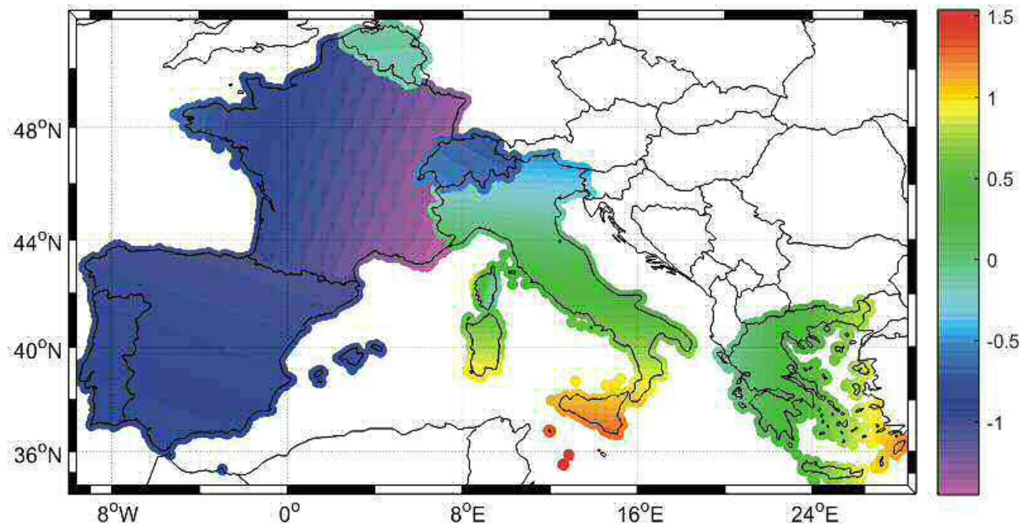


Fig. 6: Estimated biases and trends (units in m).

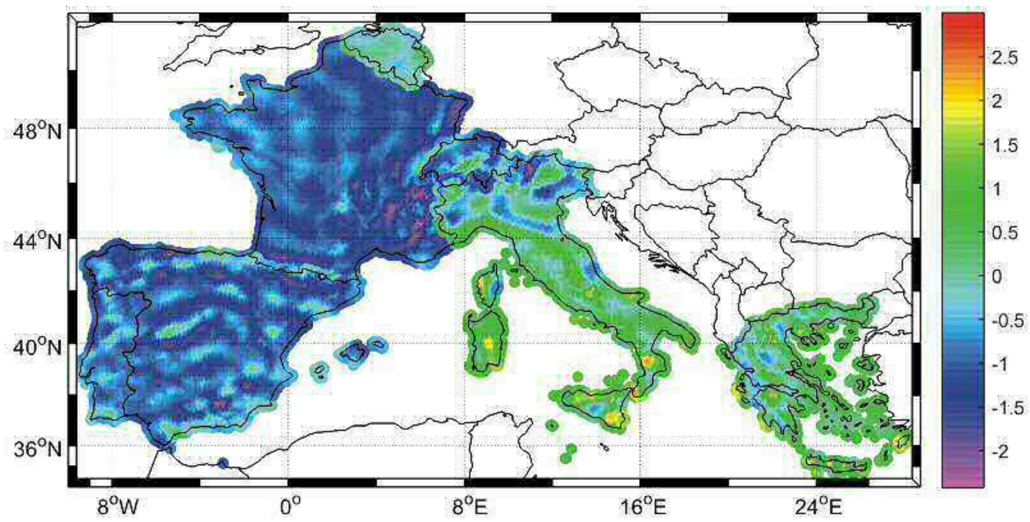


Fig. 7: Geoid residuals with respect of GOCO-05S before applying the de-trending procedure, i.e. as the models are stored in the ISG archive (units in m).

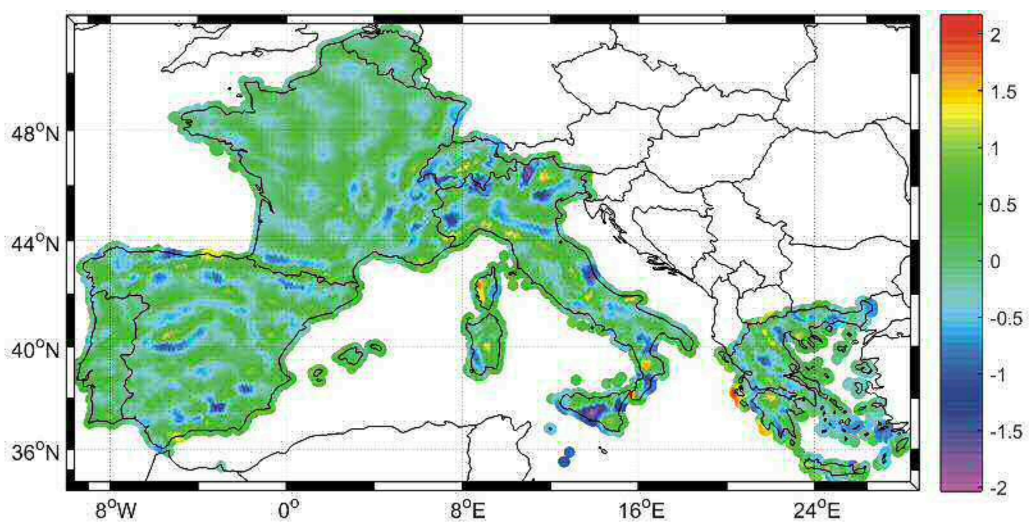


Fig. 8: Geoid residuals with respect of GOCO-05S after applying the de-trending procedure (units in m). Discontinuities at national borders are significantly reduced.

School organization and scientific support to researchers on geoid estimation

One of the main tasks of ISG consists in organizing or supporting technical schools on geoid estimation and related topics. The XII International IGS School was held in Mongolia from 6th to 10th June, 2016, at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar. This was the second geoid school held in Asia after the one in Johor-Baru, Malaysia, at the Department of Survey and Mapping, from 21st to 25th February, 2000.

The Local Organizing Committee (LOC) was composed by representatives from the following institutions/organizations:

- Mongolian University of Science and Technology (MUST),
- MonMap Engineering Services Co., Ltd,
- Mongolian Association of Geodesy, Photogrammetry and Cartography (MAGPC),
- Administration of Land Affairs, Geodesy and Cartography (ALAGAC),
- Ministry of Construction and Urban Development (MCUD).

A dedicated website was setup at the address: www.monmap.mn/geoidschool2016/ reaching more than 300 accesses by June. Over 100 online registration form submissions were collected, but many of willing participants from developing countries were not able to attend the school due to lack of budget and travel support. In the end, 30 participants coming from 9 different countries (Bhutan, China, India, Latvia, Mongolia, Philippines, Poland, Russia and Sri Lanka) attended the school, see Figure 9.

As usual, the program was structured to be self-contained for any participant at graduate level with basic knowledge of geodesy, including theoretical lectures and computer exercises based on the available software. The invited teachers were:

- Prof. F. Sansò, Politecnico di Milano, Italy,
- Prof. R. Barzaghi, Politecnico di Milano, Italy,
- Prof. M. Sideris, University of Calgary, Canada,
- Prof. R. Forsberg, National Space Institute, Denmark,
- Dr. S. Holmes, SGT Inc. USA.

The school program was the following:

- General theory on gravity field (6th June),
- The height datum unification (6th June),
- Terrain effect computation and remove/restore - theory and practical exercises (7th June),
- Residual geoid estimation - theory and practical exercises (8th June),
- Global geopotential models - theory and practical exercises (9th June),
- Presentations and case studies (10th June).

During the last day, a final session was given to summarize the school topics and distribute training certificates to the participants. Lecture notes of the courses were also distributed, as well as a CD-ROM containing software and data for exercises. The CD-ROM was freely distributed to the participants after a declaration of non-commercial use. An ice-breaker dinner and two sightseeing tours were organized by LOC, just before and after the school.

Apart from organizing the XII International Geoid School in Mongolia, in the last four years ISG provided educational activities and supported studies related to geoid estimation theory and in general to physical geodesy by hosting at Politecnico di Milano, Italy, the following students and researchers:

- A PhD student of the Center of Geodesy and Geodynamics of Nigeria, who is developing his thesis on the national gravity field estimation. For his studies he was hosted at Politecnico di Milano during two periods: 7-11 September 2015 and in spring 2016.

- A researcher of the Faculty of Petroleum and Renewable Energy and Earth Sciences at the University of Ouargla, Algeria. He was interested to the precise local geoid determination from the GRACE and SRTM satellite data with the aim of studying the tectonic activity in Algeria. He was hosted at Politecnico di Milano in autumn 2015.
- Two researchers of the Service of Surveying of the National Institute of Cartography of Cameroun, who came at Politecnico di Milano in November 2015 for a first training session on geoid computation. After that, they maintained frequent contacts with ISG staff, and a second training session took place again at Politecnico di Milano from 13 to 28 October 2017, this time involving three researchers. In this second session, they worked with data from Cameroun, considering all phases of geoid computation, including data pre-processing.
- A PhD student from the University of Curitiba, Brazil, who spent three months at Politecnico di Milano, from March to September 2016, developing studies on the height datum problem.
- A PhD student from the Technical University of Denmark (DTU), who spent three months at Politecnico di Milano, from October to December 2016, working together with ISG staff on radar-altimetry, gravimetry and gravity field estimation.
- Two academicians from Konya Selcuk University, Turkey, as well as a MSc student from Istanbul Technical University, Turkey, who spent one week at Politecnico di Milano in July 2018, attending a training course on geoid determination.

Usually, further contacts follow the hosting period, to strengthen the cooperation and to provide scientific support when researchers and students come back to their countries.

Fig. 9: Group photo of people organizing and attending the XII International IGS School.

ISG geoid repository and website update

In the last four years, the ISG archive of local/regional 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 in order to keep memory of the work done in the past and to allow for comparisons. The full (or the almost full) series of official geoid models are available for some countries, like US, Canada, Europe, Italy, France, Nordic-Baltic countries, Brazil, Japan, Australia, New Zealand. 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. Some models are classified as N/A if the data are not available to the service. More than 150 models are currently available in the ISG database, whose composition is reported in Tables 6, 7 and 8 (last update of the statistics was on 1st June 2019). The global coverage of the available gridded geoid models, together with their spatial resolution, is shown in Figure 10. Metadata of all models are managed through Data Citation Index by Clarivate Analytics and, therefore, the models are indexed by Web of Science.

Europe	74
North America	36
Asia	20
Africa	19
South America	14
Oceania	13
Antarctica	4
Arctic	3
Total	183

Table 6: Number of models per continent in the ISG archive.

< 1991	4
1991 – 1995	15
1996 – 2000	39
2001 – 2005	23
2006 – 2010	50
2011 – 2015	39
2016 – 2019	13
Total	183

Table 7: Number of models per year in the ISG archive.

Public	127
On-Demand	20
Private	20
N/A	16
Total	183

Table 8: Number of models per policy-rule in the ISG archive.

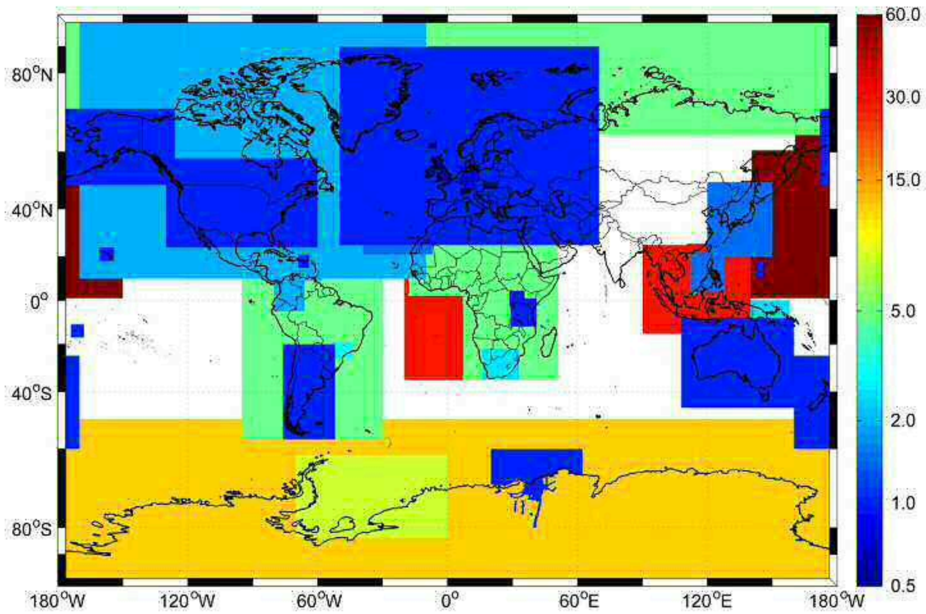


Fig. 10: Spatial coverage of the gridded geoid models available at ISG. Colourbar shows the highest spatial resolution per location (log10 scale, unit: arc-minutes).

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, the Web of Science ID and a model figure.

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, in the section dedicated to the geoid schools and in the one on the on-going projects. News section has been continuously kept up-to-date. No papers have been submitted to Newton's Bulletin in the last four years. The current home page of the ISG service is shown in Figure 11. Some statistics on the website access are displayed in Figure 12. A new webpage including statistics on the model downloads has been created (some examples of these statistics are reported in Figure 13).

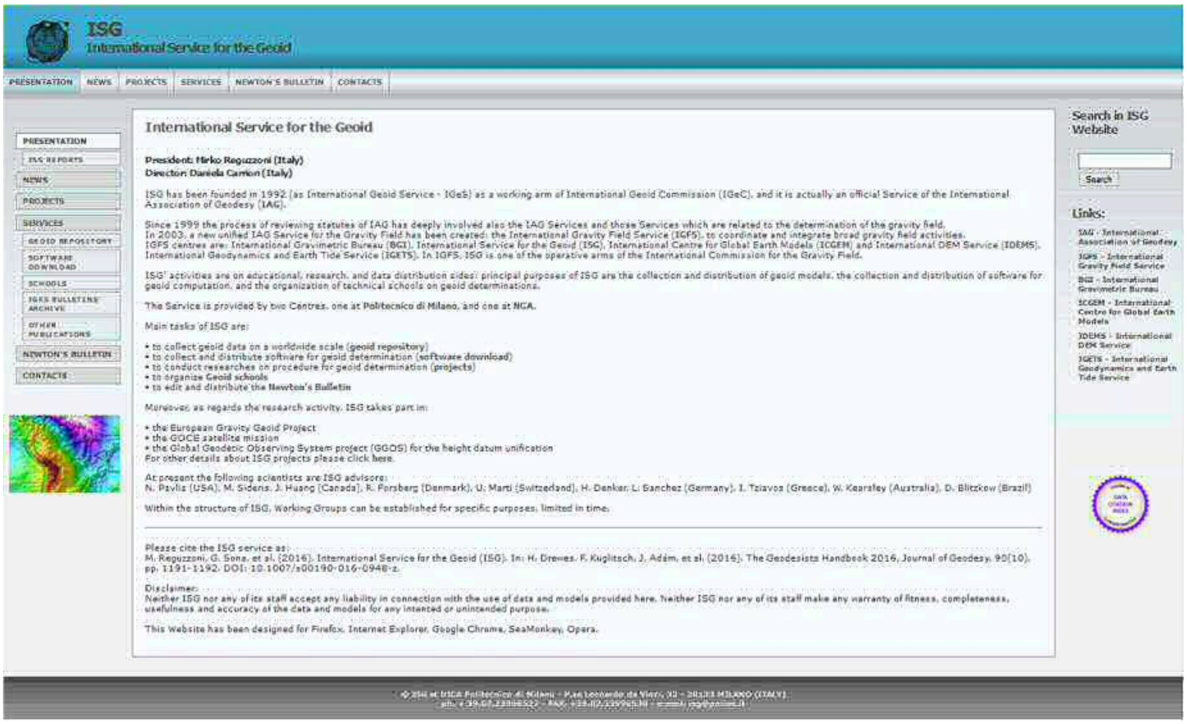


Fig. 11: Home page of the ISG website.

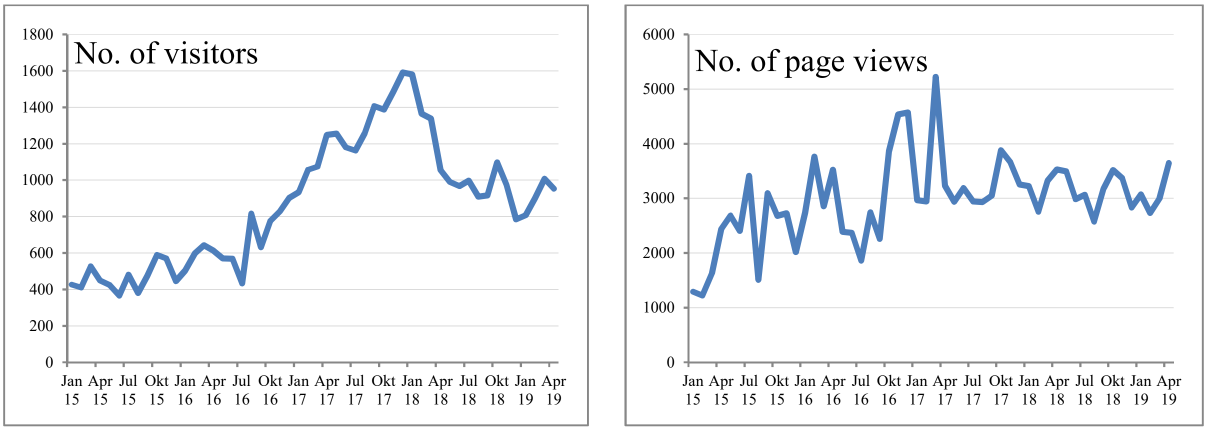


Fig. 12: Statistics on the number of visitors and page views of the ISG website.

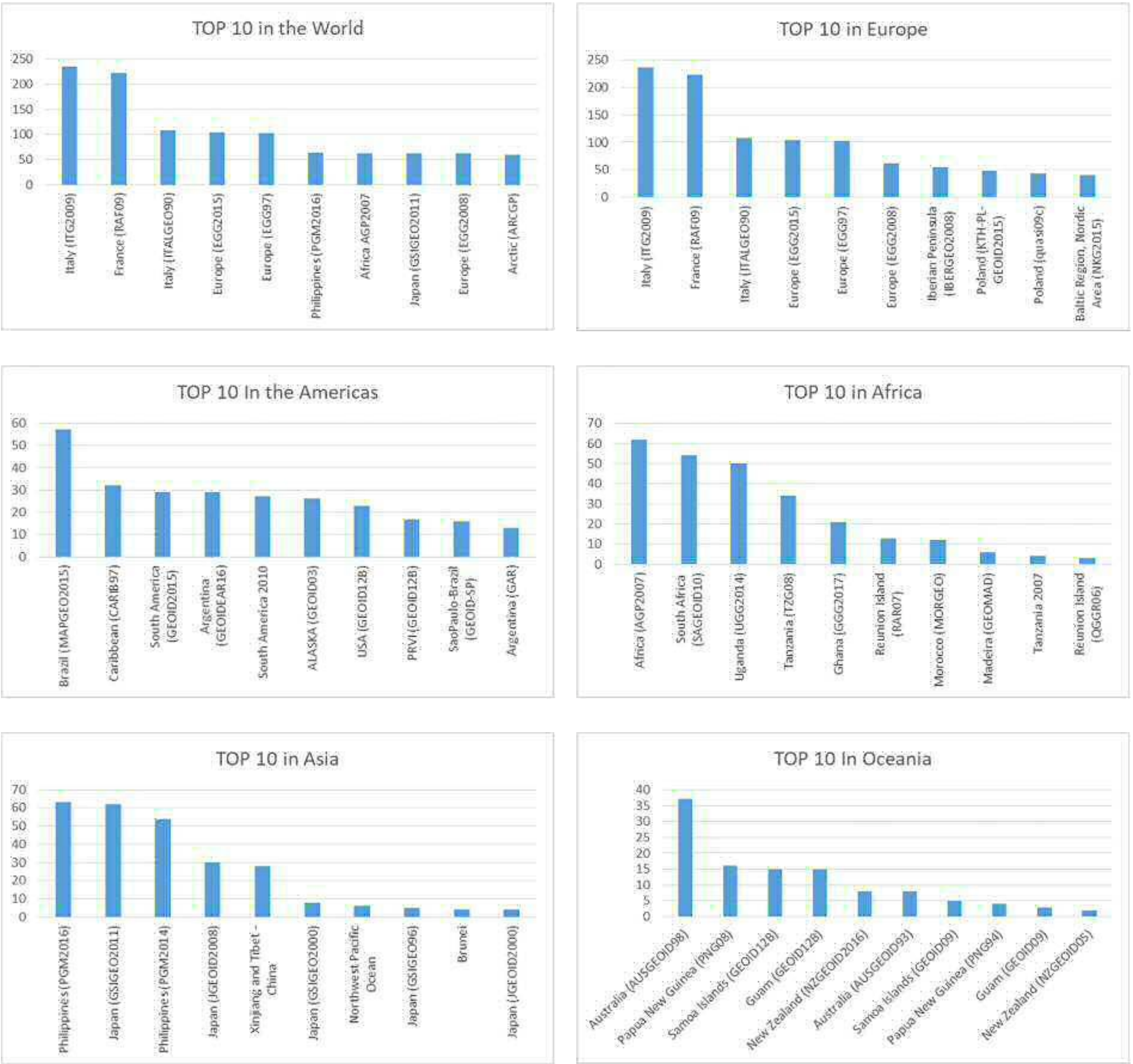


Fig. 13: Statistics on the most downloaded models from the ISG website since December 2017.

JWG 2.2.1: Integration and validation of local geoid estimates

Chair: *M. Reguzzoni (Italy)*
Vice Chair: *G. Vergos (Greece)*

Members:

- *G. Sona (Italy)*
- *R. Barzaghi (Italy)*
- *F. Barthelmes (Germany)*
- *M.F. Lalancette (France)*
- *T. Basic (Croatia)*
- *H. Yildiz (Turkey)*
- *N. Kuhtreiber (Austria)*
- *H. Abd-Elmotaal (Egypt)*
- *W. Featherstone (Australia)*
- *Jianliang Huang (Canada)*
- *Cheinway Hwang (Taiwan)*
- *Shuanggen Jin (China)*
- *G. Guimaraes (Brazil)*

Overview

A detailed description of the activities performed by this working group during the period 2015-2019 can be found in the report of the Sub-commission 2.2, also including numerical results and bibliographic references.

Permanent Service for Mean Sea Level (PSMSL)

http://www.psmsl.org

Outgoing Director: Lesley J. Rickards (UK)
Incoming Director: Elizabeth Bradshaw (UK)
National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK

Overview

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and also provides a wider Service to the sea level community. The PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is part of the National Oceanography Centre (NOC), Liverpool, with funding provided by the UK Natural Environment Research Council (a component of UK Research and Innovation). PSMSL operates under the auspices of the International Science Council (ISC) and in 2015 was accredited as a regular member of its World Data System. In 2018, PSMSL celebrated its 85th anniversary by hosting an international meeting. The "Sea Level Futures" Conference, attended by over 100 delegates from 65 international organisations, was dedicated to examining the current state-of-knowledge and future of sea level research.

The primary aim of the PSMSL is provision of the global data bank for long-term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last four years almost 10000 station-years of data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 70000 station-years. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), are responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly values and higher frequency) from the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (IOC's GLOSS) core network.

New and updated products have been made available over the last four years. These include: an improved relative sea level trends product by adding maps showing estimated seasonal cycles and number of years required to obtain a sea level trend of a given uncertainty; working with Système d'Observation du Niveau des Eaux Littorales (SONEL) to offer information about the geocentric height and rate of vertical movement of some tide gauges; updating some of the longest time series to account for the differences between Mean Tide Level (MTL) and mean sea level and adding a flag to indicate occurrence of MTL values; making data available from *in situ* ocean bottom pressure recorders from all possible sources; enhanced de-drifting code for ocean bottom pressure recorders added to website; development of automatic quality control software for tide gauge data.

PSMSL staff have continued to be active in a variety of international meetings, working groups, conferences and workshops over the last 2 years including those organised by the Global Geodetic Observing System (GGOS), IOC GLOSS, European Geophysical Union (EGU), EuroGOOS, and International Marine Data and Information Systems (IMDIS). In addition, PSMSL has answered many enquires relating to sea level and have appeared on radio and television discussing aspects of sea level change. PSMSL staff have also co-organised and contributed to tide gauge and sea level training courses. Annually statistics are collated on the number of peer-reviewed published papers that use the PSMSL dataset. Over the last six years there are over 400 papers in 116 distinct journals, and the number of citations has increased to around 70 citations per year.

1 Introduction

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and bottom pressure recorders. Established in 1933 by Joseph Proudman, who became its first Secretary, the PSMSL is responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges and also provides a wider Service to the sea level community. The PSMSL is part of the National Oceanography Centre (NOC) at Liverpool, and receives funded by the Natural Environment Research Council (NERC, a component of UK Research and Innovation).

The PSMSL reports to several bodies which operate under the auspices of the International Science Council (ISC) including the International Union of Geodesy and Geophysics (IUGG), the International Association for the Physical Sciences of the Oceans (IAPSO), including its Commission on Mean Sea Level and Tides (CMSLT). PSMSL is a service of the International Association of Geodesy (IAG) and contributes to the IAG Global Geodetic Observing System (GGOS). PSMSL also has a key role in the Intergovernmental Oceanographic Commission's (IOC's) Global Sea Level Observing System (GLOSS).

Towards the end of 2015, the PSMSL was accepted as a regular member of the International Science Council's World Data System (ISC-WDS). The ISC-WDS has a rigorous application process and PSMSL was very pleased to gain membership to this interdisciplinary body, showing that the PSMSL is regarded as a trustworthy facility in terms of authenticity, integrity, confidentiality and data availability and services. The goal of the ISC-WDS is to create and co-ordinate global 'communities of excellence' for scientific data services.

The primary aim of the PSMSL is the provision of the global databank for long-term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last four years almost 10000 station-years of mean sea level data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 70000 station-years from over 2350 stations. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), is responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly or higher frequency values) from the IOC's GLOSS Core Network.

The PSMSL database contains monthly and annual mean values of sea level. The dataset and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website (www.psmsl.org). Accompanying metadata includes station descriptions and their locations, types of instrumentation and, where available, frequency of data collection as well as notes on other issues of which users should be aware (e.g. earthquakes that are known to have occurred in the vicinity or subsidence due to local groundwater extraction). As ever, we are very grateful to our data suppliers (Annexes 1 and 2 list the countries and organisations which have supplied data during the reporting period). The PSMSL mailbox psmsl@noc.ac.uk responds to requests for information from national tide gauge agencies, decision makers (local councils, Parliamentary enquiries), the media and the general public.

2 Sea Level Futures Conference

PSMSL reached its 85th anniversary in 2018, and celebrated its long history of providing mean sea level records from tide gauges by hosting an international meeting. The "Sea Level Futures" Conference, attended by over 100 delegates (Figure 1) from 65 international organisations, was dedicated to examining the current state-of-knowledge of sea level research, and discussed the developments in observational networks and technology required over the next ten years to allow the community to continue enhancing understanding of global and regional sea level rise and variability.

Figure 1: Sea Level Futures Conference attendees

Current sea level science provides clear evidence that sea level is rising and this is already impacting coastal areas. Addressing the challenges for the coastal areas in a warming climate requires integrated, sustainable and continued observations, data products and advanced modelling capability. Conference participants recognised the need for close collaboration between scientists from different disciplines and the stakeholder community to develop a response to sea level change and implement measures to adapt to and mitigate its effects.

The key recommendations are summarised in a conference statement.

3 Prof. Philip Woodworth elected as an IUGG Fellow

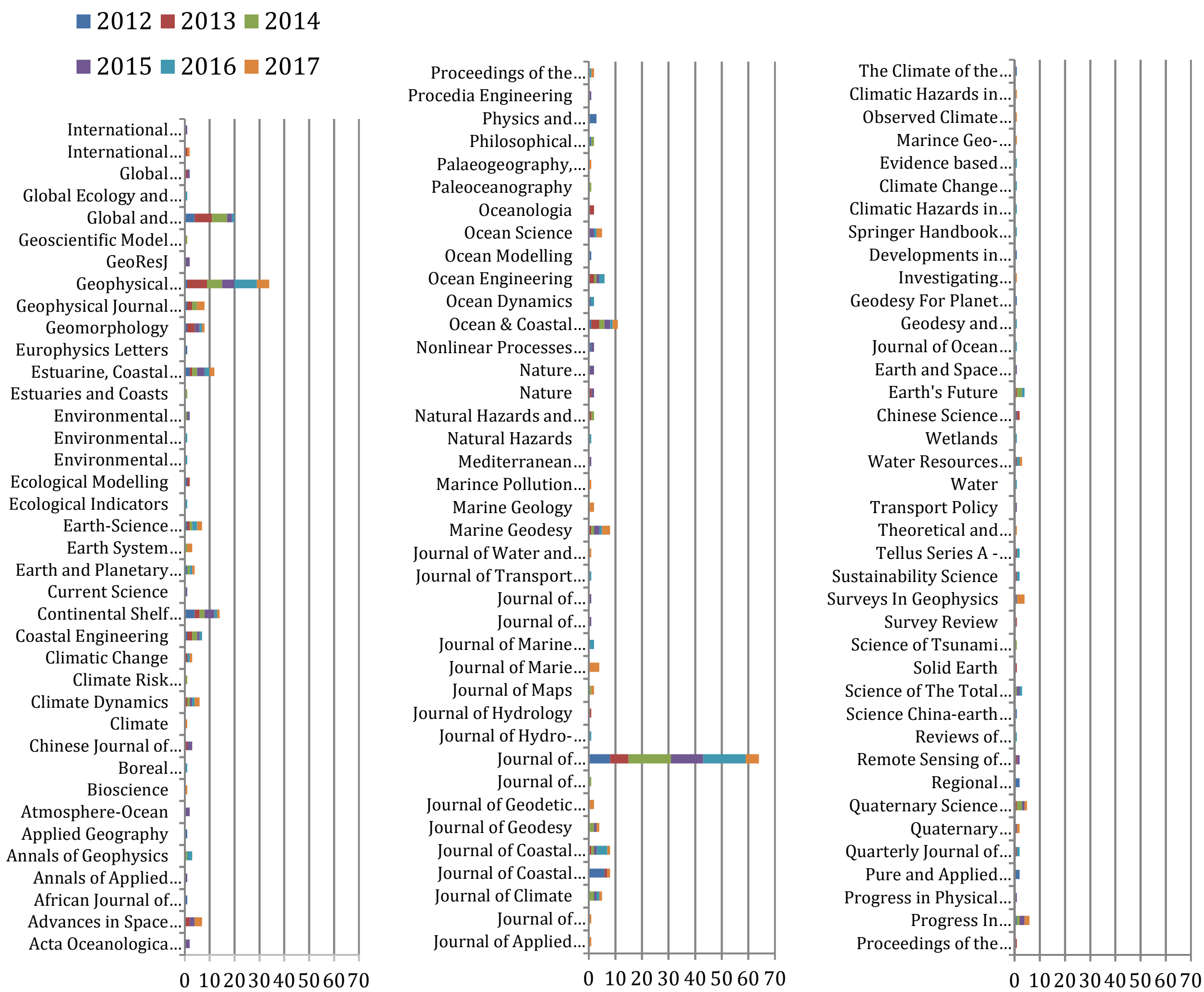
PSMSL is pleased to announce that Prof. Philip Woodworth has been elected as an IUGG Fellow – this will be formally bestowed by the IUGG President at the Award Ceremony of the XXVII IUGG General Assembly on 13 July 2019 in Montreal, Canada. Fellowship of the IUGG is a tribute, awarded by the IUGG Bureau, to individuals who have made exceptional contributions to international cooperation in geodesy or geophysics and attained eminence in the field of Earth and space sciences (IUGG by-law 22).

Prof. Woodworth was Director of the PSMSL for many years, and through promotion of the PSMSL and publications across a range of topics (underpinned by PSMSL data), he has contributed to research on sea level variability on a wide range of time scales. His work with rare historical data sets has put the changes seen during the 20th and 21st centuries into a long-term context, in particular helping to estimate acceleration of sea level rise. His work has benefited research and international communities in the fields of past sea level change, climate change, ocean circulation and tides, coastal processes, vertical crustal motions at coastlines, geology, geodesy and calibration of altimetry systems. He is currently an Emeritus Fellow of the National Oceanography Centre and Visiting Professor, Liverpool University School of Environmental Sciences.

His IUGG citation reads: "Woodworth, Philip (UK) for his significant advancement of sea-level science and outstanding contribution to international scientific cooperation, especially his leadership of the Permanent Service for Mean Sea Level (PSMSL)."

4 Number of Citations for PSMSL data series for the period 2012-2017

Annually PSMSL collates statistics on the number of peer-reviewed published papers that use the PSMSL dataset. We do this in a number of ways. Firstly, we find papers that have cited either Holgate *et al* [2013] or Woodworth and Player [2003] in Web of Science and Scopus. Not all papers will have cited either of these papers so we also perform full text searches for "PSMSL" or "Permanent Service". These papers are then manually filtered to remove any papers that are not actually referring to PSMSL. We note that it is very easy to miss papers that use our dataset but have not referred to us directly so our statistics are likely to be biased low. Figure 2 below shows the statistics for the last six years. There are over 400 papers in 116 distinct journals ranging from a variety of subject areas including oceanography, quaternary research, geodesy, climate, environment and multidisciplinary. The top three journals in terms of total publications are Global and Planetary Change (20; JCR impact factor 3.548); Geophysical Research Letters (34; JCR impact factor 4.456) and Journal of Geophysical Research (64; JCR impact factor 3.318). Other notable citations come from Nature (2; IF 38.138), Nature Communications (2; IF 11.329), PNAS (1; 9.423), and Reviews of Geophysics (1; 11.444). There were over 73 citations in journals with impact factors greater than 4.



401 papers in 6 years

2	Nature
2	Nature Communications
2	PNAS
5	Journal of Climate
1	Reviews of Geophysics
34	GRL
64	JGR

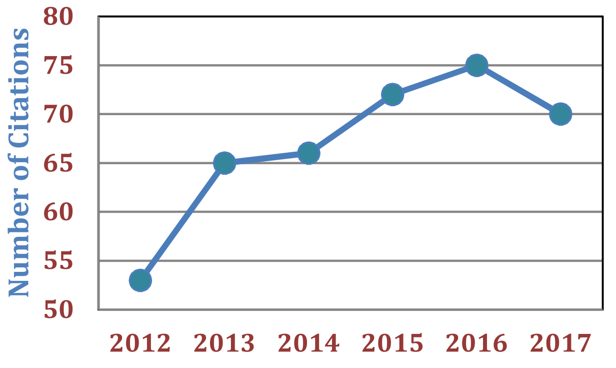


Figure 2: Statistics of PSMSL Data Set Citations

5 Mean Sea Level Data received

Figure 3 shows the amount of data received by the PSMSL since 2014 indicating how many station years have been added to the database each year and from how many stations. The number of active stations remains at about 800, but the number of station years can vary considerably from year to year. This may be due to a data provider reviewing and resupplying their historical dataset or if a backlog of data has been supplied.

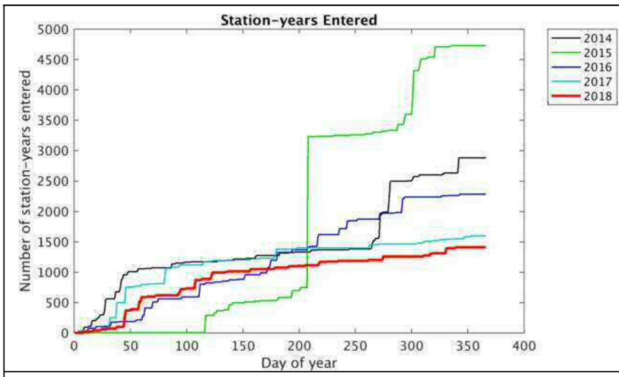


Figure3a: Number of station years added to the PSMSL database during 2014-2018

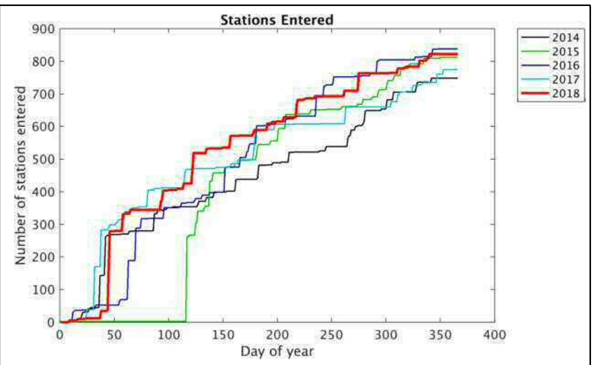


Figure 3b: Number of stations with data added to PSMSL database during 2014-2018

Figure 4 shows the stations which have provided data during 2018, or in 2017 (but not 2018). 815 stations have provided data in 2018, with a further 111 providing data in 2017. These can all be considered as active stations, but there are many stations for which no data have been supplied for many years. Some of these have undoubtedly ceased to operate; for others contact with the operators is being actively pursued. New stations are providing near-real-time data for tsunami monitoring, but a number of these do not yet supply quality controlled mean sea level values to the PSMSL; these are also being sought to add to the dataset.

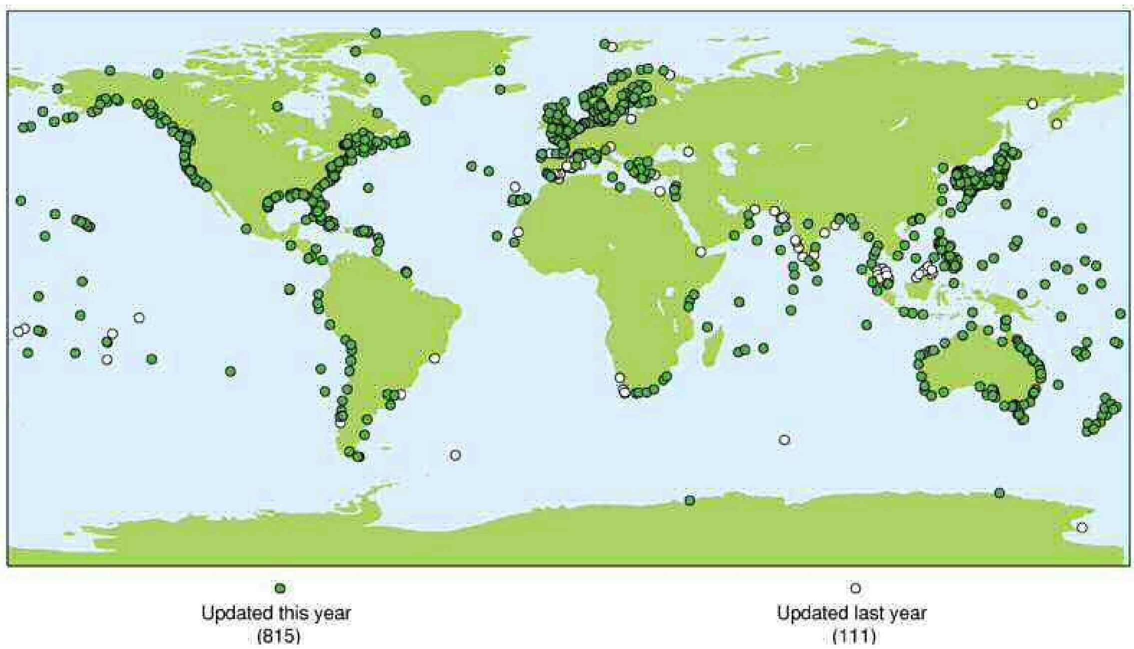


Figure 4: New data received by PSMSL during 2017-18

Figure 5 gives a more detailed view of the data held by PSMSL, indicating where data were supplied in the past – in particular, the decline in the number of stations in the Arctic is noticeable. However, many regions regularly supply mean sea level data (e.g. North America, Europe, Japan, Australia, New Zealand, South Africa, India), but there are still gaps in data receipts from the Arctic and Antarctic, parts of South East Asia, South and Central America, and Africa; these are presently being targeted to try to improve data flow. African countries received special attention through the Ocean Data and Information Network for Africa (ODINAfrica) projects and the Indian Ocean Tsunami Warning System (IOTWS), but many of these are no longer operating satisfactorily.

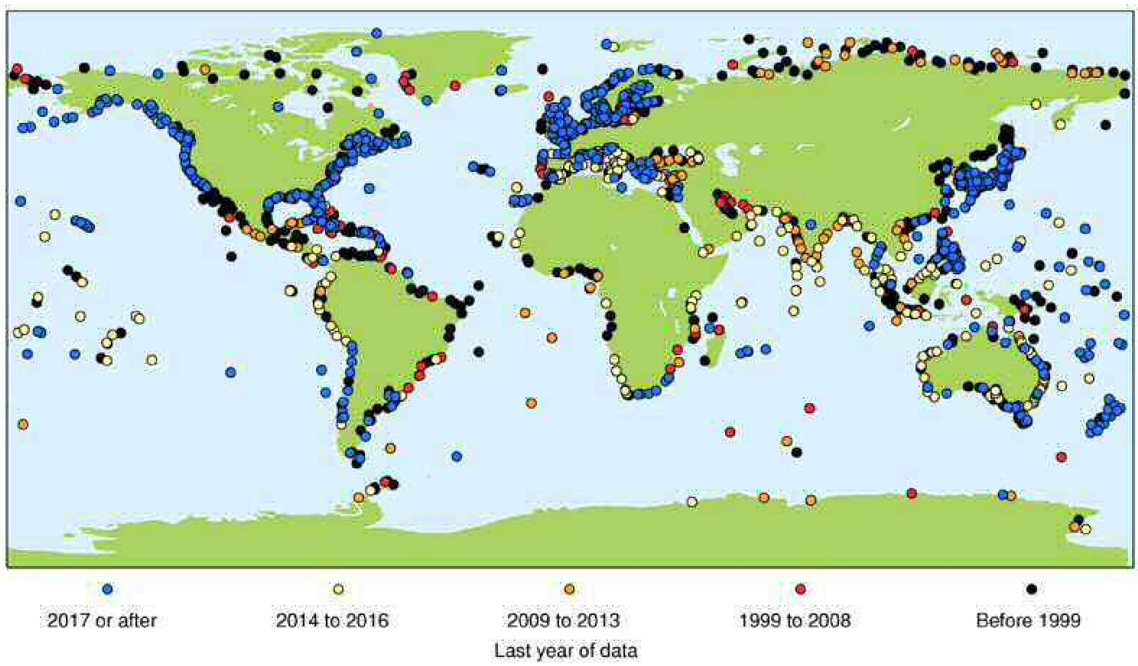


Figure 5: Year of most recent data received by PSMSL

In Figure 6 below, the uneven distribution of data supply is further illustrated; pale blue shows the data receipts from the Northern Hemisphere while the dark blue area of the plot shows the data receipts from the Southern Hemisphere.

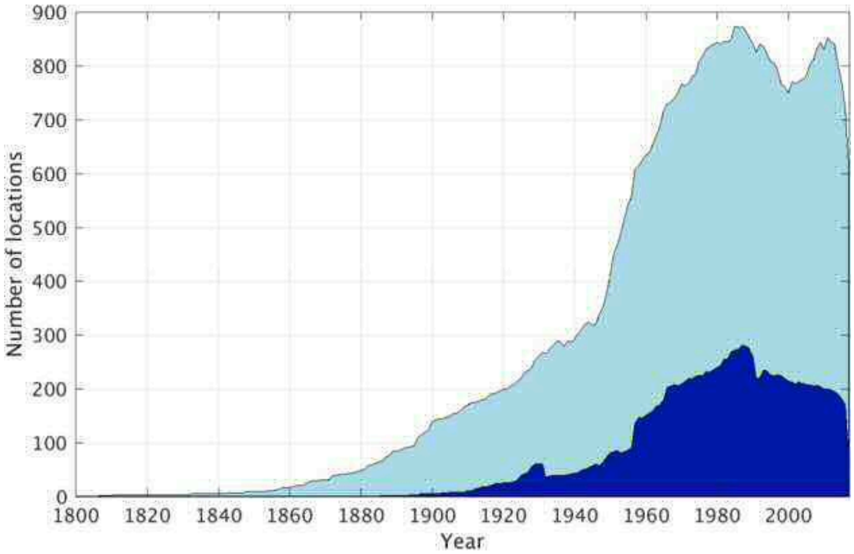


Figure 6: North-south hemisphere distribution of data received by PSMSL

The distribution of the longest time series also reflects this, as shown in Figure 7. The Southern Hemisphere has only a small number of time series of over 100 years; most are found in the Northern Hemisphere. Overall western Europe, North America and Japan have most of the longest records, and also have a high proportion of records of 50 to 100 years, although Australia, New Zealand, South Africa, Chile and Argentina also have a number of records of this length. The Arctic and Antarctic have very few records of greater than 50 years, and a number of the Russian Arctic tide gauges are no longer operational.

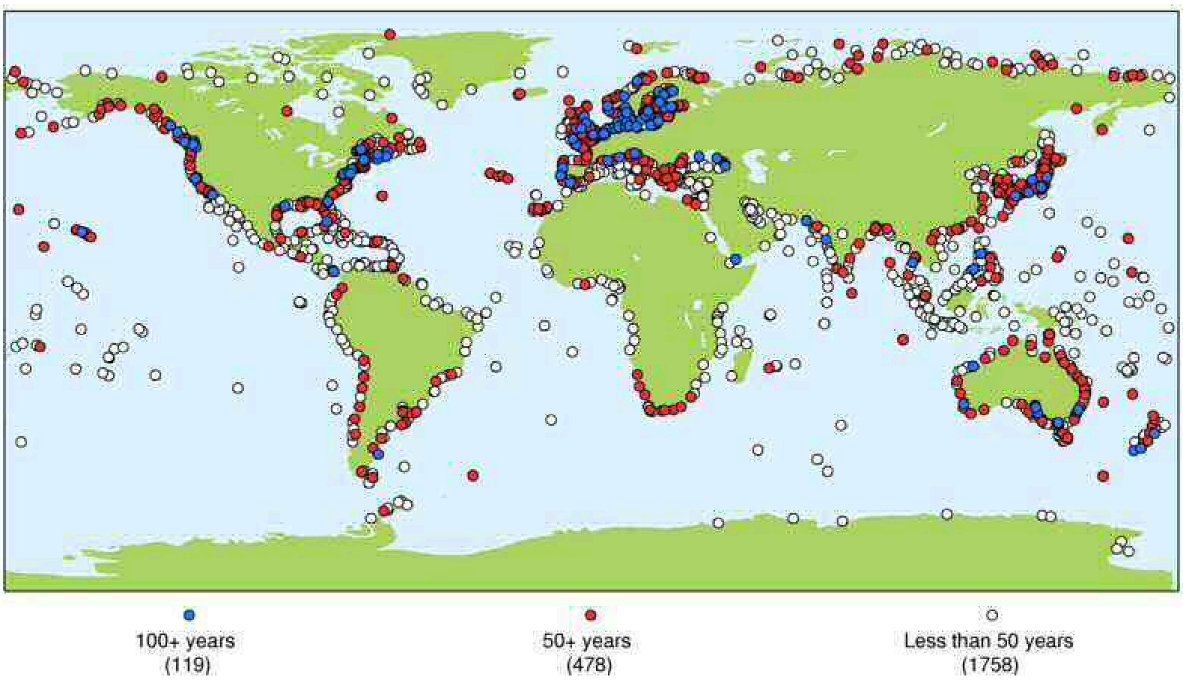


Figure 7: Distribution of long tide gauge records

6 Changes to Mean Sea Level Time Series with some Mean Tide Level values

PSMSL has introduced a change to some of the longest time series held in the database. In some older time series, the sea level values were reported as means of high and low waters, typically called Mean Tide Level (MTL). This is in contrast with the average of higher frequency readings taken over the entire tidal cycle, which is called Mean Sea Level (MSL). As these differ, this could introduce an artefact into estimates of the long-term trends where a time series includes both types of value. To improve transparency in these combined records, and to cause the minimum disruption to the current set of records, a flag has been introduced indicating MTL values in a MSL record and an estimate of the annual average difference (MTL-MSL) has been added to the Revised Local Reference (RLR) time series. More detail of the changes is available on the PSMSL website.

7 Author Archive

During 2016, Peter Hogarth has liaised with Prof. Philip Woodworth to work on some of the historic data series available through the PSMSL. As a result, he has recently published an article in Journal of Geophysical Research investigating acceleration of sea level rise. In the course of this research, he has extended the tide gauge time series available for several locations. He has made available to us his extensive notes and the additional data.

8 Global Sea Level Observing System (GLOSS) Core Network Status

The GLOSS was established by the IOC in 1985 to provide coordination for global and regional sea level networks in support of, and with direction from, the oceanographic and climate research communities. Various tide gauge networks have contributed to GLOSS, each with a different focus and each changing over time as research and operational priorities evolve.

The main component is the GLOSS Core Network (GCN), a global set of 290 tide gauge stations (Figure 8) that serves as the backbone of the global *in situ* sea level network. The network is designed to provide an approximately evenly distributed sampling of global coastal sea level variation. Ideally, each station should provide data on a variety of timescales for use in different applications; for example, real-time data can be useful for tsunami monitoring, whereas monthly and annual mean data can be used to monitor long-term changes in sea level. In addition, sites should also be fitted with GNSS equipment to monitor land movement at or near the site. Further information on GLOSS is available in the GLOSS Implementation Plan 2012 and on the GLOSS website (www.gloss-sealevel.org).

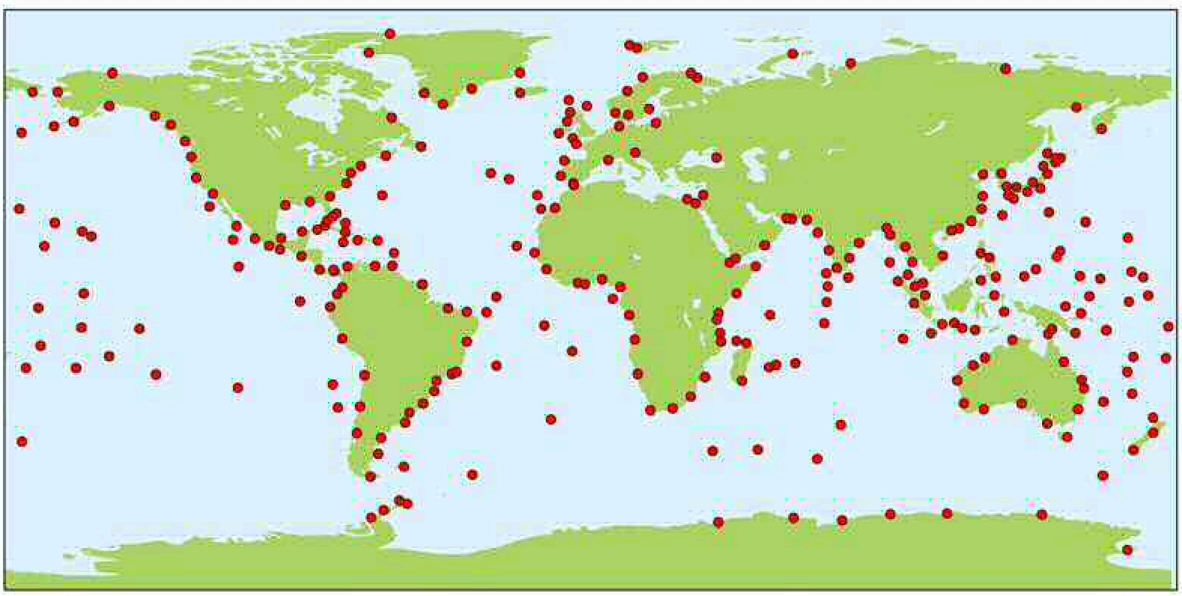


Figure 8: GLOSS Core Network

For many years PSMSL has produced maps showing the status of the Core Network from its perspective, and more recently has been generating additional maps, automatically updated weekly, showing the status for the other GLOSS data streams (e.g. real-time, fast-mode, delayed-mode and TIGA/GNSS). Figure 9 presents how PSMSL currently sees the status of the GLOSS Core Network. The map indicates whether a station is considered currently operational (green marker), has been operational in the past (orange marker), or has never operated successfully (white marker). Figure 10 shows the development of the GCN in terms of sites providing mean sea level data to the PSMSL from 1989 through to 2018 – a period of almost 30 years. The figure also includes changes to the definition of the GCN over time.

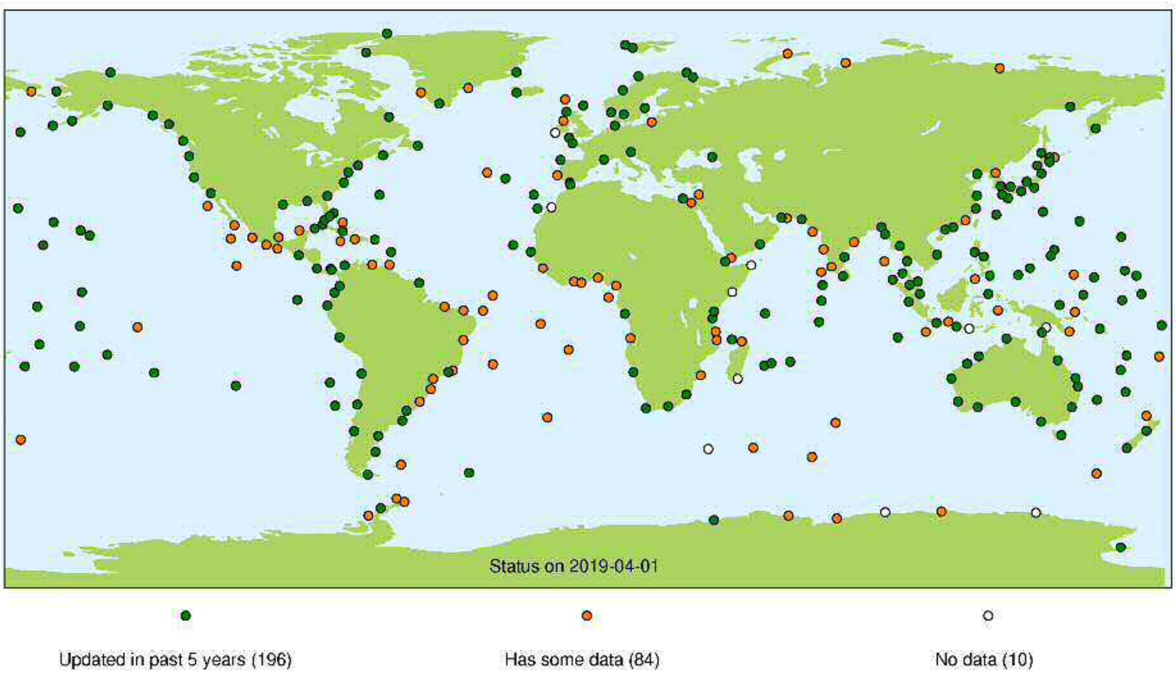


Figure 9: GLOSS Status from a PSMSL perspective

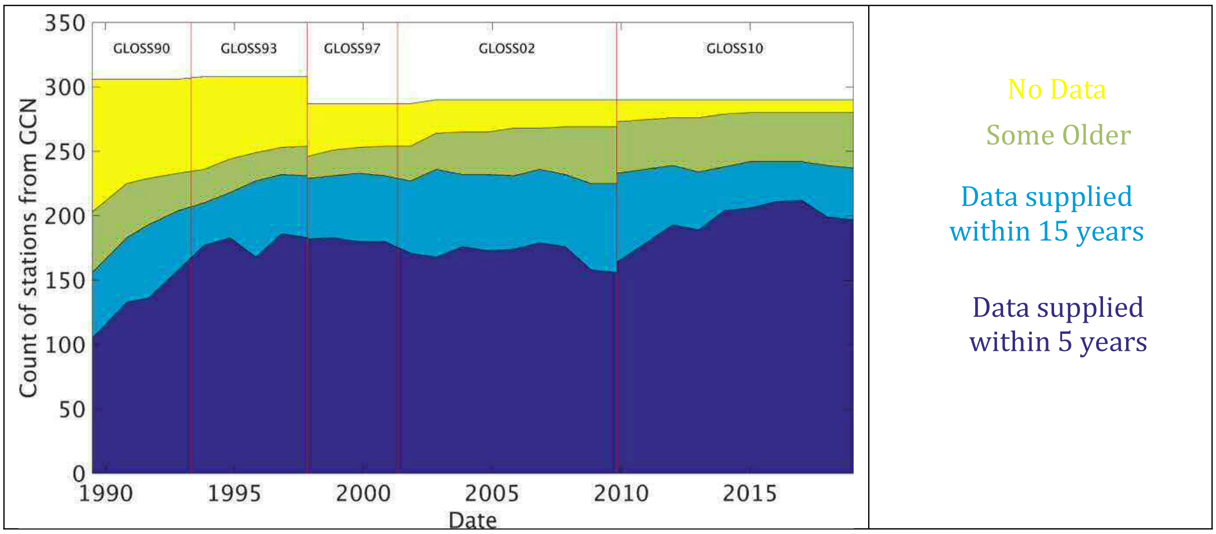


Figure 10: Status of GLOSS Core Network from a PSMSL perspective (1989-2018)

9 Data Archaeology in collaboration with GLOSS

PSMSL has taken the lead in data archaeology through the IOC GLOSS programme. The GLOSS data archaeology sub-group, under the leadership of Elizabeth Bradshaw, is collating tools and guidelines for the scanning, digitising and quality control of historical tide gauge charts and sea level ledgers. To further this effort she participated remotely in the Research Data Alliance (RDA) 10th Plenary Meeting in September 2017 including the Data Rescue Interest Group session and the 11th International Atmospheric Circulation Reconstructions over the Earth (ACRE) workshop (November 2018) where she gave a presentation on the status of GLOSS data rescue activities and links with the meteorological community.

Figure 11 shows some of the recent data rescue activities over the last 5 years. The red dots on the map are data recovered through data rescue activities. As well as numerous records in Europe, there have been newly digitised data from data sparse regions such as Dakar in Africa (36 years starting in 1902), St. Helena in the South Atlantic (1826 - 1827), Newcastle and Williamstown in Australia and Mawson and Cape Denison in Antarctica (months in the form of paper charts). In addition, Talke and Jay (2017) provides an update to the data rescue work carried out by Stefan Talke and team and includes sites not covered by the above map. Very recently PSMSL has received a dataset rescued from Porto Corsini/Marina di Ravenna, Italy (Bruni, S., et al, 2019).

However, many historical tide gauge data still exist in non-digital form. These mostly paper-based datasets are of great potential value to the sea level community for a range of applications, the most obvious being the extension of existing sea level time series as far back as possible in order to understand more completely the timescales of sea level change. In the future, coordination of a tide gauge data rescue project with ACRE programme could result in interesting synergies. The other major form of analogue sea level data is handwritten ledgers. Transcribing these is labour intensive and usually undertaken by people entering numbers by hand. GLOSS is exploring other methods for use in the future; one possibility is to have a Citizen Science approach as with the OldWeather project run in partnership with ACRE. An alternative approach is to investigate the adaption of Handwritten Text Recognition technology for use with handwritten tide gauge ledgers. Lack of funding and the time consuming nature of data rescue (manual digitisation, seeking accompanying metadata) continue to be barriers.

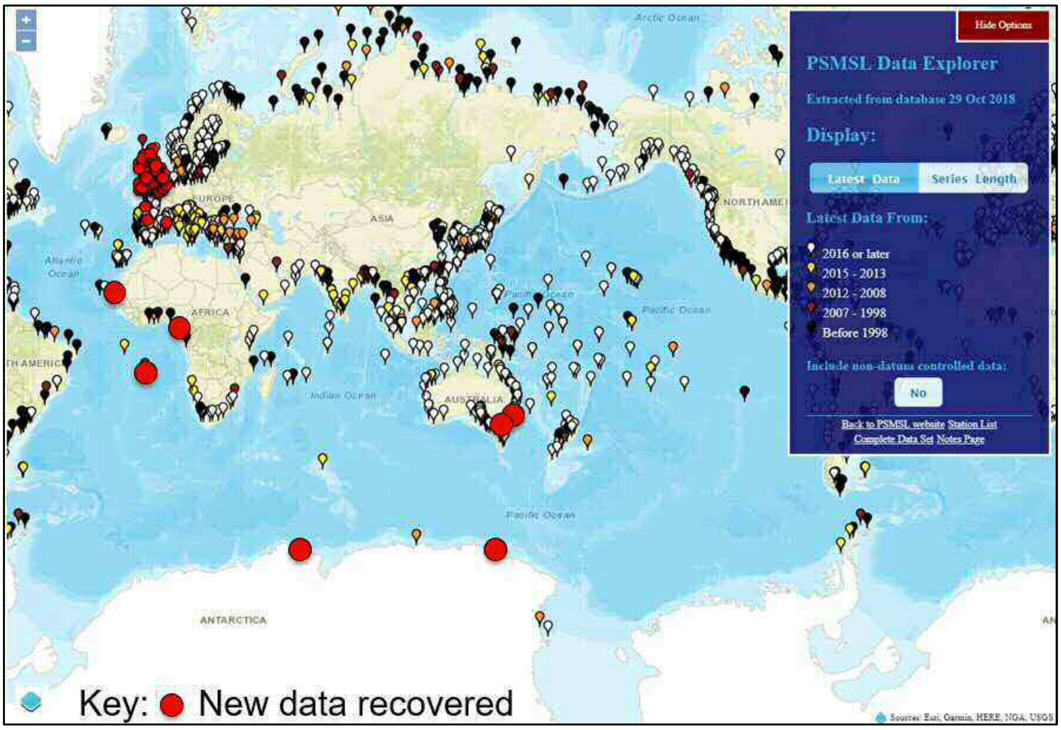


Figure 11: Sea level data rescue activities in the past 5 years

References:

Talke, S. and Jay, D., 2017. Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future. *Civil and Environmental Engineering Faculty Publications and Presentations*. 412.

Bruni, S., Zerbini, S., Raicich, F. and Errico, M., 2019. Rescue of the 1873–1922 high and low waters of the Porto Corsini/Marina di Ravenna (northern Adriatic, Italy) tide gauge. *Journal of Geodesy*, pp.1-18.

10 Global Extreme Sea Level Analysis (GESLA)

The Global Extreme Sea Level Analysis (GESLA) project grew out of the interest of several people in learning more about changes in the frequency and magnitude of extreme sea levels. The first GESLA dataset (GESLA-1) was assembled by Philip Woodworth (National Oceanography Centre, Liverpool), Melisa Menendez (University of Cantabria) and John Hunter (University of Tasmania) around 2009 and contained a quasi-global set of 'high frequency' (i.e. hourly or more frequent) measurements of sea level from tide gauges around the world.

GESLA-1 was used first in a study of sea level extremes by Woodworth and Menendez (JGR, 2010). It has since been used in a number of other published studies of extremes including the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

After some years it became apparent that GESLA-1 needed updating, which has resulted in the present GESLA-2 dataset comprising 37000 station years of information from 1300 stations (as of February 2016). The three original people have been joined in GESLA by Marta Marcos (University of the Balearic Islands) and Ivan Haigh (University of Southampton).

It can be seen that, while the study of extreme sea levels has been the main interest, the availability of as large a quasi-global sea level dataset as possible enables many other types of study, such as changes in ocean tides. The oceanographic community needs a global dataset such as GESLA, that is regularly updated and extended to include new historic data as it becomes available. Steps are underway to see how that might be accomplished in the future.

11 Developing a more structured and standardised approach to descriptive metadata

PSMSL has carried out a major redesign and reprogramming of its database. This has greatly expanded both the amount and level of structure within the metadata. In particular, the database now contains information about the links between the local tide gauges datums and national vertical datums. National vertical datums are linked to the EPSG registry, and will be linked to the ISO Geodetic Registry once it has been completed. Extra metadata from the database is gradually being added to the PSMSL website and distributed data files.

Soon the data will be released in netCDF format, which will make more of this structured metadata machine readable. In addition, PSMSL is working with other providers of tide gauge data to develop ways of distributing tide gauge data using internationally agreed standards.

12 Interactive map showing long-term trends

The web pages illustrating the trends in the tide gauge data set, as well as yearly variation of sea level with respect to an average (sea level anomalies), currently use the 10 Jan 2017 release of the data set. The interactive map showing fitted trends now uses a better statistical model that accounts for autocorrelation in the time series, allowing us to produce realistic estimates of error in the trends. There is also an estimate of the number of years required at each station to produce a trend with an uncertainty of 1.0, 0.5 and 0.1 mm/year.

Both the estimated trend and the uncertainty will change as one changes the time span chosen by moving the sliders. Secondly, in order to calculate these results, monthly means are now used instead of annual means. The trends also now use the corrected data which was measured using Mean Tide Level rather than Mean Sea Level. Example trend maps are shown below (Figure 12).

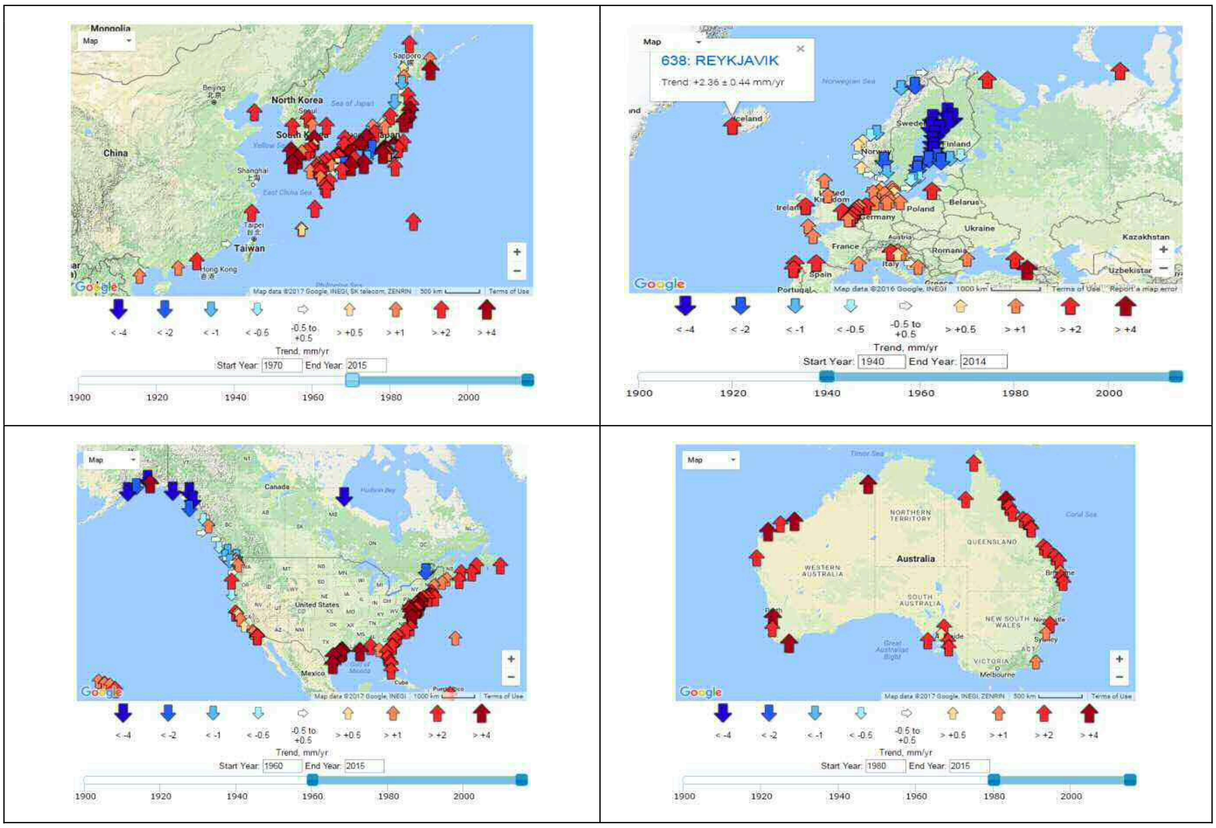


Figure 12. Interactive Relative Sea Level Trends Map

The relative sea level trends product has been further enhanced (Figure 13) by adding maps showing the estimated seasonal cycles and number of years required to obtain a sea level trend of a given uncertainty.

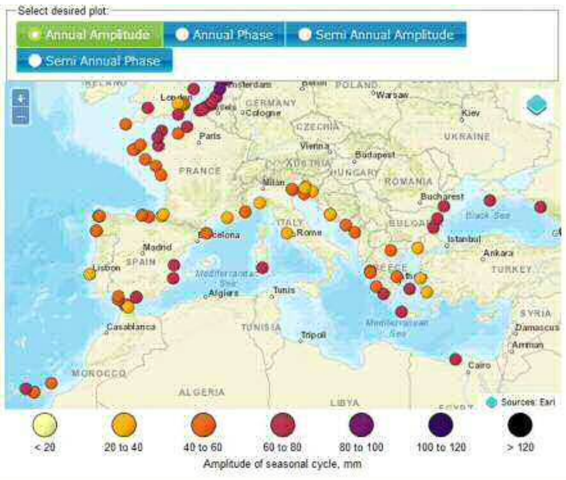


Figure 13a Estimated seasonal cycles

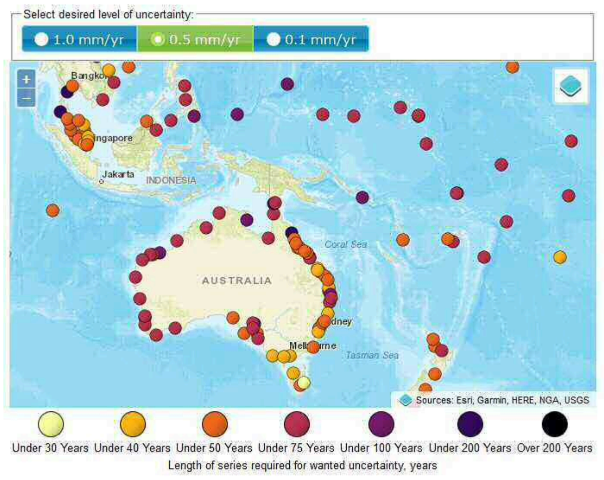


Figure 13b: Series length required for selected level of uncertainty

13 Ellipsoidal Links for Revised Local Reference Data

The mean sea level data distributed by PSMSL are heights above a local datum. For the Revised Local Reference (RLR) dataset, the stability of the local station datum is ensured by fixing its height to a geodetic benchmark assumed to be on reasonably stable ground. The measurements taken from tide gauges in this way are known as relative mean sea level; height is measured relative to the local land. As a result, the data can be affected by vertical movement of the land.

For some analyses we may wish to attempt to remove the land movement signal from the tide gauge record, for example, for reconstruction of historical global mean sea level, or to compare sea level measured by tide gauges with sea level measured by satellite altimetry. One solution to both of these cases is to use continuous Global Navigation Satellite System (GNSS) measurements from a receiver located near the tide gauge. The GNSS receiver measures heights relative to an ellipsoid and can be used to estimate the rate of vertical movement of the local land mass. The tide gauge datum can be associated with these estimates if routine geodetic levelling campaigns are carried out between the tide gauge benchmark and the GNSS receiver.

PSMSL continues to work with Système d'Observation du Niveau des Eaux Littorales (SONEL), the GLOSS data centre for GNSS measurements, to offer information about the geocentric height and vertical rate of movement of some tide gauges. These estimates are dependent on linking the tide gauge's primary benchmark with the GNSS receiver through levelling. As a result, these are currently only available at small subset of stations. The details of the link are shown on the station's RLR diagram page and a fuller description of the work is available here. The reference ellipsoid used for the University of La Rochelle GPS solutions is GRS80. The available information has been improved using feedback from users: for example, we have created a table of all sites where a tie has been established.

14 Release of Bottom Pressure Recorder de-drifting code

As requested by IAPSO, PSMSL archives bottom pressure recorder data. When bottom pressure recorders are deployed, readings drift over time. It is impractical to recalibrate the instrument mid-deployment, so an estimate of the drift must be removed before the data can be used.

The common approach has been to fit a short-term exponential drift, combined with a longer-term linear drift. However, the accuracy of this fitted drift can be improved by first removing all known annual or longer period fluctuations, such as changes due to the pole tide. As part of a recent project, software has been developed which attempts to improve de-drifting by removing these fluctuations.

The PSMSL website now contains a link to the Matlab code developed: this code will have wider uses, as it includes functions to can calculate the long-period equilibrium tides and the polar tide. Please note that this technique cannot separate instrumental drift from any other secular trend, so recorders subject to this drift cannot be used to derive sea-level trends.

15 Development on automatic quality control software

The PSMSL continues to be involved with developing training information and organising training courses, for operators of tide gauges and users of their datasets. As part of a project funded by the UK Foreign and Commonwealth Office supporting small island states, PSMSL were tasked with developing prototypes for automatic quality control software for tide gauges, and a simple data portal for distributing tide gauge data and sea level information.

The outputs are now available at https://psmsl.org/cme. The automatic quality control software uses MATLAB, and includes code to carry out tidal analysis and create tidal predictions. We have plans to keep developing the quality control software in the future, including creating a version in Python.

Figure 14 illustrates the data plotter outputs of the quality control process. The user can select output from one of three tide gauges in the Windward Islands, and choose to display hourly data (maximum one year), hourly data with the fitted tide removed, or daily means. Display options are unprocessed data (data before the quality control is applied), automatically quality controlled data, and a "composite best channel" option, where the algorithm combines output flagged good from all available sensors at a site into a single series. An estimate of the fitted tide is included if hourly and quality control data options are selected.

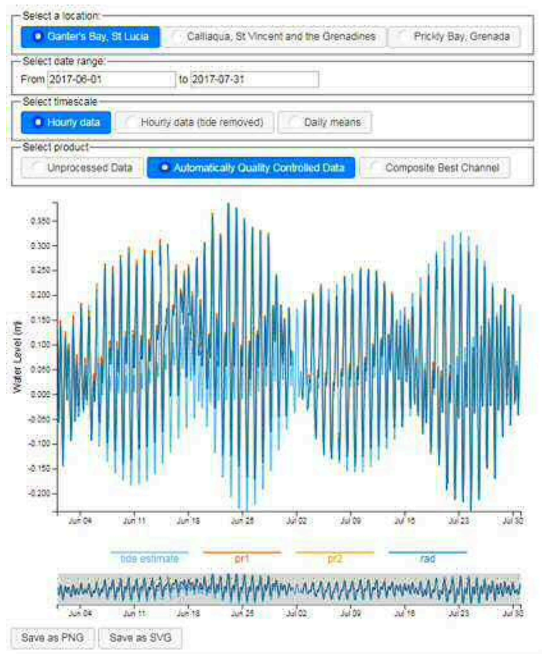


Figure 14: Data plotter output of the automatic quality control process

The plot can be zoomed and panned using a mouse, or by resizing the grey rectangle in the small overview plot at the bottom of the figure. The image can be saved in raster (.png) or vector (.svg) formats using the buttons at the bottom of the plot.

16 Ground based GNSS - Multipath Reflectometry (GNSS-MR)

Simon Williams has been involved in recent studies that have demonstrated the utility of ground based GNSS Multipath Reflectometry (GNSS-MR) for sea level studies. GNSS receivers suffer from multipath (Figure 15), but if the physical and geometric effects multipath has on the measured signals are understood then this knowledge can be used to measure other environmental parameters.

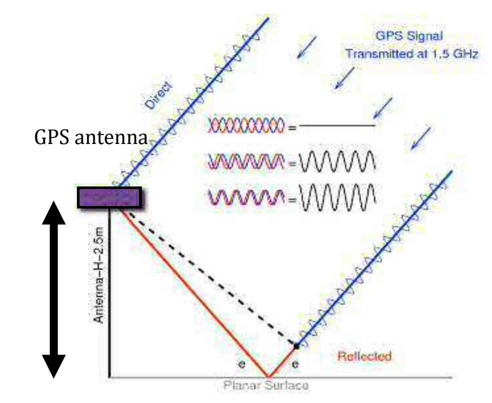


Figure 15: GNSS-MR Schematic

Two Current Projects are underway on GNSS-Multipath Reflectometry:

1. Comparison of GNSS-MR and Satellite Altimetry (GOCE++ CCN), with DTU, Denmark

   This is an example from one of the first "accidental" sites (i.e. not installed to do this), Peterson Bay in Alaska. There are three signals from different satellites passing over at different tidal states: low tide (so closer to the antenna), mid-tide and high tide, further from the antenna. We see that we have different frequencies – higher frequency for a larger reflector height. These signals can be taken and run through a Lomb-Scargle periodogram (power spectrum) and pick the peak – which is the reflector height. Conclusions so far indicate that ground based GNSS-MR using pre-existing geodetic quality equipment can measure sea level remotely with a daily accuracy of around 2-3 cm and a monthly accuracy of about 1-2 cm. There is some bias in the results – probably due to the antenna phase centre.

2. LocTIPS: Low Cost GNSS Tide & Sea Level Measurements for Inter-tidal Public Safety (with co-workers at NOC)

   A recent NERC-funded proof of concept award has successfully demonstrated that GNSS signals reflected off the sea surface and received by very low cost (£100) receivers can be used to estimate the difference in height between the receiver and the water rather than a geodetic quality one (~£10k) – with an antenna designed to reduce multipath. This represents a method of remotely sensing tidal elevations and, if averaged over time, mean sea level. This project is in collaboration with the Royal National Lifeboat Institution (RNLI) to provide tidal information for predicting when people can safely travel to and from Coney Island, Sligo, Ireland, over the strand (beach). The results so far compare well with tide gauge measurements (Figure 16). Results look favourable with an accuracy similar to that of the geodetic receivers. There is also the potential to measure other environmental variables (e.g. wave height, beach profiles).

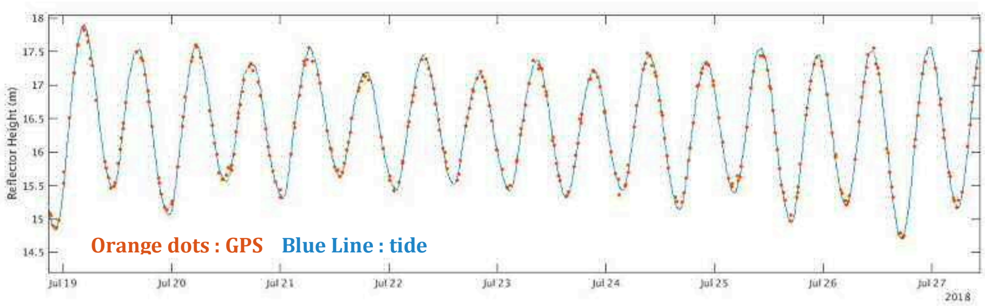


Figure 16: GNSS-MR results compared to tide gauge observations

17 PSMSL Staff and Advisory Group

Primary funding for PSMSL comes from NERC *via* the NOC; other projects provide small amounts of funding. Between 2015 and 2016 this has been approximately equivalent to 3 full time staff, but during 2017 and 2018 this decreased to the equivalent of 2 full time staff, however in reality all of those listed in the table below have contributed to PSMSL. As ever, we are grateful to others in the NOC Sea Level and Technology Groups who contribute to, or represent PSMSL at, meetings, conferences, or other fora. We have said goodbye to Mark Tamisiea who left PSMSL has returned to the USA. During his time with us, he made a considerable contribution to PSMSL and he will be missed. However, he has generously continued to represent PSMSL at some GGOS meetings.

Dr. Lesley Rickards, Director	Dr. Angela Hibbert, Capacity building
Mrs. Kathy Gordon, Data Manager	Dr. Svetlana Jevrejeva, Principal Scientist
Dr. Andrew Matthews, Data Scientist	Dr. Simon Williams, Senior Scientist
Miss Elizabeth Bradshaw, Data Scientist, BODC	Prof. Philip Woodworth, Scientific Advisor

Lesley Rickards, who has been PSMSL Director since 2007, has recently stepped down from this role. She is replaced by Elizabeth Bradshaw, who has worked alongside the PSMSL for many years. Kathy Gordon and Andrew Matthews continue in their current roles and Svetlana Jevrejeva has continued to act as the principle PSMSL scientist. However, she is just starting a two year sabbatical at the Centre for Climate Research of Singapore.

The PSMSL is also served by an Advisory Group which at present consists of: Dr. R. Neilan (JPL, USA), Prof. G. Mitchum (University of South Florida, USA), Dr. Guy Wöppelmann (Université de La Rochelle, France), Dr. P. Knudsen (Danish National Space Institute), Dr. R. Bingley (Nottingham University, UK), Dr. Begoña Perez Gomez (Puerto del Estados, Spain), Dr. Mark Tamisea (University of Texas, USA), and Dr. Thorkild Aarup (IOC, UNESCO).

18 Summary and forward look

PSMSL has continued to be active over the last four years with regard to important workshops and conferences, and busy with regard to data acquisition and analysis. The functions provided by the PSMSL are in as much demand as ever, and new products continue to be developed and activities have expanded. Future plans include:

- Improved integration of the mean sea level data set with sources of higher frequency data and improving the quality of accompanying metadata;
- Continued development of interoperable metadata formats for tide gauge data;
- Assess whether PSMSL follows FAIR data principles (Findable, Accessible, Interoperable, Reusable), and improve areas where we do not;
- Keeping contact with data suppliers (the trend being to acquire data from websites rather than direct supply) and ensuring that data made available in real-time are also contributed to PSMSL;
- Mint a digital object identifier (DOI) for the PSMSL dataset (in collaboration with BODC);
- Development of protocols concerning how sea level data recovered from historical records can be incorporated into the PSMSL dataset;
- Continue collaboration with SONEL (IAG TIGA Working Group data centre) and with GGOS;
- More information on the website about links between tide gauge datums and national datums and ellipsoids - available in both human and machine readable formats, using internationally agreed standards;
- Plan incorporation of sea level records measured using GNSS reflectometry into the PSMSL
- Contribute to ISC World Data System metadata catalogue and training pages
- Creation of software for automatic first level quality control of high frequency data
- Redesign and update of the content on the PSMSL website;
- Further develop data archaeology with the Group of Experts on GLOSS.

Annex 1: Stations received from individual countries 2015-2019

American Samoa		Malta
Antarctica		Marshall Islands
Argentina		Martinique
Australia		Mauritius
Bahamas		Mayotte
Bangladesh		Mexico
Belgium		Micronesia, Federated States of
Bermuda		Monaco
British Indian Ocean Territory		Myanmar
Canada		Namibia
Cape Verde		Nauru
Chile		Netherlands
China		New Caledonia
Cocos (Keeling) Islands		New Zealand
Colombia		Northern Mariana Islands
Cook Islands		Norway
Costa Rica		Oman
Croatia		Palau
Cuba		Panama
Curaçao		Papua New Guinea
Denmark		Peru
Dominica		Philippines
Dominican Republic		Portugal
Ecuador		Puerto Rico
El Salvador		Réunion
Fiji		Russian Federation
France		Saint Pierre and Miquelon
French Guiana		Samoa
French Polynesia		Senegal
Georgia		Seychelles
Germany		Singapore
Greece		Solomon Islands
Greenland		South Africa
Grenada		South Georgia & South Sandwich Is.
Guadeloupe		Spain
Guam		Sri Lanka
Haiti		Svalbard and Jan Mayen
Hong Kong		Sweden
Iceland		Tanzania, United Republic of
India		Thailand
Indonesia		Tonga
Isle of Man		Tuvalu
Israel		United Kingdom
Italy		United States
Japan		United States Minor Outlying Islands
Jersey		Uruguay
Kenya		Vanuatu
Kiribati		Viet Nam
Korea, Republic of		Virgin Islands, U.S.
Malaysia		Wallis and Futuna
Maldives		Åland Islands

Annex 2: Data Suppliers 2015 - 2019

Supplier	**Country**
Servicio de Hidrografia Naval, Argentina	Argentina
Australian Ocean Data Centre	Australia
National Tidal Centre	Australia
NSW Public Works	Australia
Agency for Maritime and Coastal Services	Belgium
Director of Hydrography and Navigation (DHN)	Brazil
Canadian Hydrographic Service	Canada
Servicio Hidrografico y Oceanografico de la Armada (SHOA)	Chile
National Marine Data and Information Service (NMDIS)	China
Hidrografski Institut, Split	Croatia
Cuban National Tidal Service	Cuba
Danish National Space Center	Denmark
Det Dansk Meteorologiske Institute	Denmark
Captainerie du Port de Djibouti	Djibouti
Oceanographic Institute of the Navy	Ecuador
National Institute of Oceanography and Fisheries	Egypt
Finnish Meteorological Institute	Finland
Institut Geographique National, France	France
Service Hyd. et Ocean. de la Marine	France
Dept. of Oceanology and Meteorology, Georgia	Georgia
Bundesamt fur Seeschifffahrt und Hydrographie Hamburg	Germany
Hellenic Navy Hydrographic Service	Greece
Hong Kong Observatory	Hong Kong
Icelandic Coast Guard - Hydrographic Dept.	Iceland
Survey of India	India
National Cartographic Centre of Iran	Iran, Islamic Republic of
Survey of Israel	Israel
ARPAE	Italy
Instituto Talassografico di Trieste	Italy
ISPRA	Italy
University of Ferrara	Italy
Geographical Survey Institute	Japan
Japan Meteorological Agency	Japan
Japan Oceanographic Data Centre, M.S.A.	Japan
National Institute for Polar Research	Japan
National Oceanographic Research Institute	Korea, Republic of
Department of Survey and Mapping	Malaysia
Malta Maritime Authority	Malta
Meteo – France	Martinique
Port Autonome de Nouakchott	Mauritania

Supplier	Country
Meteorological Services, Mauritius	Mauritius
Rijkswaterstaat	Netherlands
Land Information New Zealand (LINZ)	New Zealand
National Institute of Water and Atmospheric Research	New Zealand
Norwegian Mapping Authority	Norway
Hydrographer of The Pakistan Navy	Pakistan
National Mapping and Resource Information Authority	Philippines
Instituto Hidrografico, Lisbon	Portugal
World Data Center B1	Russian Federation
Maritime Port Authority of Singapore	Singapore
Directorate of Hydrography, S.A.	South Africa
Aranzadi	Spain
Dr. Josep Pascual Massaguer	Spain
Geolab	Spain
Instituto Espanol de Oceanografia	Spain
Puertos del Estado	Spain
Swedish Met. and Hyd. Institute	Sweden
Oceanographic Division, Hydrographic Dept.	Thailand
Channel Coastal Observatory	United Kingdom
National Oceanography Centre / Environment Agency	United Kingdom
Port of London Authority	United Kingdom
NOAA / NOS	United States
Panama Canal Commission	United States
University of Hawaii Sea Level Centre (UHSLC)	United States
Oceanographic, Hydrography and Meteorology Service of the Uruguayan Navy (SOHMA)	Uruguay

Annex 3: Acronyms

ACRE	Atmospheric Circulation Reconstructions over the Earth
BODC	British Oceanographic Data Centre
CME	Commonwealth Marine Economies
DOI	Digital Object Identifier
DTU	Danmarks Tekniske Universitet (*Technical University of Denmark*)
EPSG	European Petroleum Survey Group
GCN	GLOSS Core Network
GESLA	Global Extreme Sea Level Analysis
GGOS	Global Geodetic Observing System
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
IAG	International Association of Geodesy
IAPSO	International Association for the Physical Sciences of the Oceans
ICSU-WDS	International Science Council – World Data System
IGS	International GNSS Service
IOC	Intergovernmental Oceanographic Commission
IOTWS	Indian Ocean Tsunami Warning System
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council (formerly ICSU)
ISO	International Standards Organisation
IUGG	International Union of Geodesy and Geophysics
JCR	Journal Citation Reports
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
MSL	Mean Sea Level
MTL	Mean Tide Level
NERC	Natural Environment Research Council
netCDF	Network Common Data Form
NOC	National Oceanography Centre, UK
ODINAfrica	Ocean Data and Information Network for Africa
PNAS	Proceedings of the National Academy of Sciences of the USA
PSMSL	Permanent Service for Mean Sea Level
RDA	Research Data Alliance
RLR	Revised Local Reference
SONEL	Système d'Observation du Niveau des Eaux Littorales
TIGA	IGS Working Group Tide Gauge Benchmark Monitoring Project

Journal of Geodesy

http://link.springer.com/journal/190

Editor in Chief: Jürgen Kusche (Germany)

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 makes the final decision on whether a manuscript is accepted for publication. He is advised by an Editorial Board (EB). The 2015-2019 EB comprised 21 members (associate editors) from 18 countries:

S. Bettadpur (USA), C. Brunini (Argentina), T. v. Dam (Luxemburg), D. Dong (China), Y. Gao (Canada), M. Hernandez-Pajares (Spain), T. Hobiger (Sweden), A. Hooper (UK), C. Huang (China), A. Jäggi (Switzerland), W. Keller (Germany), R. Lohman (USA), Z. Malkin (Russia), B. Meyssignac (France), M. King (Australia), R. Riva (The Netherlands), W.-D. Schuh (Germany), I. Tziavos (Greece), S. Verhagen (The Netherlands), M. Vermeer (Finland), P. Wielgosz (Poland), Y. Yuan (China), P. Xu (Japan).

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. These are then physically combined in one issue (but normally published online once individually accepted). The most recently published special issue (September 2018, volume92, issue 9) was dedicated to “Investigations of reference systems for monitoring global change and for precise navigation in space”, and another special issue (on “Satellite Laser Ranging”) is 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 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 (2017) Impact Factor is 4.633, based on Thomson Reuters JCR (Journal Citation Report). Measured by the IF, JoG is 2017 among the top 10 journals within Springer’s topical journal collections: rank 6 out of 30 in Remote Sensing journals, and rank 7 out of 85 in Geochemistry and Geophysics journals. For the last years JoG has seen the following evolution of IF and citations (the 2018 IF will likely be published in July 2019):

Table 1: JoG Impact Factor and total journal article citations for 2015-2017

Year	Impact Factor	Citations
2015	2.486	2881
2016	2.949	3838
2017	4.633	4436

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 2015-2018

Year	submitted	accepted
2015	247	77
2016	271	97
2017	260	97
2018	302	103

The acceptance rate is quite stable, around 34%.

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. 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 potential reviewers. The other observation is that turnaround times measured in days from submission to first decision have recently increased; this can be largely explained by the increased editorial load from receiving more submissions.

Table 3: JoG number of review invitations and completed reviews and average turnaround time (submission to first decision in days) for 2015-2018

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

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. Starting with January 1, 2019, two new elements have been introduced; authors now provide Author Contribution Statement (ACS) and Data Availability Statement (DAS) upon submission.

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.

IAG Symposia Series

http://www.springer.com/series/1345

Editor-in-Chief: Jeff Freymueller (USA)
Assistant Editor-in-Chief: Laura Sanchez (Germany)

Overview

The IAG Symposia Series is a book series of peer-reviewed proceedings of selected IAG Symposia organized by the International Association of Geodesy. It deals primarily with topics related to Geodesy as applied to the Earth Sciences and Engineering: terrestrial reference frame, Earth gravity field, geodynamics and Earth rotation, positioning and engineering applications. Volumes are available online at the Springer web site (http://www.springer.com/series/1345), since volume 101 (Global and Regional Geodynamics, 3-5 August 1989), published in 1990. Most recent volumes are also available from the Springer web site as e-Books. Articles published in the IAG Symposia Series since 2000 are indexed by the major indexing service (Scopus, Web of Science). All IAG-sponsored Symposia and meetings are required by the IAG Bylaws to publish a proceedings volume in the series, although this requirement has not been enforced in recent years.

Following the IUGG General Assembly in Prague (July 2015), the new Editor-in-Chief is Jeffrey Freymueller, with Laura Sanchez serving as the Assistant Editor-in-Chief. The review procedure is carried out using the Spring Editorial Manager system (http://www.editorialmanager.com/iags). Editors are selected for each symposium from the list of conveners, taking into account the number of expected symposium manuscripts. Specifications for authors are provided to all authors through the Springer web site.

Starting in 2019, all future volumes of the series will be Open Access. Submission statistics had been trending downward for a number of years, but we think the decline will be reversed with the change to Open Access.

There was a plan to rename the series to the “IAG Topical Series”, but this proved infeasible. The name change would have caused a substantial lag in indexing, and it was clear that indexing was of critical importance to the authors. After long negotiations, IAG and Springer finally agreed on terms for a contract for the future, and this will be signed soon by the IAG Secretary General.

Structure and activities

The following paragraphs provide information on the IAG symposia volumes published or under review process in the 2015-2019. Three new volumes were published from Symposia held during the last 4 years, with two more in progress. In addition, Pascal Willis handled the final stages of the volumes for meetings held prior to the Prague IUGG, which were finally published after 2015. They are reported here for completeness (in a smaller font). Editorial work is nearly complete on one of the two volumes in progress, and will be completed very soon (the author will either submit revisions soon or the paper will be withdrawn). About 2/3 of the papers are finalized in the other one. We are currently preparing the material for Springer for the Montreal IUGG volume, and should have that turned in by the end of this meeting.

Volumes

Volume 142
International Symposium on VIII Hotine-Marussi Symposium on Mathematical Geodesy
Rome, Italy, June 17-21, 2013
Editors: Nico Sneeuw, Pavel Novàk, Mattia Crespi, Fernando Sansò
Published

Volume 143
Scientific Assembly of the International Association of Geodesy: IAG 150 Years
Potsdam, Germany, September 1-6, 2013
Editor: Pascal Willis
Published

Volume 144
3rd International Symposium on Gravity Field Service (IGFS)
Shanghai, China, June 30-July 6, 2014
Editor: Shuanggen Jin
Published

Volume 145
International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH)
Matsushima, Japan, July 22-26, 2014
Editor: Manabu Hashimoto
Published

Volume 146
International Symposium on Reference Frames for Applications in Geosciences (REFAG2014)
Kirchberg, Luxembourg, October 13-17, 2014
Editor: Tonie van Dam
Published

Volume 147
Earth and Environmental Sciences for Future Generations (2015 IUGG General Assembly)
Prague, Czech Republic, June 22 – July 2, 2015
Editors: Jeffrey T. Freymueller, Laura Sanchez
Published in 2018, 43 papers

Volume 148
International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS16)
Thessaloniki, Greece, September 2016
Editors: Riccardo Barzaghi, Roland Pail, George Vergios
Published in 2019, 27 papers.

Volume 149
International Symposium on Advancing Geodesy in a Changing World
IAG-IASPEI Scientific Assembly, Kobe Japan
Editors: Jeffrey T. Freymueller, Laura Sanchez
Published in 2019, 23 papers.

Volume 150
Fiducial Reference Measurements for Altimetry:
Proceedings of the International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications
17 manuscripts submitted
2 rejected or withdrawn
1 still waiting for author revision
Publication expected in late 2019

Volume 151
Proceedings of the IX Hotine-Marussi Symposium
31 manuscripts submitted
6 rejected or withdrawn
11 still in review
14 accepted
Will include a rather long review (highlight) paper by Fernando Sanso.
Publication expected in 2019 or 2020

Volume 152
IUGG Montreal
Submissions to open in July 2019

Review Process

All submissions are screened automatically using the using the iThenticate software, which is designed to detect plagiarism and self-plagiarism. Self-plagiarism is by far the most common such problem. The iThenticate software can be fooled at times, and some cases of fairly high overlap can be harmless (for example, reference citations can be flagged as overlaps, and it is hard to avoid some overlaps in sections that summarize mathematics). We did not reject outright any submissions in 2015-2017, but we always alerted the editors. In one case, an author was requested to revise the paper to reduce overlap prior to sending it to reviewers.

For each manuscript, two independent experts are selected by the editors to review the submitted manuscript. Based on the returned reviewers reports, the editor makes a decision, which needs to be confirmed by the Editor-in-Chief. To improve communication with the authors, monthly reports are sent out by the Editorial Manager system. Information emails are also sent out to authors, while papers are handled by Springer Production, until their final publication online and in print.

Indexing

We discovered a couple of years ago that the indexing of recent volumes of the series was not complete. Indexing is of critical importance to potential authors. The solution to this problem was for us to repeatedly remind Springer to submit the volumes for indexing. We were able to solve this problem for the volumes that had been skipped as well, so to the best of our knowledge all published volumes have been indexed.

An Attempted Name Change – Cancelled

About two years ago, IAG took the decision to rename the series as the "IAG Topical Series". However, this decision had to be reversed. Unfortunately, it would have caused problems with the indexing, which would have been fatal to the health of the series. Thus, we have in the end kept the same name.

Jeff Freymueller's move to Michigan State University

Last fall, Jeff Freymueller moved to Michigan State University, after 23 years at the University of Alaska Fairbanks. The move took a lot of time over the summer and fall, and Laura Sanchez very ably took over handling most of the editorial work during this time. This included the final handling of the Kobe volume, and the key work on the two current volumes. We will work on a good distribution of responsibilities for the upcoming Montreal volume and those from future meetings.

Future Outlook

Open Access

As mentioned above, all future volumes of the series will be Open Access. The contract with Springer has been negotiated (by the Secretary General), and is ready to be signed. In addition, IAG will more forcefully enforce the requirement that IAG Symposia publish a Proceedings volume. We expect more authors will be interested in submitting because of Open Access, and the new contract model makes it feasible to publish the small volumes that would likely result from smaller meetings. All in all, it is a much better economic model for us, with the additional advantage of Open Access.

Based on the recent experience, we expect that most volumes will be in the range of 150-200 pages, except for the IUGG meeting and perhaps the IAG meeting volumes.

We are in the process of writing up new guidelines for the conveners of IAG Symposia. The key point is that they should include US $50 per registrant in their registration fee to pay for the publication of the proceedings volume. Springer will invoice the organizers directly, so the Editor-in-Chief will collect the information needed from the organizers and send it to Springer.

In the event that the money collected from the registration fees is not enough to pay for the volume, then IAG would have to step in any pay the remainder. But we think this is not very likely given the structure of the contract.

As papers will be electronic and Open Access, they also can be published as soon as they have been accepted. We think this will make the publication process much faster than in the past, although the final compilation into an e-book will have to wait until all papers have been handled.

Future Volumes

We plan to have the Book proposal form and the information needed for the submissions portal sent to Springer by the end of this meeting. This should allow the submissions portal to be opened before the end of July. We plan an initial submissions deadline of September 15. Even with expected extensions to the deadline, this should allow the review process to be well underway before the AGU + holidays disruptions kick in.

Recurring problems

1. With almost every volume we find one AE who simply will not do anything, or where there is some considerable difficulty or delay. It is always a different person each time (we do not go back to troublesome people), and sometimes there is an innocent cause like a change of email address. But sometimes people agree to do it and then do not do the work. In some cases, Laura and I have had to take over the AE role ourselves. This is not ideal, but one of us can serve as AE and the other make the Editor-in-Chief decision.

2. Reviewers. Finding responsive reviewers is often a challenge, although the majority of people do a good job when given reminders. But there are always some papers delayed by this. We have set up automated reminders, but we also depend on the AEs to remind reviewers. Checking on everything is simply a time-consuming task.

Recommendations

We reported on some recommendations in our 2017 report, and these have been acted upon. We now have Open Access for the series, and a more clear procedure for who Springer will invoice for each volume. At this point we have no further recommendations, and we need to see how the changes play out.