Commission 2 – Gravity Field

http://www.iag-commission2.ch

President: Urs Marti (Switzerland)
Vice President: Srinivas Bettadpur (USA)

Structure

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Annex 1	CCM – IAG Strategy for Metrology in Absolute Gravimetry

Overview

This report covers the period of activity of the entities in Commission 2 for the year 2011 to 2015. Commission 2 consists of six sub-commissions (plus 6 regional sub-commissions), one joint project and several joint working groups and study groups. Most of the entities of the Commission were very active and most of them made progress in their stated objectives. Each of the chairs of the entities was asked to summarize their activities. These reports can be found further down. Here is only given a short summary.

Conferences and meetings

Commission 2 was involved in the organisation of several conferences. The official commission symposium was "Gravity, Geoid and Height Systems", which was held in 2012 in Venice. It was organised in common with the IGFS and GGOS Theme 1. Its proceedings are published as volume 141 of the IAG Symposia series.

The session " Gravity Field Determination and Applications" at the IAG scientific assembly 2013 in Potsdam was very successful with 100 oral and 85 poster presentations.

In 2014, Commission 2 assisted the IGFS in the organisation of its 3rd general assembly in Shanghai.

Further conferences with significant contributions from commission 2 include:
- AOGS-AGU (WPGM) Joint Assembly 2012, Singapore
- International Symposium on Planetary Sciences (IAPS), Shanghai, China 2013
- "Terrestrial Gravimetry. Static and Mobile Measurements - TGSMM-2013" in St Petersburg 2013
- several meetings of AGU, EGU and CGU

The administrative meetings of the steering committee of commission 2 were held in Venice (2012), Potsdam (2013) and Shanghai (2014). A forth one will be held during the IUGG general assembly 2015 in Prague. These meetings were open to all interested persons and were usually held commonly with the IGFS.

Activities of the Sub-Commissions

SC 2.1 Gravimetry and Gravity Networks
One activity is the future organization of the International and regional campaigns of absolute gravimeters. They are assured until 2017. The future of these campaigns are regulated by a strategic paper between the metrological (CCM-GGM of the BIPM) and the geodetic side (IAG commission 2, especially SC 2.1), which was adopted by IAG and CCM in 2014. It can be found in Annex 1.

One other important issue is the replacement of the out-dated global gravity network IGSN71 and the transfer of the former Global Geodynamics Project (GGP) into a permanent service under the umbrella of the IGFS. These tasks are handled mainly in the JWG 2.2.

A special workshop TGSSM2013 for the practical issues of measuring gravity was held in St. Petersburg (Russia) in September 2013. The next such conference of this kind is foreseen for Spring 2016 again in St. Petersburg.

SC 2.2 Spatial and Temporal Gravity Field and Geoid Modeling

This SC deals with the theoretical practical problems in gravity field determination. Many results were presented at various conferences using the latest GRACE, GOCE and combined models in combination with terrestrial and airborne data. The validation of global models in comparison to local solutions and/or GPS/levelling is an activity of many groups and in special of JWG 2.3.

SC 2.3 Dedicated Satellite Gravity Missions

This SC is deeply involved in the derivation of new releases of global gravity field models based on GRACE and GOCE mission data, applying updated background models, processing standards and improved processing strategies. The SC actively contributed to the development and investigation of alternative methods of global gravity field modelling and related problems. It is as well deeply involved in national and international studies in the planning and design of future gravity field missions - especially of a GRACE follow-on mission, which is planned for 2017.

SC 2.4 Regional Geoid Determination

SC 2.4 coordinates the activities of the 6 regional sub-commissions on gravity and geoid determination and helps in the organization of conferences, workshops and schools. The activities in these regional SCs vary from 'almost no activity' to 'very active'. See descriptions below. In some regions, there are activities on the national level, but none in international cooperation or data exchange.

SC 2.5 Satellite Altimetry

From 2011-2015 this SC performed a diverse research into development of altimeter wave-form retrackers, improvement of global and regional marine gravity field models, studies of sea-level extremes, improvement of dynamic ocean topography models, applications over ice-covered and river surfaces, modelling and assessing of ocean tides and calibration of altimetry data. Of them, the most significant improvements are made in the new marine gravity field (~2 mGal accuracies) and ocean mean dynamic topography models due to new data sources from GOCE and non-repeated altimetry missions.

Future activities include the SCs help in establishing a permanent altimetry service and give to it a better visibility to the public.

SC 2.6 Gravity and Mass Displacements

This new (since 2011) SC profits especially from the long time series and excellent quality of GRACE data. There is an enormous potential for the interpretation of these data in several topics, for which special study groups and working groups have been established. Many interesting and promising results have been presented at several conferences in the fields of sea level rise, ocean circulation, ice melting, land hydrology and gravity/solid earth coupling.

Activities of the Joint Project 2.1, Geodetic Planetology

This is a joint project of commissions 1, 2 and 3 and the ICCT. One of its main goals is the establishment of geodetic planetology as a permanent IAG entity such as an Intercommission Committee on Planetology (ICCP). This task seems very difficult to reach. The main problem is to motivate scientists to work in this field. There are only very few active groups. A real exchange or collaboration between the groups of Planetary Sciences and IAG is not visible. The project chair recommends to dissolve this project and not to transform it into a permanent entity of IAG.

Activities of Study Groups

There are nine Joint Study Groups where Commission 2 is involved as a partner, but none of them reports directly to commission 2. Their reports can be found in the ICCT section (8 groups) or under Commission 3 (1 JSG).

Activities of Working Groups

There are 8 Working Groups reporting to Commission 2. All of them are established as Joint Working groups with Commission 3 and/or the IGFS. Their reports can be found in the corresponding chapters and as a summary in the reports of the leading sub-commissions.

Another JWG "Vertical Datum Standardization" in which Commission 2 is involved, reports to GGOS. Its activities can be found there.

Sub-Commission 2.1: Gravimetry and Gravity Networks

Chair: Leonid F. Vitushkin (Russia)
Vice-Chair: Hideo Hanada (Japan)

Sub-Commission 2.1 with its joined with IGFS Joint Working Groups (JWG) JWG 2.1 "Techniques and Metrology in absolute gravimetry" (chaired by Vojtech Palinkas) and JWG2.2 "Absolute gravimetry and absolute gravity reference system" (chaired by Herbert Wilmes) was active in the most fields of activity in the frame of its Terms of Reference (ToR). It promoted scientific studies of the methods and instruments for terrestrial, airborne, shipboard measurements, establishment of gravity networks and improvement of strategy in the measurement of gravity networks. The Sub-commission provides the geodesy-geophysics community with the means to access the confidence in gravity measurements at the well-defined level of accuracy through organizing, in cooperation with metrology community, Consultative Committee on Mass and Related Quantities (CCM) and its Working Group on Gravimetry (CCM WGG), Regional Metrology Organizations (RMO) the international comparisons of absolute gravimeters on continental scale.

Under the auspices of chair board of IAG and Commission 2 the Sub-commission works in cooperation with the CCM on the implementation of metrology assurance in absolute gravimetry, in particular, through the development of common strategy documents.

The Reports of SC2.1 prepared by the members of its Steering Committee and by JWG 2.1 and JWG 2.2 promote the exchange of information on national activities in various fields of gravimetry.

The comparisons of absolute gravimeters

The first comparison of absolute gravimeters at the International Bureau of Weights and Measures (BIPM, Sèvres, France) took place in 1981 (8 gravimeters took part) and the latest comparison was organized by CCM and SC2.1 in November 2013 [1] in Walferdange (Luxembourg) with 25 absolute gravimeters (10 of them are from National Metrology Institutes (NMI) and from Designated Institutes (DI) for metrology in gravimetry.

In 2008 and 2011 the comparisons of European Regional Metrological Organization (RMO) EURAMET were also organized in the underground laboratory in Walferdange, Luxembourg (see Report of JWG 2.1).

In 2012 the first regional comparison in the frame of Asia-Pacific Metrology Programme was organized in Changping Campus of NIM - National Institute of Metrology of China.

The scientific Second North-American Comparison of Absolute Gravimeters (NACAG-2013) was organized in the Table Mountain Geophysical Observatory (Longmont, Colorado).

Thus after the closure of international comparisons of absolute gravimeters at the BIPM, where the comparisons were organized from 1981 to 2009, the expansion of the sites for the comparisons over the continents took place.

The growing request from geodesy community for the determination of metrological characteristics of absolute gravimeters and corresponding growing request for the participation in comparison had put the question about gradual transition to establishing a metrological service for absolute gravimeters on the basis of the primary measurement standards in gravimetry maintained at NMIs and DIs and about calibrations of absolute gravimeters at the level of NMIs and DIs. The creation of such metrological system will require a lot of efforts of both the metrology and the geodetic-geophysical communities because so far the evaluation and presentation of the results of comparison organized by CCM or RMO were different for the absolute gravimeters belonging to NMIs and DIs and for the absolute gravimeters from other institutes and services.

In short, the only measurements of the gravimeters belonging to NMIs and DIs in the key comparisons organized according to the rules of metrology community (http://www.bipm.org/en/cipm-mra/cipm-mra-documents/) are used for the evaluation of the results of comparisons and placed in the key comparison data base on the website of BIPM. The results of scientific comparisons of other gravimeters will be documented in a registry part of the international "AGrav" database (http://agrav.bkg.de/agrav) for absolute gravity measurements, maintained by International Gravimetric Bureau (BGI) and the Federal Agency for Cartography and Geodesy (BKG).

The results of the key comparisons of absolute gravimeters are the values of free-fall accelerations at the stations of gravimetry site where the comparison was organized, the uncertainties of these values and the degrees of equivalence of the results of the measurements of each gravimeter participated in the comparisons.

The examples of presentation of the results of key comparisons in the reports published in the key comparison data base of BIPM are shown in Fig. 1 and 2. Only the results of the gravimeters belonging to NMIs and DIs are presented in the reports on http://www.bipm.org/exalead_kcdb/exa_kcdb.jsp?_p=AppB&_q=free-fall+acceleration&x=11&y=8

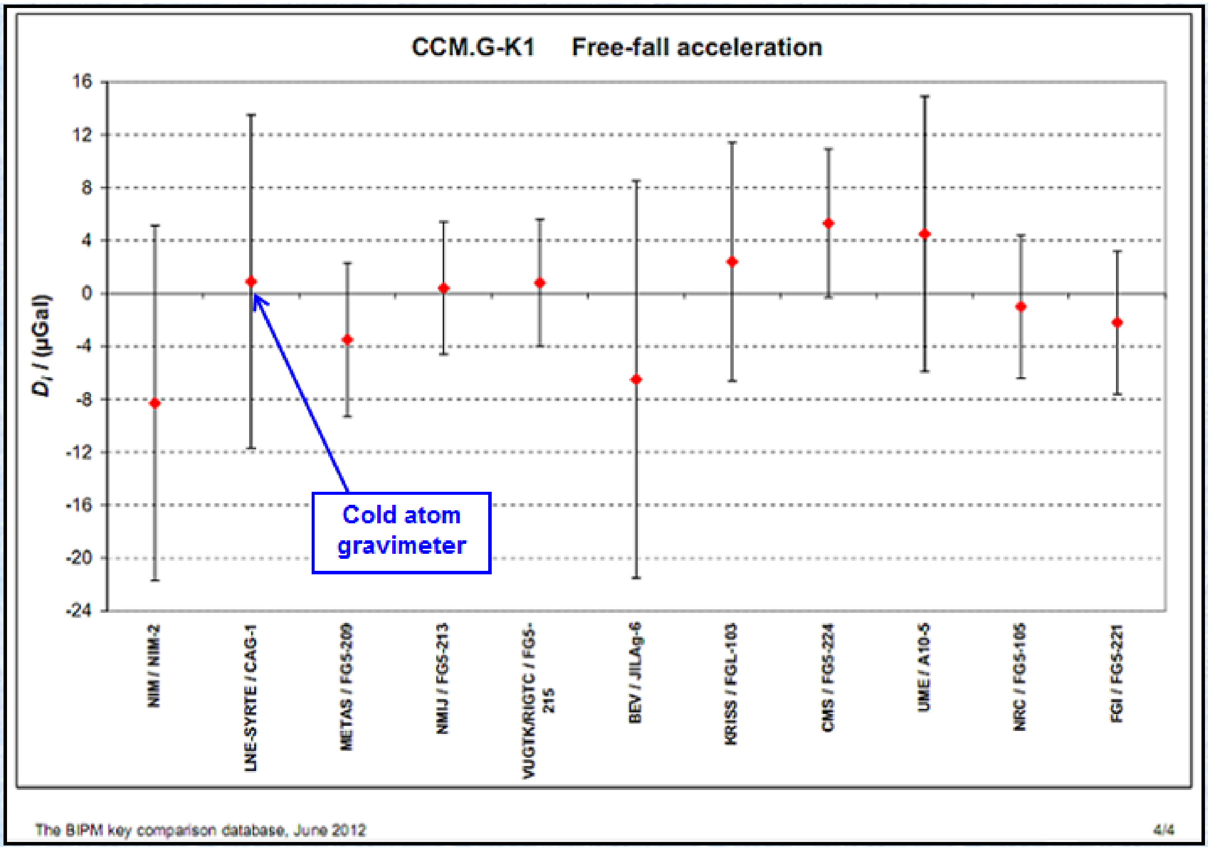

Fig. 1. The results of Key comparison CCM.G-K1 (2009, BIPM, Sèvres, France).

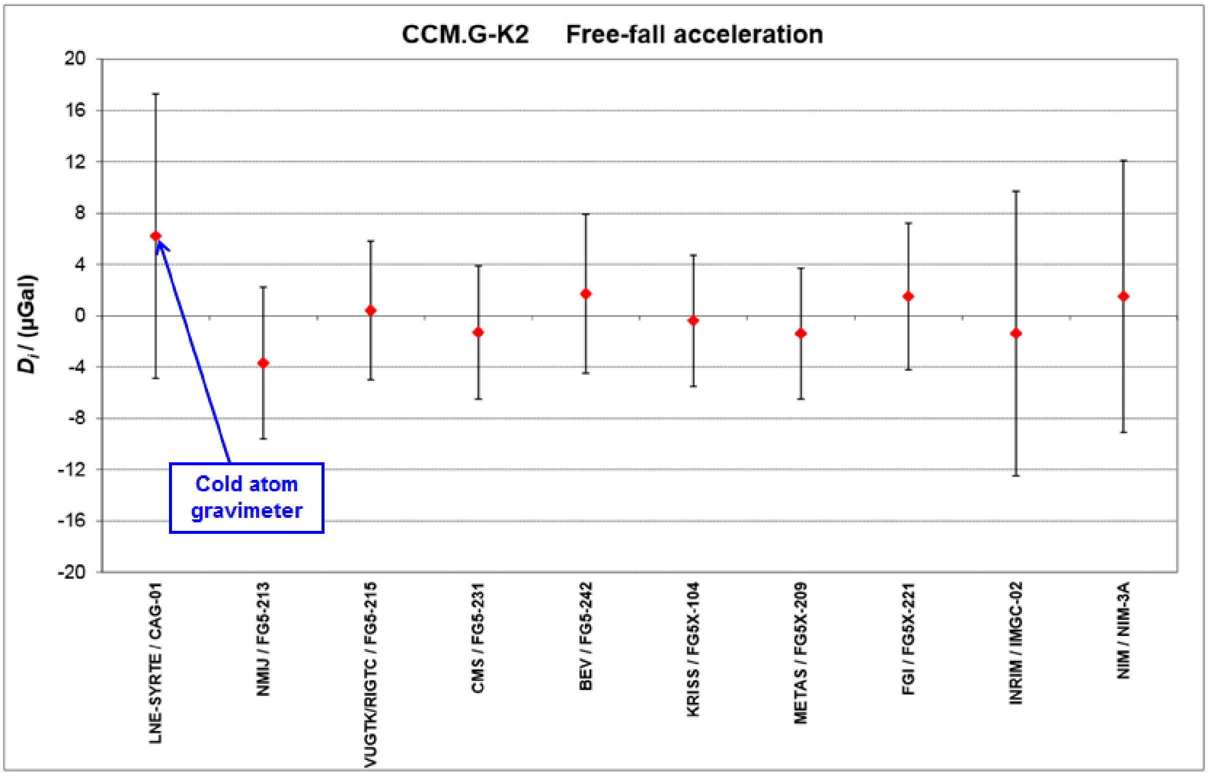

Fig. 2. The results of Key comparison of absolute gravimeters CCM.G-K1 (2013, Walferdange, Luxembourg).

In Figures 1 and 2 D_i is the degree of equivalence of the result of each participated gravimeter defined as the deviation of its result from the key comparison reference value. On horizontal axis "the name of the laboratory/ type of gravimeter" is shown. The error bars represent the expanded uncertainties (U_k) at 95% confidence level.

Further investigations of the sources of the uncertainties of the absolute gravimeters based on different principles of operation (laser interferometric absolute ballistic gravimeters of different constructions with macroscopic test body, cold atom gravimeters, etc.), of the reproducibility of their measurements, of the linking between the results of different comparisons and other essential issues still necessary. As an example we can refer to further discussion on the applications of the corrections for gravitational self-attraction of the absolute gravimeter itself and for the effects related to the finiteness of the speed of light.

In 2013 the CCM, IAG Commission 2 and CCM WGG proposed the first version of the "CCM-IAG Strategy for metrology in absolute gravimetry". This document was then discussed by the CCM WGG, JWG2.1 and JWG2.2 members and modified at the meeting of the chairs of SC2.1 and CCM WGG, JWG2.1 and JWG2.2 in BKG in February 2014. The modified version (see Annex 1) of the "Strategy" was once again discussed and adopted by the working groups. Finally the Executive Committee of IAG welcomed the "Strategy" as the offer of collaboration between the geodetic and metrology communities in the field of absolute gravity measurements and as the document which will assist in the establishment of a global gravity reference system (see letter of Chris Rizos, President of IAG in Annex 2). The Annex 3 is the letter of chairs of SC2.1, JWG2.1 and JWG2.2 addressed to Executive committee of IAG. This letter clarifies the central ideas for the development of "Strategy".

The cooperation between SC2.1, its JWGs and CCM WGG is realized through the mutual membership of their members and joined meetings. The establishment of the connections between the CCM and IAG on the basis of the official documents as mentioned above the

"Strategy" document will ensure the metrological support of gravity measurements in the frame of important geodesy projects like the Global Geodetic Observation System (GGOS), Global Geodynamic Project (GGP), currently transformed to a new service of IAG, development of a new global system of absolute gravity reference stations and others.

Support of the R&D of gravity measurement techniques

The SC 2.1 supports the projects of the theoretical and experimental research and development of absolute gravimeters and gravity gradiometers (see, e.g. [2-4]). It encourages and promotes special absolute/relative gravity campaigns, techniques and procedures for the adjustment of the results of gravity surveys on a regional scale (see, for example, later the reports of Vice-President of SC2.1 Hideo Hanada and of the member of SC2.1 Steering Committee Yoichi Fukuda).

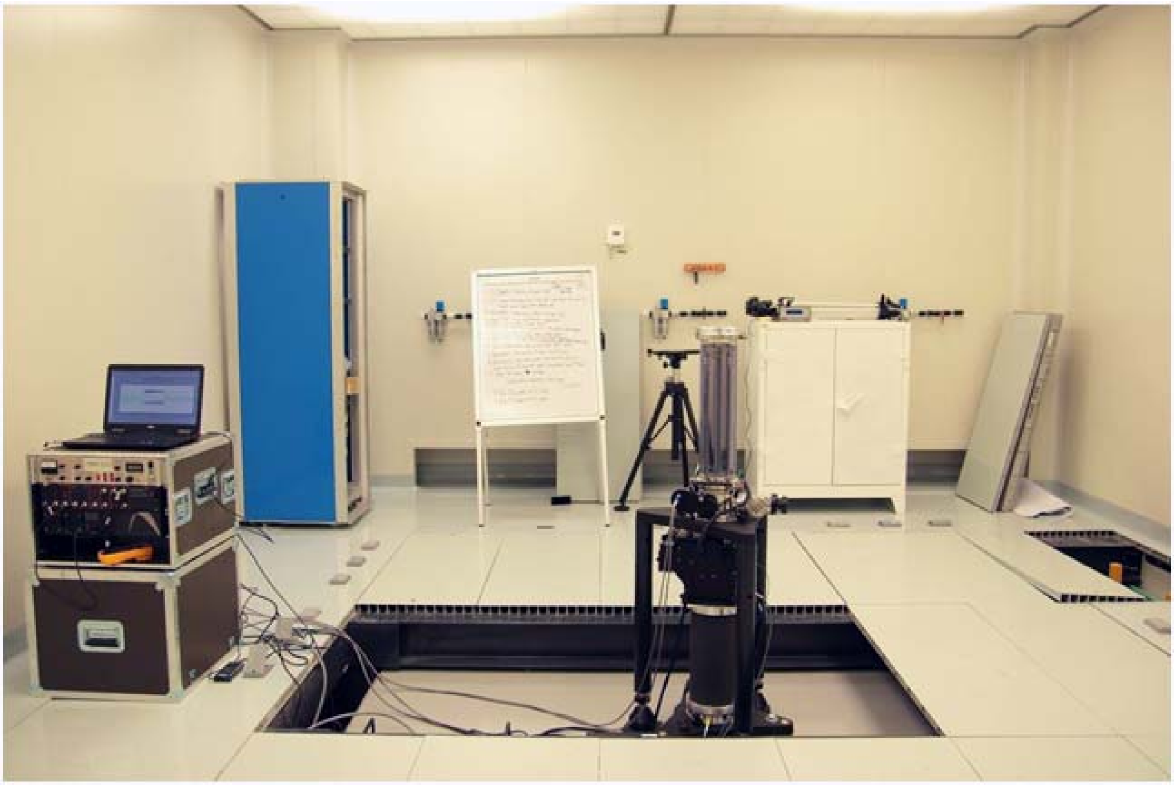

Fig. 3. A gravimetric site in the national metrology institute of Mexico CENAM.

The SC2.1 encouraged the NMI of Mexico CENAM to construct a new gravimetric site where the comparison of absolute gravimeters can be organized and supported the organization of the next CCM key comparison of absolute gravimeters in Changping Campus of NIM (China) in 2017.

A general view of the gravimetric site in CENAM with an absolute gravimeter on the top of the big concrete slab is shown in Fig. 3 (presented by Ignacio Hernandez Gutierrez, CENAM).

The "D.I.Mendeleyev Research Institute for Metrology" (Russian acronym VNIIM) reported to SG2.1 on the development of a new absolute ballistic gravimeter VNIIM-ABG-1 [5].

The NIM (China) informed SC2.1 on the development of new models of absolute ballistic gravimeters including a cold atom gravimeter.

Workshops, conferences, symposiums

The SC2.1 and its JWGs organize and participate in the meetings, workshops, symposiums and conferences (see, e.g. [6, 7]).

In February 2012 JWG 2.1 and JWG 2.2 in cooperation with CCM WGG organized in Vienna the Discussion Meeting on Absolute Gravimetry dedicated to the analysis of some systematic effects in absolute gravimeters and results of international comparisons of absolute gravimeters (see details in the Reports of JWG2.1 and JWG2.2).

The SC2.1 has organized the Third IAG Commission 2 Symposium "Terrestrial Gravimetry. Static and Mobile Measurements - TGSMM-2013" in St Petersburg, Russian Federation (http://www.elektropribor.spb.ru/tgsmm2013/eindex). This symposium was organized for the third time with three-year interval and dedicated mainly to the techniques and methods of terrestrial gravity measurements.

The Fourth IAG Commission 2 Symposium "Terrestrial Gravimetry. Static and Mobile Measurements - TGSMM-2016" in St Petersburg, Russian Federation is already planned for April 12 – 15, 2016.

The TGSMM symposiums definitely helped to diminish the load on IAG GA with the details of the measurement techniques and metrology in gravimetry and represents a forum for reporting and discussion in this field.

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Reports of members of the Steering committee

Gravimetry in Japan *(Reported by Hideo Hanada)*

Absolute gravimetry

Tsubokawa et al developed a prototype of small sized absolute gravimeter using silent drop method which can reduce the rotation of a falling body and vibration induced from dropping mechanism. The accuracy is estimated to be about $8x10^{-9}m/s^2$ (0.8 μGal) as a standard error from 601 drops. Kazama et al. compared the frequency of atomic clocks used in absolute gravimeters, and found that the frequency of the Rubidium clock in the A10 gravimeter (No. 1) shifts by about +0.15 Hz from 10 MHz. They pointed out the importance of correction of frequency difference. Sakai and Araya of the Earthquake Research Institute, University of Tokyo (ERI) are trying to miniaturize the absolute gravimeter of rise and fall method in order to apply it to observation in volcanic area. At present, combination of one absolute gravity station as a reference and many gravity stations surveyed by relative gravimeters are usually used in volcanic area and it takes longer time and is troublesome. The new absolute gravimeter which lifts a corner cube about 10 cm up and has the target accuracy of in the order of $1x10^{-7}$ m/s^2 (10 μGal), will overcome these difficulties.

Relative gravimetry

Murata of the National Institute of Advanced Industrial Science and Technology (AIST) checked the drift rate of a Scintrex CD Gravimeter (#270) in the period not used for gravity surveys, and found annual variation of the drift rate. Tokue et al. of Tokyo Institute of Technology (TITEC) proposed a 2D and 3D numerical model of a two-axes gimbal system for supporting of relative gravimeters, and made a prototype of the gimbal. The gimbal system can maintain the gravity meter horizontally and can attenuate a vibration caused by the body.

Other kinds of gravimetry

Fujimoto et al. of Tohoku University began to build a brand-new hybrid gravimetry system in 2010, which consists of a gravimeter and a gradiometer both for underwater gravimetry. The former aims at quantitative mapping of density anomalies below the seafloor, and the latter can be more sensitive in detection of density variations. The hybrid system can estimate the subterranean structure more accurately than a gravimeter alone. The gradiometer consists of a pair of high precision accelerometers that have been developed for an absolute gravimeter. Both of the sensors will be kept vertical with each gyro. The new underwater gravimeter of the hybrid system, on the other hand, was designed considering the results of the examination of the old one in the previous year. While the concept of design remains unchanged, a gravity sensor is kept vertical with forced gimbals by use of a gyro, the gravimeter has adopted a newly developed dynamic gravity sensor, a high precision gyro, and a highly rigid mechanism for the gimbals in order to improve the precision.

Gravity networks

Geographic Survey Institute (GSI) is constructing new gravity standardization net, "Japan Gravity Standardization Net 2010 (JGSN2010)", to improve former one and contribute to research for the earth's internal structure. Constructing it requires to conform JGSN2010 to a gravity reference system. In this presentation, we will report the proposal of Japan Gravity Reference System and the plan of future construction of JGSN2010. It consists of 29 stations measured by absolute gravimeters and 172 stations measured by relative gravimeters. Standard error of absolute stations will be less than $1x10^{-8}$ m/s^2 (1 µGal) and that of relative stations will be less than $1x10^{-7}$ m/s^2 (10 µGal). The website of JGSN2011 (in Japanese) is http://www.gsi.go.jp/common/000071404.pdf#search='JGSN2011'. Doi et al. of National Institute of Polar Research (NIPR) have started a project to implement absolute gravity measurements with GPS measurements at two areas, i.e. Syowa Station and Langhovde in East Antarctica in the framework of the 53rd Japanese Antarctic Research Expedition (JARE53). The objectives of the measurements are precise determination of gravity field of Antarctic region and estimation of crustal movements associated with Glacial Isostatic Adjustment (GIA). The absolute gravity measurements have already been made by A10 tentatively with standard deviation of 2.4 µGal.

Gravity gradiometer

Araya et al. of Earthquake Research Institute of University of Tokyo (ERI) are developing a gravity gradiometer for hybrid gravimetry system including a gravimeter and a gravity gradiometer. The gravity gradiometer comprises two vertically-separated accelerometers with astatic reference pendulums, and the gravity gradient can be obtained from the differential signal between them. Rotation of the instrument would be a major noise source and is controlled to keep it vertical installed on a gimbal. We operated the developed gradiometer at a quiet site on land and estimated its self-noise to be 6 E (6x10-9 s-2) in the range from 2 to 50 MHz where gravity gradient signal is expected to be dominant when an autonomous underwater vehicle passes above a typical ore deposit.

Shiomi et al. of Aso Volcanological Laboratory, Kyoto University are developing another kind of gravity gradiometer employing the free-fall interferometer similar to that developed for tests of the Weak Equivalence Principle. [1] Two test bodies are put in free fall and their differential displacements during the free fall are monitored by a laser interferometer. Unlike the tests of the Equivalence Principle, the centres of mass of the test bodies are separated along the vertical direction before free falls. This separation allows us to obtain the vertical difference in the gravitational fields. Because of the differential measurements, the obtained gravity gradients are, in principle, insensitive to the motion of the vehicles on which the measurements are carried out. The target sensitivity is a few microgals which is about two orders of magnitude better than the sensitivity of mechanical gravimeters which are typically used on aircraft and ships. This gravity gradiometer would allow us to carry out on-board measurements in inaccessible areas, with an unprecedented high sensitivity.

References

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East Asia and Western Pacific Gravity Networks (Reported by Y. Fukuda)

Geospatial Information Authority of Japan (GSI) has organized local comparisons of absolute gravimeters in Japan annually since 2002. The comparisons have been taken place at a quiet site near Mt. Tsukuba. Each time about 4-5 FG5s from GSI, universities and other institutions including National Metrology Institute of Japan (NMIJ), which has regularly joined ICAGs, participated in the comparisons. The comparison results generally show good agreements and they ensure the reliability of the gravity values measured by the FG5s which participated in the comparisons.

The Japan Gravity Standardization Net 1975 (JGSN75) which was established in 1976 has been used as the reference of the Japanese gravity network until now. GSI has conducted a huge number of gravity measurements so far, and the accuracies of the data have been improved drastically. Using the newly obtained data including absolute gravity data, GSI is working to revise JGSN75 whose accuracy is 0.1mgal and establish a new gravity network with the accuracy of 0.01 mGal. GSI has already finished to calculate the new gravity values at the reference gravity points (34 points) and the 1st order gravity points (80 points), however still needs time to complete the net adjustments of the 2nd order gravity points (about 14,000 points).

GSI has conducted the gravity measurements at the reference and the 1st order gravity points repeatedly and detected the gravity changes before and after the 2011 Tohoku-Oki earthquake. The obtained gravity changes were several tens micro gals and showed the tendency of gravity increases along the coastal areas and decreases at inland areas.

GSI and Earthquake Research Institute of the University of Tokyo have cooperatively conducted repeated absolute gravity measurements at Omaezaki FGS since 2000. The station is located in the area of the anticipated great Tokai earthquake, where the clear subsidence due to the plate motion is observed. Using the obtained gravity data so far, the estimated rate of the gravity increase is 0.0011 mGal/yr.

Gravimetry in North America (reported by Derek van Westrum

North American Comparison of Absolute Gravimeters (*NACAG 2014*)
See: http://www.ngs.noaa.gov/GRAV-D/Comparison/index.shtml

- The results of the first North-American Comparison of Absolute Gravimeters (NACAG-2010) are published [1].
- The NACAG scheduled for 2013 at the Table Mountain Geophysical Observatory (TMGO) was postponed due to governmental restrictions and coincident, severe local flooding. However, NACAG-2014 did occur in mid-September with the following participants:
  - National Geospatial Intelligence Agency (NGA): A10-009, FG5-107
  - Natural Resources Canada (NRCan): FG5-236, A10-003
  - National Institute of Standards and Technology (NIST): FG5-204
  - United States Geological Survey (USGS): A10-008
  - Micro-g LaCoste, Inc.: FG5X-302
  - National Geodetic Survey, host institute (NGS): FG5X-102, A10-025

- Preliminary results have been distributed to the participants, and published results are expected by summer of 2015.

NGS (USA) Cooperation with INEGI (Mexico)

- A memorandum of understanding is being drafted between NGS and the Mexico National Institute of Statistics and Geography (INEGI) for cooperation on the establishment of new absolute gravity measurements at 10-16 sites throughout Mexico. Work to commence after 2015.

FG5-X Absolute Gravity Meter at CENAM (Mexico)

- FG5X-252 was delivered to the Centro Nacional de Metrologia (CENAM) in Santiago de Queretaro, Mexico in early 2015

Superconducting Gravity (NGS)

- SG CT 024 (NGS, located at TMGO) was returned to its observation pier, AK, in 2013 after repairs and upgrades at GWR Instruments in San Diego.
- A second set of electronic upgrades is due to occur on-site at TMGO in summer 2015 (the contract with GWR is finalized).
- SG CT 024 will be once again contributing to the Global Geodynamics Project (GGP) database (http://www.eas.slu.edu/GGP/ggphome.html) sometime in the summer of 2015. Data from 2013-2015 (between the two upgrades) will uploaded after additional quality control.

Superconducting Gravity (Canada)

- SG GWR12 (Canadian Superconducting Gravimeter Installation, operated by NRCan, located in Cantley, Québec) continues to operate and submit data to the GGP. Improvements to the building housing the cryogenic compressor and water-level monitoring wells were completed during the spring of 2015.
- SG iGrav-001 (Tecterra/University of Calgary) is continuing to operate at NRCan's seismic vault at the Pacific Geoscience Centre (Sidney, British Columbia) and also supplies data to the GGP. This SG has supported monitoring efforts of tectonic processes related to the great earthquake cycle along Canada's south-western coastal margin. (Tidal monitoring is augmented by NRCan's collocated L&R ET-12).

Absolute Gravity (Canada)

- FG5-105 (National Research Council of Canada, located in Ottawa, Ontario) continues to support NRC's Watt Balance experiments towards the redefinition of the kilogram. NRCan continues to supplement NRC's work by providing technical expertise and comparisons and joint operations with NRCan's FG5-236. NRC (FG5-105) and NIST (FG5-204) continue to cooperate on their respective Watt Balance experiments and have compared their AGs (with invitations extended to NRCan and NGS).
- FG5-106 (Natural Resources Canada, located in Sidney, British Columbia) has had limited field operations of late and has primarily been used to monitor transient deformation and mass transfer associated with "Episodic Tremor & Slip" (ETS) events in the northern Cascadia Subduction Zone. In order to further support earthquake hazards studies, FG5-106 is (in addition to ETS monitoring) expected to resume some long-term deformation studies on Vancouver Island and the adjacent mainland. Additionally (on a small scale) FG5-106 will support groundwater variability studies (in conjunction with GRACE observations) in the Canadian Prairies.

- FG5-236 (Natural Resources Canada, located in Ottawa, Ontario/Cantley, Québec) continues to control the definition of the gravity datum for Canada through a network of approximately 70 primary absolute gravity sites. During the upcoming field season, FG5-236 will focus on repeating observations at primary AG sites in western Canada and along the eastern side of James Bay, Québec. For repeated measurements at the primary sites, the largest secular signal recorded across most of the Canadian landmass is associated with glacial isostatic adjustment.
- A10-003 (Natural Resources Canada, located in Ottawa, Ontario/Cantley, Quebec) field efforts have primarily focused on carbon capture & storage efforts through participating in multiple technique monitoring efforts of CO_2 injection into a deep (~3000 m) saline aquifer near Estevan, Saskatchewan.
- A10-024 (Tecterra/University of Calgary, located in Calgary, Alberta) is expected to support studies mapping groundwater mass variability in Alberta.
- Refinements to NRCan's absolute gravity database, housed by the Canadian Geodetic Survey (CGS) are on-going.

Establishment of Left Hand Canyon Calibration Line (NGS)

- In order to facilitate the calibration of both NGS relative instruments and those of visitors, a new calibration line just west of TMGO has been established. Its final values are scheduled to be published summer 2015. It consists of three publicly accessible sites with ~100 mGal intervals between them. Additionally, second-order gravity gradients were determined at each site.

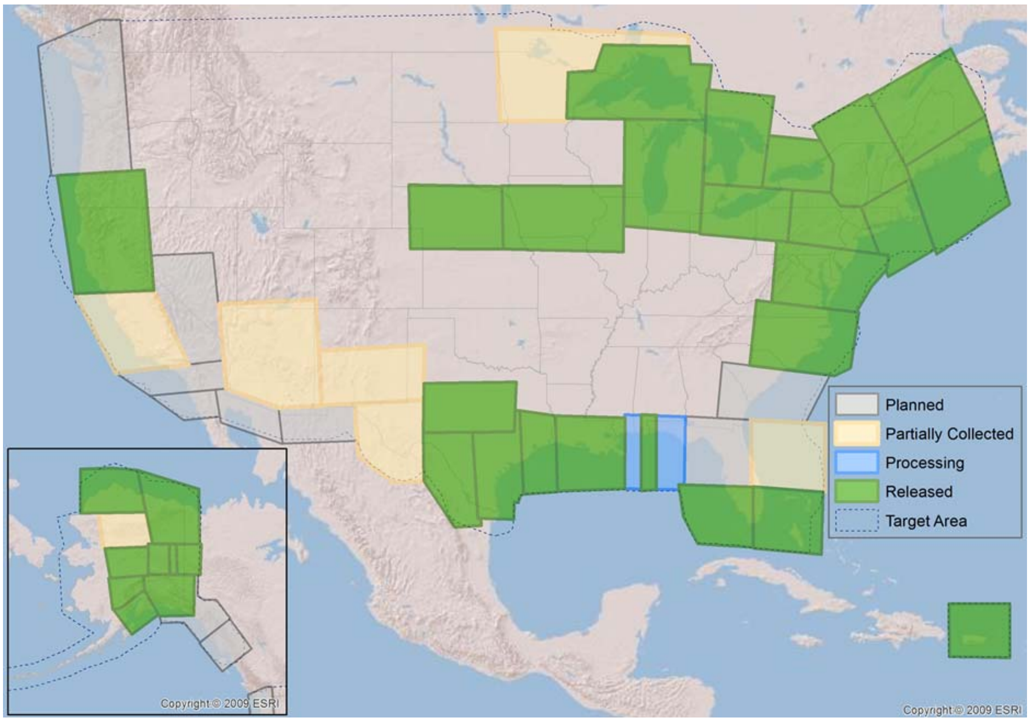
New Vertical Datum (USA Canada)

- The expected adoption year of the new U.S. vertical datum is 2023
- The reference surface of this new datum will be a geopotential surface (geoid)
- The U.S. and Canada have agreed on a W_o value of 62636856 m^2/s^2 for the reference surface
- On 28 November 2013, the Canadian Geodetic Survey (CGS) of Natural Resources Canada released the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), which is now the reference standard for heights across Canada. This new height reference system is replacing the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which had been adopted officially by an Order in Council in 1935. CGVD2013 is defined by the equipotential surface that best represents the coastal mean sea level of North America, as adopted in a joint agreement between the United States and Canada. This new vertical datum is realized by the geoid model CGG2013 and is compatible with Global Navigation Satellite Systems (GNSS). The intention to release CGVD2013 was announced at the Scientific Assembly of the International Association of Geodesy (IAG) in September 2013. Feedback from the scientific community confirmed that this decision was a positive step towards the global unification of height systems.

Gravity for the Redefinition of the American Vertical Datum (GRAV-D) (NGS)

For a complete description of the project, please see: http://www.ngs.noaa.gov/GRAV-D/

- NGS is currently in the possession of three of Micro-g LaCoste airborne gravity meters for production surveying.
- Government/Contracted flights have covered nearly 45% of the U.S (coverage plot as of March 2015 below). Flights scheduled through 2022.



Geoid Slope Validation Surveys (GSVS11, GSVS14, GSVS16) (NGS)
See: http://www.ngs.noaa.gov/GEOID/GSVS14/

- The GSVS surveys are designed to validate the short wave lengths of various geoid models. [2]
- The surveys consist of airborne gravity, LIDAR, differential leveling, static GPS, deflection of the vertical (w/DIADEM(*)), gravity gradients, relative gravity (L&R meters), and absolute gravity (FG-5 & A10). Terrestrial measurements are made at approximately 1-2km intervals for approximately 200km.
- GSVS11 = Texas, GSVS14 = Iowa, and work is beginning on the third and final GSVS16 = Colorado.
- The primary study was to look at the differences comparing geoid slopes determined by 1) various geoid models, 2) GPS/Leveling segment differences and, 3) the DIADEM DOV.
- GSVS11 was over terrain with little to no separation between the ground surface and geoid, GSVS14 studied the same issues with a large separation between surfaces. GSVS16 is to test "worst case" – far above the geoid with rugged local terrain.

(*) DIADEM = The Digital Astronomical Deflection Measuring System (http://www.ggl.baug.ethz.ch/people/buerki)

Subsurface mass monitoring (hydrology) studies (USGS)

- The USGS group in Tucson, Arizona is using iGrav (#4 and #6) and absolute gravimeters (FG5X-102 and A10-008) to monitor a controlled aquifer recharge event. [3].

Abbreviations

CENAM = Cento Nacional De Metrologia (National Center for Metrology), Mexico

CGS = Canadian Geodetic Survey (of NRCan)

CONUS = Continental U.S. (Lower 48 states)

INEGI = Mexico National Institute of Statistics and Geography

NGA = formally NIMA formally DMA = National Geospatial Intelligence Agency

NGS = National Geodetic Survey

NIST = National Institute of Standards and Technology

NRC = National Research Council of Canada

NRCan = Natural Resources Canada

NSF = National Science Foundation

USGS = U.S. Geological Survey

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Shipboard Gravimetry *(reported by Dag Solheim)*

Golden opportunity (not to be missed)

The last years several dedicated national marine mapping projects have been initiated. Ideally marine gravity measurements should be an integrated part of these projects, whenever applicable, in order to maximize the return of the considerable investments involved in these projects. An example of such an activity is the Norwegian MAREANO-project (http://www.mareano.no/en). Gravity is unfortunately not an integrated part of this project, but gravimeters may be installed on the ships for free. Another example are Danish measurements along the coast of Greenland.

Considering the importance of such measurements in determining a high precision geoid both on land and sea, these projects represent an opportunity not to be missed if geodesy is to provide information on the ocean circulation on smaller scales than typically 100km provided by the ESA Satellite GOCE. Satellite altimetry in combination with an accurate and detailed geoid will eventually become an important and valuable new source of information for oceanography and climate research. To achieve this, improved knowledge about the geoid is necessary, something that can be accomplished by having access to detailed high quality marine gravity data sets.

Marine gravity data sets are also of huge value to geologists, geophysicists, oil companies in search of new oil and gas fields as well as for connecting height systems on a global scale. IAG should encourage gravity measurements to be a part such projects and if necessary provide guidelines and recommendations.

Processing of data.

There seems to be two slightly different schools on how to process marine gravity data. A fast and efficient method processing the data as a continuous stream of data and afterwards selecting the "good part" of the data based on criteria like the Eötvös correction, velocity and heading. Another approach is to divide the stream of data into straight line segments and process each segment separately.

The first method is generally very efficient but is highly dependent on the algorithm used to determine reliable data. The second method is normally much more laborious but the processing of each line segment may be fine-tuned in a way not possible by the first method. This can be very advantageous when alternating between sailing with and against the waves/wind in which case the need for filtering may vary a lot. The second method is also often accompanied by graphical visualization aids making it easier to identify erroneous data. Both methods may be further developed, increased quality for the first method and improved efficiency for the second.

Marine gravity survey example

The second method was used when processing the data from a joint Icelandic Norwegian survey between Iceland and the island Jan Mayen in the North Atlantic. As can be seen from the cross over statistics in table 1, excellent results were obtained. With σ_T, the standard deviation of each track and assuming that all tracks have the same standard deviation, then σ_T is related to the standard deviation of the cross overs, σ_X, by $\sigma_T = \sigma_X/\sqrt{2}$.

Table 1. Cross over statistics of the free air anomalies (units mGal)

	#	Mean	Minimum	Maximum	RMS	σ_X	σ_T
Before adjustment	186	0.21	-1.49	1.29	0.55	0.51	0.36
After adjustment	186	0.00	-0.58	0.78	0.20	0.20	0.14

The post cross over statistics may be slightly misleading and too optimistic. A more realistic measure of the accuracy may be obtained by comparing the 2D filtered version of the data set with unfiltered one. The statistics of these comparisons are shown in table 2.

Table 2. Inter comparison of filtered and unfiltered data set (units mGal)

#	Mean	Minimum	Maximum	RMS	σ_X
18390	0.00	-5.30	2.07	0.33	0.33

Even though cross over computations are very easy to perform, they are, for some strange reason, not always done when using the first method. Small cross over differences is a required condition for a high accuracy data set. Large cross overs are an indication of significant errors in the data set. Small cross overs do however not necessarily imply high quality data. Further investigations are needed to decide upon that.

Importance for the geoid on land

As mentioned above marine gravity data are of great importance for the geoid on land. This has been clearly demonstrated in the Sognefjorden area in Norway. Figure 1 shows the difference between the gravity field with and without the marine gravity data in the fjord. The effect on the geoid is presented in Figure 2.

Without marine gravity data and when not correcting for the bathymetry, the computed gravity value on the fjord, based on data on land only, is too high, as expected since the density of sea water is less than that of rocks. When the gravity field decreases the geoid also decreases in accordance with what is shown in figures 1 and 2.

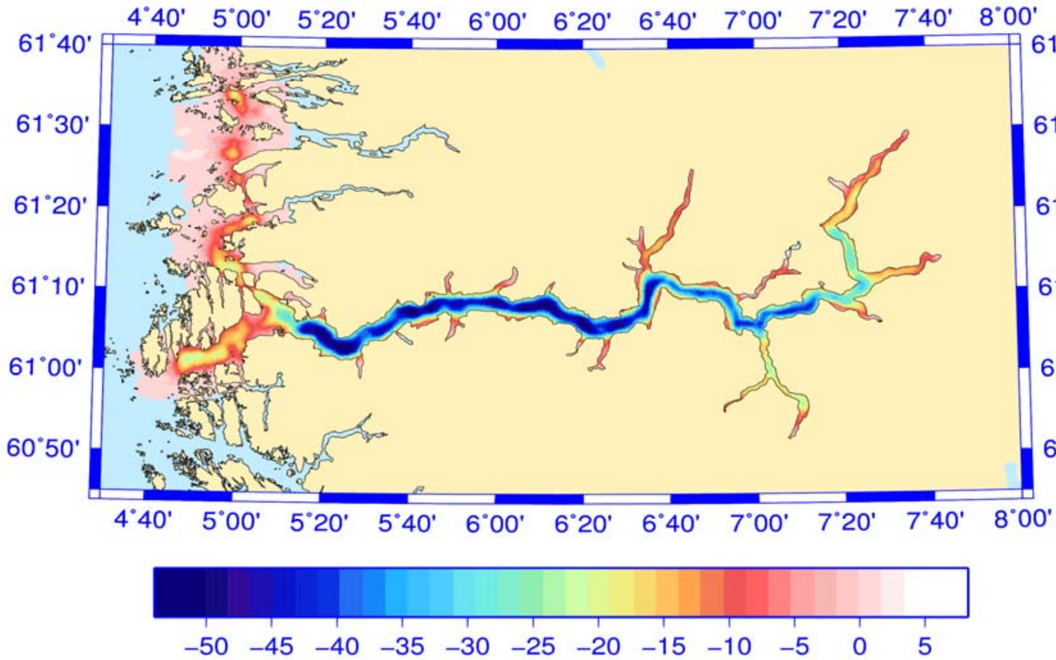

Fig. 1. Gravity signal from the Sognefjorden (units mGal)

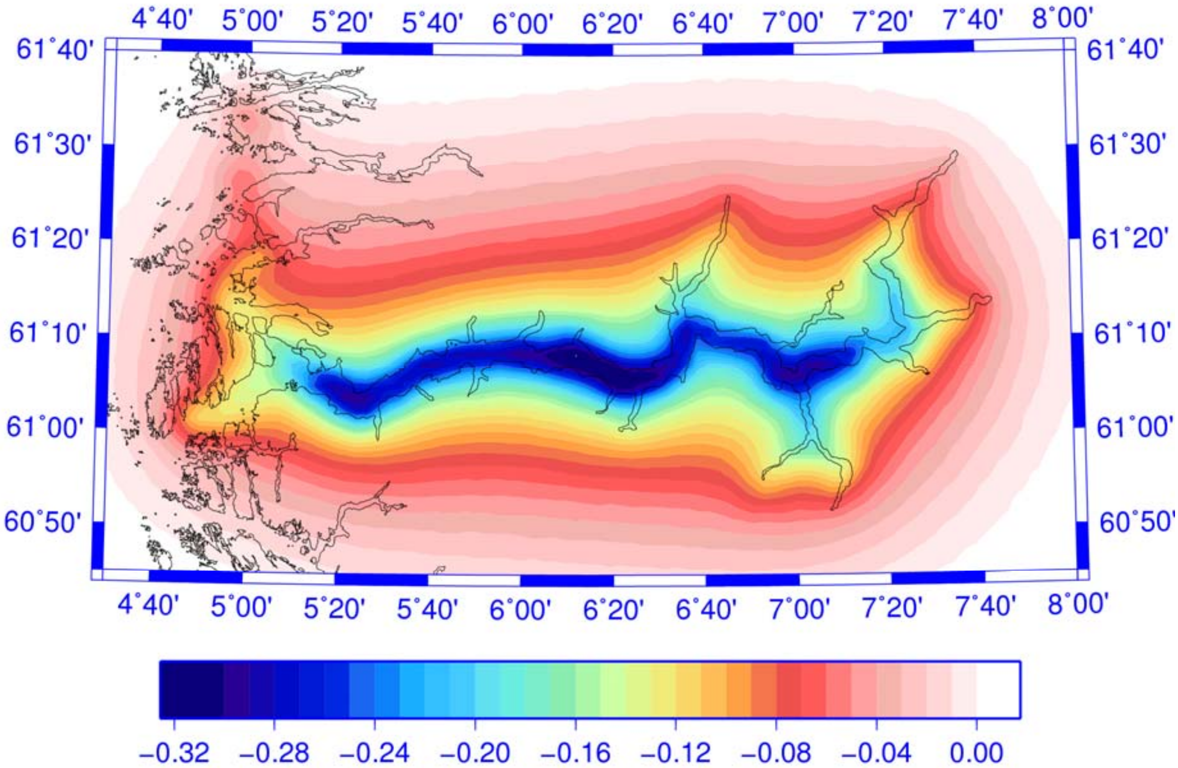

Fig. 2. Effect on the geoid when including the marine gravity data shown in Fig. 1 (units mGal)

If a detailed high precision geoid is to be determined in areas with deep fjords, either access to marine gravity data is needed or a proper handling of the bathymetry (missing mass) is necessary. Ideally access to both a detailed bathymetric model and marine gravity data would be preferable.

Airborne gravimetry on airship platform *(reported by Leonid Vitushkin)*

In the period from 20 to 30 January 2014 the first tests of the airship relative gravity measurements were initiated by the leading Russian lighter-than-air manufacturer "Augur – RosAero-Systems" (Russia).

The participants of the experiment were also:
- State Research Center of the Russian Federation "Concern CSRI Elektropribor, JSC" (relative gravimeter Chekan, operator-gravimetrist, data processing), St Petersburg, Russia;
- Federal State Unitary Research-and-Production Enterprise "Geologorazvedka" (magnetometer, data processing), St Petersburg, Russia,
- D.I.Mendeleyev Research Institute for Metrology (VNIIM), (experts, participation in the flights), St Petersburg, Russia,
- Elkin, Ltd (planning and coordination of the experiment, operator of magnetometer), St Petersburg, Russia.

The airship AU-30 and the gravimeter Chekan in the cabin of the airship are shown in figures 1 and 2.

Fig. 1. The airship AU-30 with carrying capacity of 1.5 t. (http://rosaerosystems.com/airships/obj17)

Fig. 2. Relative gravimeter Chekan in a cabin of AU-30.

The first tests performed under a hard weather conditions (temperature of about - 30ºC and a strong wind) allowed making the conclusions that

- the airship AU-30 in principle may be used as the platform for airborne gravity measurements and magnetometry,
- the gravity measurements on the airship can increase the resolution in gravity measurements thanks lower speed and lower heights of the airship with respect to aircrafts,
- one of the advantages of the airship is the possibility of hovering at one place,
- the absence of vibrations,

Nevertheless, it should be taken into account that a specific infrastructure is necessary for the flight support and some improvements should be undertaken to provide the yaw direction stability.

It is planned to continue the experiments with the airship gravity measurements.

Activity of Technical University of Darmstadt, Germany in strapdown airborne gravimetry *(reported by Matthias Becker).*

The Physical and Satellite Geodesy group, TU Darmstadt (PSG), continued their research on strapdown airborne gravimetry (Deurloo et al. 2012, Deurloo et al. 2015). In cooperation with DTU Space / R. Forsberg, PSG was participating in two aerogravity campaigns, in Chile (2013) and Malaysia (2014). A navigation grade strapdown IMU (iMAR RQH) was flown side-by-side with a LaCoste and Romberg S-gravimeter (LCR), enabling a close comparison of the two instruments. A thermal correction of the IMU accelerometer could be shown to significantly reduce drifts in the scalar gravity estimates, yielding a LCR-IMU agreement for the wavelengths >25 km on the level of 1-2 mGal. Theoretical research has been done on the estimability of 3D-gravity in the strapdown setup. With GNSS coordinate observations being available, an analysis on how observation accuracies, additional observations, and flight maneuvers may improve the estimability of both the scalar gravity and the deflection of the vertical is shown in Becker et al. (2014).

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Sub-Commission 2.2: Spatial and Temporal Gravity Field and Geoid Modelling

Chair: Yan Ming Wang (USA)

Terms of Reference

The primary objective of this Sub-Commission (SC) is to promote and support scientific research on the determination of Earth's gravity field which is categorized as spatial and temporal. The research-topics endorsed by this SC are the following:

- Studies of the effect of topographic density variations on the Earth's gravity field, including the geoid
- Rigorous yet efficient calculation of the topographic effects, and refinement of topographic and gravity reductions
- Studies on harmonic upward and downward continuation
- Non-linear effects of the geodetic boundary value problem on geoid determination
- Optimal combination of global gravity models with local gravity data
- Exploration of numerical methods in solving the geodetic boundary value problem (domain decomposition, finite elements, and others)
- Studies on data requirements, data quality, distribution and sampling rate, for a cm- accurate geoid
- Studies on the interdisciplinary approach for marine geoid determination, e.g., research on realization of a global geoid consistent with the global mean sea surface observed by satellite altimetry
- Studies on airborne and ship-borne gravimetry and the Antarctica gravity field
- Studies on W_0 determination, and on global and regional vertical datum realization
- Studies on ocean, solid-Earth and polar tides
- Studies on time variation of the gravity field due to postglacial rebound and land subsidence
- Studies on geocenter movement and time variation of J_n and its impact on the geoid
- Studies on sea level change and vertical datum realization

Activities and results

The SC has proposed and participated in scientific meetings, summer schools, and seminars. Research results are presented at various meetings and conferences: AOGS-AGU (WPGM) Joint Assembly 13 - 17 August, 2012, Singapore; the International Symposium on Gravity, Geoid and Height Systems 2012, Venice; the IAG Scientific Assembly, September 1 - 6, 2013, Potsdam; and the annual scientific meetings AGU, CGU and EGU, as well as in scientific journals and proceedings.

During this report period (2011 - 2015), there are significant developments in every aspect of the determination of the Earth's gravity field. Evident improvement in determination of the gravity field at long wavelengths is contributed by the dedicated gravity satellite missions GRACE and GOCE (e.g., Fecher et al. 2011; Goiginger et al 2011; Gruber et al. 2011; Mayer-Gürr et al. 2012, 2015; Pail et al. 2011; Bettadpur et al. 2012; Bonin et al. 2013); improvement at medium wavelengths is achieved by airborne gravity projects (e.g., Forsberg et al.

2012; Smith et al. 2013; Preaux et al. 2011; Wang et al. 2013) on the local/regional scale. The forward modeling of the gravitational potential of the topography fills in the ultra-high frequency of the gravity field. The topography has been expanded into ultra-high spherical harmonics (e.g., Balmino et al. 2012; Hirt and Rexer 2015). Ellipsoidal expansion is also explored (Wang and Yang 2013).

Another major development is the effort on establishing global and regional vertical datums by the international community and cooperation between neighbouring counties (Sideris 2014; Smith et al. 2011; Lamothe et al. 2013; Liebsch et al. 2014). The vertical datums are gravimetric geoid based and their accuracy are verified by other independent data sets, such as the GPS/leveling, gravity and deflections of the vertical collected by the National Geodetic Survey (Smith et al. 2013). The dynamic effect of this datum is also studied by (Rangelova et al. 2012).

Time varying gravity has been successfully mapped by the satellite mission GRACE and GOCE globally. The gravity models have numerous applications in geodesy, glaciology, hydrology, oceanography and solid Earth Science.

Future Activities

The SC will work closely with the officers of commission 2 to promote the gravity filed determination through organizing meeting, conferences, seminars and summer schools. It encourages establishing special study groups on important contemporary research areas, e.g., the contribution of airborne gravimetry to the gravity field determination, establishment and maintenance of the global and regional vertical datums.

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Sub-Commission 2.3: Dedicated Satellite Gravity Missions

Chair: Roland Pail (Germany)

The main tasks of the Sub-Commission 2.3 are defined as follows:

1. generation of static and temporal global gravity field models based on observations by the satellite gravity missions CHAMP, GRACE, and GOCE, as well as optimum combination with complementary data types (SLR, terrestrial and air-borne data, satellite altimetry, etc.).
2. investigation of alternative methods and new approaches for global gravity field modelling, with special emphasis on functional and stochastic models and optimum data combination.
3. identification, investigation and definition of enabling technologies for future gravity field missions: observation types, technology, formation flights, etc.
4. communication/interfacing with gravity field model user communities (climatology, oceanography/altimetry, glaciology, solid Earth physics, geodesy, ...).
5. communication/interfacing with other IAG organizations, especially the GGOS Working Group for Satellite Missions and the GGOS Bureau for Standards and Conventions

Static and temporal global gravity field models

Activities and results

Sub-commission members are deeply involved in the derivation of new releases of global gravity field models based on GRACE and CHAMP mission data, applying updated background models, processing standards and improved processing strategies, e.g.: EIGEN-6S ([6]), AIUB-GRACE03S ([10]). In addition to improved static gravity field models, also monthly, 10-days, weekly and even daily GRACE solutions (GFZ, CSR, JPL, CNES-GRGS, Univ. Bonn/TU Graz) have been derived. The GRACE Science Data System has continued processing the latest releases 05 of monthly and weekly models. A time series for the whole mission lifetime April 2002 – February 2015 is available from all three centres (CSR, GFZ, JPL) except for periods where the accelerometer instrument unit and/or the microwave assemblies had to be switched off due to GRACE battery problems. Special emphasis has been given to the de-aliasing of short-term tidal gravity signal contributions, in order to reduce the unrealistic meridional striping patterns ([18]). For this, a procedure to correct inconsistencies in ECMWF's operational analysis data used to generate GRACE atmosphere and ocean de-aliasing level-1B products (AOD1B) has been developed ([3]). Additionally, the complete release 05 AOD1B time series has been reprocessed till 1979 in order to allow for a consistent processing of SLR and altimetry data ([5]). Compared to RL04, the current RL05 time-series shows improvements of about a factor of 2 in terms of noise reduction (i.e. less pronounced typical GRACE striping artefacts) and spatial resolution (cf. Fig. 1).

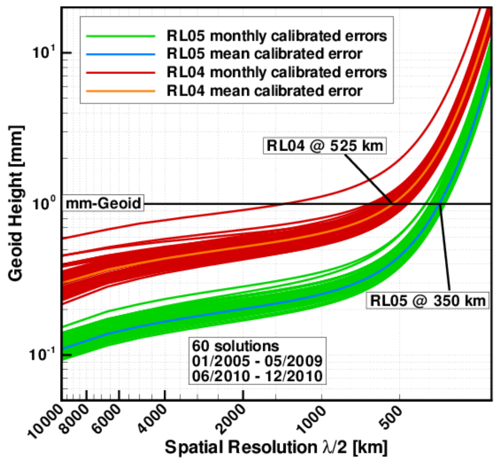

Figure 1: Degree variances of calibrated GRACE errors

Additionally, the static and temporal GRACE-only gravity models GGM05S ([16]) and ITSG-Grace2014s ([8]) have been released.

Several members of the SC 2.3 are also active participants in the ESA project GOCE High-Level Processing Facility (HPF), which is responsible for the generation of GOCE final orbit and gravity field products. This task is performed by a consortium of 10 university and research facilities in Europe. In the frame of this project, innovative strategies for the solution of several specific problems of high-level gravity field modelling, precise orbit determination and the analysis and calibration of space-borne accelerometer, gradiometer, and star-tracker observations have been investigated. An alternative algorithm for the angular rate reconstruction in the frame of the gravity gradient processing has been developed ([14]) implemented in the official ESA Level 1b processor ([15]), and the complete mission data has been reprocessed, leading to a substantial improvement of the gravity field solutions ([12]). In the report period the Releases 3 to 5 of GOCE Gravity field models have been computed and released. Three different strategies are applied for gravity field processing ([11]): the direct approach (DIR), the time-wise approach (TIM), and the space-wise approach (SPW). While the DIR models ([2]) are satellite-only combination models, the TIM models ([1]) are based solely on GOCE data. The newest DIR and TIM releases 5 comprise the GOCE data from the entire mission. The SPW approach has been redefined to provide gravity gradient grids mainly for geophysical users ([13]). These gravity field models have been externally validated applying different validation strategies ([7]). As an example, Fig. 2 shows the rms of geoid height differences between various GOCE models and 675 GPS/levelling observations in Germany.

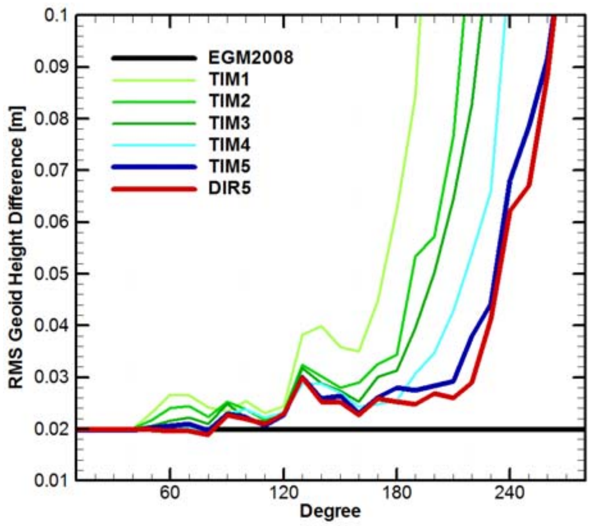

Figure 2: Rms of geoid height differences in Germany

In addition to these GOCE models, also combinations with complementary satellite data from GRACE, CHAMP and SLR such as GOCO05S ([9]), and additionally terrestrial and satellite altimetry data such as EIGEN-6C4 ([6]) and TUM2013C ([4]) have been computed with intense participation of members of the SC 2.3. EIGEN-6C3, the precursor model of EIGEN-6C4, has been selected by the Canadian Department of Natural Resource Funding (NRCan) as base model of the latest Canadian height reference system CGVD2013 (Canadian Geodetic Vertical Datum of 2013).

The potential of observing time-variable gravity from GOCE orbit and gradiometer data was investigated by [17].

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Alternative methods and new approaches for global gravity field modelling

Activities and results

Sub-commission members have actively contributed to the development and investigation of alternative methods of global gravity field modelling and related problems, such as the optimum combination of different gravity data types, and stochastic modelling issues. As an example, an alternative approach for the combination of high-resolution and satellite-only global gravity models has been proposed ([22]). An alternative solution could be found, by first performing local combinations exploiting the local characteristics of the gravity field (and of the available data), and then merging the different local solutions into a unique global one ([19], [20]). In any case, a crucial issue is the use of the error covariance information of the satellite-only models (e.g. the GOCE full error covariance matrix) when integrating them with local gravity data. Consequently, a strategy to make global and local covariances consistent with one another has to be devised; a preliminary study has been done by [21].

The dependency of the resolvable gravitational spatial resolution on space-borne observation was investigated by [23], and an improved sampling rule for mapping geopotential functions from a near polar orbit was derived ([24]).

Several members of the SC 2.3 have proposed a European Gravity Service for improved Emergency Management (EGSIEM, www.egsiem.eu) which is funded by the Horizon 2020 Framework Program within 2015 and 2017. EGSIEM aims to demonstrate the potential of GRACE and future GRACE-FO (Follow-on) data products to go beyond the state-of-the-art of flood and drought forecasting by adding a long-term water storage memory component to early warning services, potentially improving forecasting persistence and hence extending forecast lead-time. To this end, EGSIEM addresses three key objectives to establish 1) a scientific combination service to deliver the best gravity products for applications in Earth and environmental science research based on the unified knowledge of the European GRACE community, 2) a near real-time and regional service to reduce data product latency to 5 days and increase the temporal resolution of the mass redistribution to a daily product, 3) a hydrological and early warning service to develop gravity-based indicators for extreme hydrological events and to demonstrate their value for flood and drought forecasting and monitoring services.

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Future gravity field missions

Activities and results

Members of SC 2.3 were deeply in involved in national and international studies in the planning and design of future gravity field missions. On ESA level, during the reporting period two studies on the "Assessment of a next Generation Mission for Monitoring the Variations of Earth Gravity" were conducted in parallel by joint industrial and scientific consortia and meanwhile have been finalized ([25] and [34]). Goals of these studies were the definition of mission requirements resulting from science requirements, the definition of measurement objectives and the required performance, the identification of engineering requirements for key technology, a complete mission analysis, and finally an end-to-end simulation by means of numerical methods.

Further studies and mission proposals on national and international level have been worked out during the reporting period. Several German members of the SC 2.3 were involved in a German preparatory study "NGGM-Germany" funded by the German Aerospace Center (DLR) for a future gravity field mission constellation in preparation of the upcoming call for ESA Earth Explorer 9 ([30]).

Members of this SC play a central role in the implementation of the next gravity field mission, i.e. the US-German project GRACE Follow-on (GRACE-FO) under MoU between NASA and GFZ ([28]). The primary objective of GRACE-FO is to continue the current GRACE gravity data series with a gap as short as possible. Therefore it is essentially a re-build of GRACE using the same microwave inter-satellite ranging system. In addition, as a secondary objective, it will carry an experimental Laser Ranging Interferometer (LRI) intended as technology demonstrator for future missions ([35]). The LRI will measure with about 20-30 times less measurement noise and provide in addition precise data about the orientation of each spacecraft with respect to the line of sight to the other spacecraft. This additional data will allow mutual comparisons and diagnostics between the microwave and laser systems. Preparations for the required new data analysis algorithms are already under way. The LRI is a joint development of NASA/JPL and a German team under the technical leadership of the AEI Hannover and general management by GFZ. The project passed its Critical Design Review in February 2015. The System Integration Readiness Review in July 2015 is the next major milestone towards launch in August 2017.

The COSMIC-2 is a joint Taiwan-US mission for radio sounding of the atmosphere and ionosphere using GNSS. The mission will deploy a constellation of 12 satellites at inclinations from 24 to 72 degree and varying altitudes, each equipped with an SLR retro-reflector. In 2016, the first 6 of the 12 satellites will be launched, and the remaining 6 will be launched in 2018. The tri-G GNSS receivers of the COSMIC-2 satellites will deliver sub-cm accuracy in the kinematic orbits, which will be assessed by SLR observations to the satellites. With proper models of the surface forces and cm dynamic orbits of the COSMIC-2 satellites, one can estimate gravity fields from the kinematic-dynamic orbit differences of the 12 COSMIC-2 satellites up to a medium harmonic degree at perhaps one month interval. The result will benefit time-varying gravity observations and applications. Additionally, the potential of deriving temporal gravity from the Iridium Next Generation was investigated ([31]).

Several scientific studies on specific challenges of future gravity field missions have been investigated, such as improved de-aliasing of atmosphere and ocean signals ([27]), improved de-aliasing methodology by including covariance information of the background models ([37]), the optimum orbit choice for aliasing reduction ([32]), an improved spatio-temporal parameterization of the time-variable gravity field ([36]), and the impact of numerical processing errors on future gravity missions with improved sensor accuracy ([26]). A global mass transport model, which is used for future mission simulations, was developed ([29]), and updated by [27].

On an organizational and programmatic level, in a joint initiative of SC 2.3 and the GGOS Satellite Mission Working Group a letter by the IUGG President Harsh Gupta to ESA and NASA was triggered, which expresses the strong need of the science community for a future gravity field mission, in accordance with the IUGG 2011 Resolution 2: „Gravity and magnetic field missions". Under the umbrella of the International Union of Geodesy and Geophysics (IUGG) and as a joint initiative with the Global Geodetic Observing System (GGOS) of International Association of Geodesy (IAG) Sub-Commission 2.3, a document on consolidated science and user needs has been set up by a representative panel of international experts covering the main fields of application of satellite gravimetry (continental hydrology, cryosphere, ocean, solid Earth, atmosphere) and representing five member associations of IUGG ([33]). Figure 3 shows the scientific and societal challenges that have been identified for a future sustained satellite gravity observing system.

Additionally, members of the SC support the activities of the NASA/ESA Interagency Gravity Science Working group aiming at the realization of a joint future gravity mission constellation.

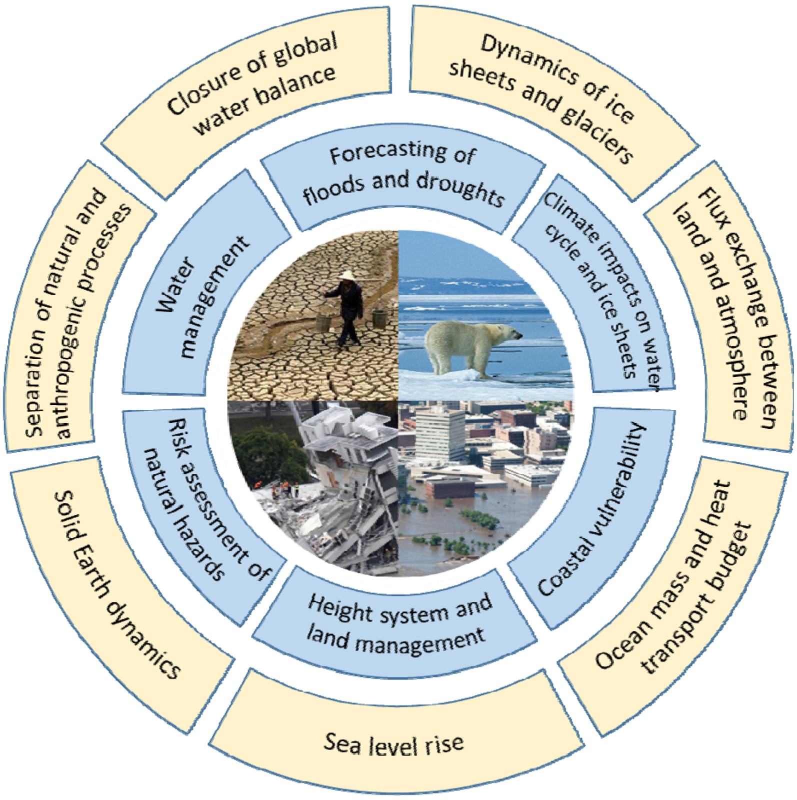

Figure 3: Main scientific (yellow) and societal (blue) objectives addressed by a future sustained satellite gravity observing system.

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Communication / interfacing with user communities

Activities and results

In the course of the preparation of the Science and User Needs document for a future sustained satellite gravity observing system, an international user workshop with about 40 international participants covering all main application fields was held on 26/27-09-2014 in Herrsching/Munich.

Online service access points for geoscientific data products, such as the Information System and Data Center (ISDC) portal maintained by the GFZ ([39]) show a steadily growing number of users from various user communities (climatology, oceanography, glaciology, geodesy, solid Earth physics, etc.).

The International Center for Global Earth Models (ICGEM; [38]) has been furthermore well established as user service component of the International Gravity Field Service (IGFS) of the IAG. ICGEM is also maintained by GFZ and comprises a widely used archive of all existing global gravity field models and an increasingly used service for calculation and visualization of gravity field functionals.

Selected References

[38] http://icgem.gfz-potsdam.de

[39] http://isdc.gfz-potsdam.de

Communication / interfacing with other IAG organizations

Activities and results

A strong interface has been built with the GGOS Bureau of Networks and Observations and the GGOS Satellite Mission Working Group therein, as well as the GGOS Bureau for Standards and Products, where members of the SC2.3 play an active role, especially concerning the definition of consistent gravity standards ([40]) and vertical reference systems.

Selected References

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Sub-Commission 2.4: Regional Geoid Determination

Chair: Hussein Abd-Elmotaal (Egypt)

Webpage: http://www.minia.edu.eg/Geodesy/Comm2.4/

The main purpose of Sub-Commission 2.4 is to initiate and coordinate the activities of the regional gravity and geoid sub-commissions. These have been re-structured from the former regional geoid projects into SCs in 2011 in order to give them a more long-term character. Currently there are 6 of them:

SC 2.4a: Gravity and Geoid in Europe (chair H. Denker)

SC 2.4b: Gravity and Geoid in South America (chair M.C. Pacino)

SC 2.4c: Gravity and Geoid in North and Central America (chair D. Avalos)

SC 2.4d: Gravity and Geoid in Africa (chair H. Abd-Elmotaal)

SC 2.4e: Gravity and Geoid in the Asia-Pacific (chair W. Featherstone)

SC 2.4f: Gravity and Geoid in Antarctica (chair M. Scheinert)

The chair persons of these regional SCs form the steering committee of SC2.4.

These regional SC nominally cover the whole world with the exception of a larger region in the middle east (see Figure 1). 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.

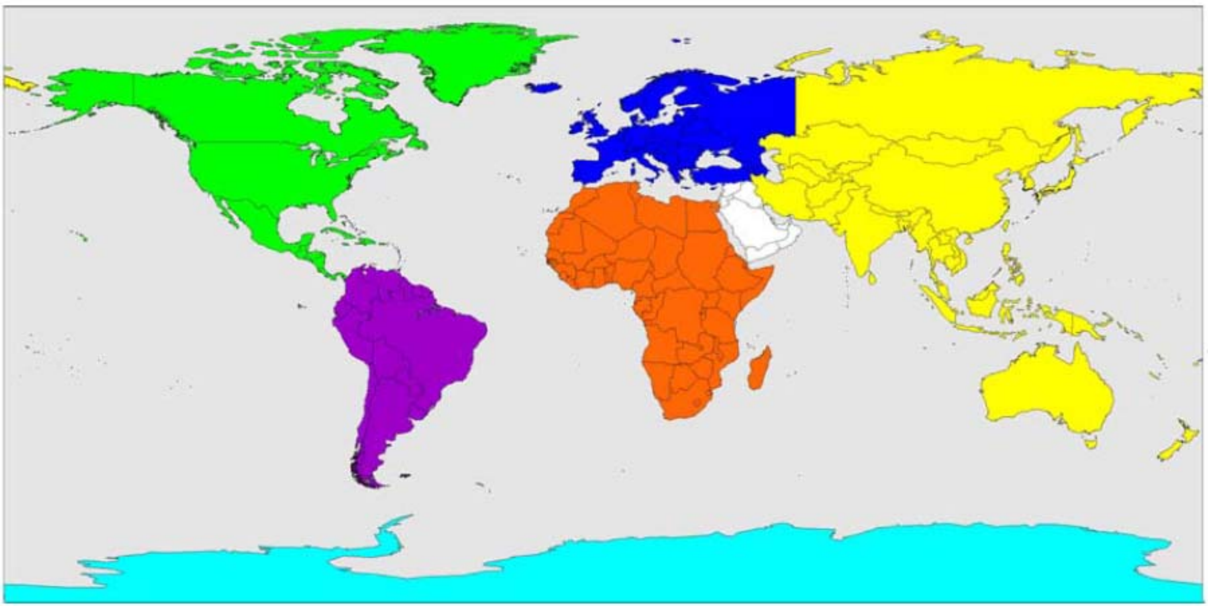

Figure 1: Coverage of the regional sub-commissions

In comparison to the former regional geoid projects the covered areas have been extended in 2 cases:

a) Central America and the Caribbean are associated with the North American SC. But there is a very close collaboration as well with the South American SC in some countries.

b) The former regional geoid project of South Asia and Australia has been extended to all 48 member countries of PCGIAP (Permanent Committee for GIS Infrastructure for Asia and the Pacific). In the case of gravity field determination, the collaboration of these countries is not very strong.

Short summary of the activities of the regional SCs

SC 2.4a (Europe) is going to release a new computation of the European geoid/quasigeoid in 2015. Due to the already very good quality of the gravity data set, improvements by including GOCE data, are expected only in some limited areas. New terrestrial gravity data will be available for some countries (Germany, Bulgaria).

SC 2.4b (South America) is improving the gravity data coverage and the corresponding data-base in several countries by activities of many groups. A new geoid model Geoid2014 was presented and a continental adjustment of the leveling network is under way.

SC 2.4c (North and Central America) extended their activities into several countries of Central America and the Caribbean and good contacts have been established. Good contacts exist as well with the South American SC and several North American universities. The main goal is in definition of a common North American height datum and in some countries the education for setting up national gravity networks and the calculation of national/regional geoid models. Several meetings about vertical networks and geoid determination have been organized in the region.

SC 2.4d (Africa) is trying to improve the collaboration between the countries and to collect the available terrestrial gravity data from different sources. Many tests are made with the newly available satellite data and with global and national DHMs. An IUGG project "Detailed Geoid Model for Africa" has been carried out. A new geoid model for Africa is going to be presented in IUGG2015.

SC 2.4e (Asia Pacific) was not very active. There were some contacts through the PCGIAP, which still have to be improved. It is very difficult to make contacts and, moreover, get data in this region. In this region, most activities still remain on the national level, where good results were presented in several countries. The chair of the SC proposes to not continue it in its present form.

SC 2.4f (Antarctica) is active in trying to densify the gravity data coverage mainly by airborne but also be terrestrial campaigns. Other activities include getting access to already existing data. The publication of a gridded gravity data set and a geoid model is planned for the near future.

SC 2.4 very active in organising courses and related sessions at international conferences such as the GGHS2012 conference in Venice (2012), the IAG Scientific Assembly in Potsdam 2013, and the IGFS2014 in Shanghai.

Meetings of the steering committee of SC 2.4 toke place at the commission 2 meetings during IAG2013 in Potsdam and during IGFS2014 in Shanghai.

Sub-Commission 2.4a: Gravity and Geoid in Europe

Chair: Heiner Denker (Germany)

The topic of regional geoid determination was handled from 2003 – 2011 within Commission 2 Projects, and since 2011 the responsibility for this task is within Sub-Commission 2.4, which is further sub-divided according to different regions of the world, such as Sub-Commission SC 2.4a "Gravity and Geoid in Europe". 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, geophysics and engineering, e.g., height determination with GNSS techniques, vertical datum definition and unification, dynamic ocean topography estimation, geophysical modelling, and navigation. SC 2.4a has cooperated with national delegates from nearly all European countries, whereby existing contacts have been continued and extended.

The last complete re-computation of the European geoid/quasigeoid was EGG2008 (European Gravimetric Geoid 2008); the used theory, possible refinements, the detailed computation procedure, as well as applications such as height datum unification are described in a monograph published by Denker (2013). Besides this work, the efforts concentrated on the use of the available GOCE global geopotential models, which were first evaluated by the existing terrestrial gravity field data sets, showing that the GOCE models improved from release to release with the inclusion of longer observation time series. The agreement between the latest GOCE models (5th generation) and terrestrial data is about 2-3 cm for height anomalies, 1 mGal for gravity anomalies, and 0.3" for vertical deflections, respectively, being fully compatible with the relevant error estimates. The combination solutions based on GOCE and terrestrial data perform in many cases similar to corresponding calculations relying on EGM2008, which is due to the high quality of the European data sets utilized in the EGM2008 development; however, in several areas with known weaknesses in the terrestrial gravity data (e.g., Bulgaria, Romania, etc.), the inclusion of the GOCE models instead of EGM2008 leads to significant improvements in terms of GPS/leveling fits, especially regarding the 5th generation GOCE models. Several of the GOCE investigations were carried out in the framework of the REAL GOCE project funded by the German Ministry of Education and Research (BMBF) and the German Research Foundation (DFG); for further details see Ihde et al. (2010) as well as Voigt and Denker (2011, 2014a/b/c, 2015). Furthermore, regional gravity field computations based on the point mass modelling approach were investigated by Lin et al. (2014).

Besides the global geopotential models, also selected terrestrial gravity data sets were upgraded and extended, e.g., in Germany and Bulgaria. Regarding Bulgaria, it appears that the recently supplied point gravity values can replace the previously existing mean values. A few other countries were also approached and provided some smaller updates of the existing gravity data sets. In addition, own gravity measurements around the metrological institutes in France, Germany, Italy and the United Kingdom were collected and used to extend the existing data base. The latter observations are related to the ITOC (International Timescale with Optical Clocks) project, in which the Leibniz Universität Hannover is involved through a so-called Researcher Excellence Grant (REG), funded by the European Metrology Research Programme (EMRP). The ITOC project is aiming at the comparison of optical clocks with a projected performance at the level of 10^{-18}, and according to the laws of general relativity, such clocks are sensitive to the gravity potential equivalent to 1 cm in height. Hence, the optical clocks may offer in the near future completely new options to independently observe and verify geopotential differences over large distances; for further details on the entire ITOC project see Margolis et al. (2013).

A complete re-computation of the European quasigeoid (EGG2015) based on the 5th generation GOCE geopotential models shall be presented at the coming 26th IUGG General Assembly 2015. The new model will be evaluated by different national and European GPS and levelling data sets, where emphasis is put on the effect of the data updates and the modeling 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 will be discussed.

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

Chairs: Maria Cristina Pacino (Argentina), Denizar Blitzkow (Brazil)

Primary Objectives

The project entitled Gravity and Geoid in South America, as part of the Sub-commission 2.4b of IAG, was established as an attempt to coordinate efforts to establish a new Absolute Gravity Network in South America, to carry out gravity densification surveys, to derive a geoid model for the continent as part of the height reference and to support local organizations in the computation of detailed geoid models in different countries.

Besides, a strong effort is being carried out in several countries in order to improve the distribution of gravity information, to organize the gravity measurements in the continent and to validate the available gravity measurements.

Activities

Introduction

This report shows the many activities going on by different organizations like universities and research institutes. Due to the big efforts undertaken by the different organizations in the last few years to improve the gravity data coverage all over the countries there are available at the moment approximately 892,604 gravity data points in South America. Figure 1 shows gravity data distribution.

Geoid Model

A new version of the geoid model for South America (Geoid2014) was computed, limited by 15º N and 57º S in latitude and 30º W and 95º W in longitude (Blitzkow et al., 2014). The terrestrial gravity data for the continent have been updated with the most recent surveys. The complete Bouguer and Helmert gravity anomalies have been derived through the Canadian package SHGEO (Ellmann and Vaníček, 2007). The oceanic area was completed with the mean free-air gravity anomalies derived from a satellite altimetry model by the Danish National Space Center, called DTU10 (Andersen, 2010). The short wavelength component was estimated via FFT with the modified Stokes kernel proposed by Featherstone (2013). The model was based on EIGEN-6C3stat up to degree and order 200 as a reference field (Sako et al., 2014). A zero degree term of -0.41 m was added, see Figure 2. This converts geoid undulations that are intrinsically referred to an ideal mean-earth ellipsoid into undulations that are referred to WGS 84.

Evaluation of Geopotential Models

This report focuses on GOCE GGMs. Table 1 shows the characteristics of the models considered: name, year of GGMs publication, maximum spherical harmonic degree and input data information. GO_CONS_GCF_2_DIR_R5 (DIR_R5) is a satellite-only model based on a full combination of GOCE-SGG with GRACE and LAGEOS. It was produced by GFZ German Research Centre (GFZ) for Geosciences Potsdam and Groupe de Recherche de Géodésie Spatiale (GRGS)/CNES, Toulouse (Bruinsma et al., 2013), GO_CONS_GCF_2_TIM_R5 (TIM_R5) is the 5th release of the GOCE gravity field model computed by time-wise approach. It was produced by Graz University of Technology, Institute for Theoretical and Satellite Geodesy University of Bonn, Institute of Geodesy and Geoinformation TU München, Institute of Astronomical and Physical Geodesy (IAPG) (Pail et al., 2011**)**. GFZ and GRGS/CNES produced EIGEN-6C4, which is a global combined gravity filed model (Shako et al., 2014; Förste et al., 2014). The others satellite-only models studied are GOGRA04S and JYY_GOCE04S, produced by IAPG, TU München (Yi et al., 2013). Finally, GOCO03S model has been produced by the Gravity Observation Combination (GOCO) in 2012. It is an initiative of TU München, Institute of Astronomical and Physical Geodesy; Univ. Bonn, Institute of Geodesy and Geoinformation; TU Graz, Institute of Theoretical and Satellite Geodesy; Austrian Academy of Sciences, Space Research Institute; Univ. Bern, Astronomical Institute. It is a satellite-only model and uses GOCE and GRACE satellites (Mayer-Gürr, et al., 2012).

GPS observations carried out on benchmarks of the spirit levelling network in South America, which have been delivered under the SIRGAS (Geocentric Reference System for Americas) project (Hoyer et al., 1998; SIRGAS, 1997), were used for testing the selected GGMs and the geoid model. At the moment there are GPS/BM data available from the following countries: Argentina, Brazil, Chile, Ecuador, Uruguay and Venezuela, in a total of 1,861 points (Figure 3).

The geoidal heights associated with GPS/BM have their inaccuracies due to the error of the spirit levelling as well as of the GPS. The GPS/BM information is still sparse, without a homogeneous distribution, so that this result is geographically limited, but the mentioned comparison is very much useful to look after the consistency between the two heights. The original ellipsoidal heights derived from the GPS measurements refer in principle to a tide-free *(tf)* system in terms of the treatment of the permanent tide effect (Poutanen et al., 1996). However, as no tidal correction was applied to the height observations of the levelling network, the available normal orthometric heights refer, in principle, to a mean-tide system (*mt*) (Ferreira et al., 2013).

For the present analysis, these values were transformed into the tide-free system by using the formula (Tenzer et al., 2010),

$$H_{tf} = H_{mt} + \left\{(1 + k - h)\left[-0.198\left(\frac{3}{2}\sin^2\varphi - \frac{1}{2}\right)\right]\right\} \quad (1)$$

where k and h are the tidal Love numbers and their values are 0.3 and 0.62, respectively, and φ is the geocentric latitude. This was necessary because the GPS and the applied GGMs are related to a tide-free system.

Table 2 shows the results in terms of mean value, RMS difference, standard deviation (σ) difference, extreme values of the differences among height anomalies of several GGMs (maximum degree) and GEOID2014 geoidal heights with GPS/BM geoidal heights.

Figures 3 and 4 show the GPS/BM distribution with a colour palette for differences between GPS/BM geoidal heights and EIGEN6C4 and DIR_R5 height anomalies, respectively. Figures 5 shows map of the discrepancies between GPS/BM and GEOID2014 model, respectively. Almost 50% of the discrepancies in absolute terms are around 0.2 meters, which is within the GPS/BM points inaccuracies.

Table 3 shows RMS differences among GPS/BM geoidal heights with GGMs height anomalies (max degree) and GEOID2014 geoidal heights for each country. It is possible to observe that the zero degree term added in the geoid model shows a worse result for Argentina and Ecuador, not for other countries. For example, in Argentina, the RMS difference between GPS/BM and GEOID2014 is 0.60 m (Table 3). But, RMS difference with respect to GEOID2014, without zero degree term, is 0.30 m and, just in the Buenos Aires province, is 0.21 m. The vertical datum is not the same for different countries. For example, the vertical datum discrepancy between Brazil and Argentina is higher than 20 cm, and Brazil and Ecuador is higher than 80 cm (Sánchez and Brunini, 2009; Sánchez, 2005). The height difference of each country was not corrected for the discrepancies. Although zero degree term has no relation with the difference between the vertical datum of each country, it emphasizes eventually these differences.

The gravity disturbances derived from EIGEN6C4 and EGM08 show the best agreement when compared with terrestrial gravity anomalies. Table 4 shows the results in terms of mean value, standard deviation (σ) difference, RMS difference and extreme values of the differences between gravity anomalies derived from terrestrial gravity data and gravity disturbances derived from GGMs. Most of the still existing inconsistencies of this GGM are in mountainous regions, mainly in the Andes.

The general conclusion is that the recent geopotential models represent an important improvement on the knowledge of the gravitational potential in South America.

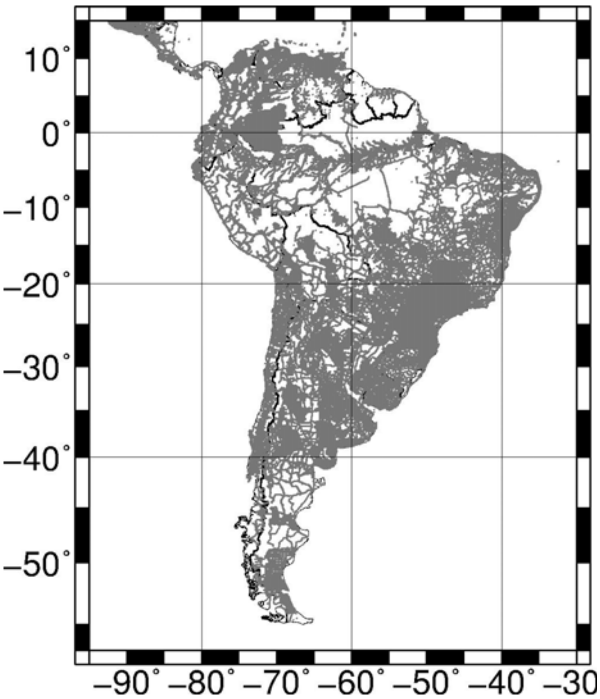

Figure l: South America gravity data

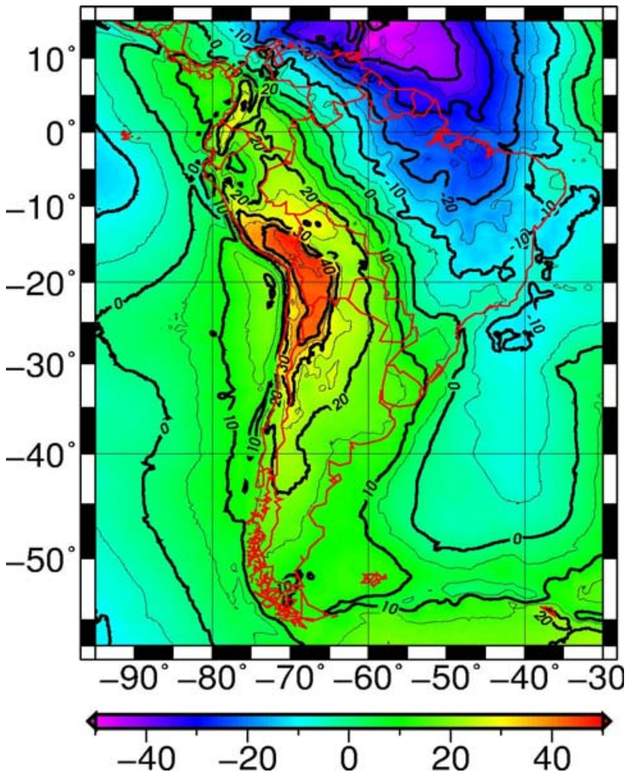

Figure 2: South America geoid model

Table 1 –GGMs used

Model	Year	Degree	Data
EIGEN-6C4	2014	2190	S(Goce,Grace,Lageos),G,A
TIM_R5	2014	280	S(Goce)
DIR_R5	2014	300	S(Goce,Grace,Lageos)
JYY_GOCE04S	2014	230	S(Goce)
GOGRA04S	2014	230	S(Goce,Grace)
GOCO03S	2012	250	S(Goce,Grace,...)
EGM2008	2008	2190	S(Grace),G,A

Source: International Centre for Global Earth Models (ICGEM) - Satellite (S); airborne and terrestrial gravity (G); Altimetry (A) survey.

Table 2 - Statistics of the differences between GPS/BM geoidal heights and height anomalies of the GGMs (max degree) for South America in meters.

	EGM2008	GOCO03S	JYY_GOCE04S	GROGA04S	TIM_R5	DIR_R5	EIGEN6C4	GEOD2014
Mean	-0.31	-0,28	-0,29	-0,29	-0,32	-0,32	-0,32	0,17
σ diff	0.46	0,61	0,59	0,58	0,54	0,54	0,44	0,52
RMS diff	0.55	0,67	0,65	0,65	0,63	0,63	0,55	0,55
Max.	2.10	2,57	2,46	2,47	2,48	2,58	2,09	2,24
Min.	-3.42	-2,80	-2,88	-2,88	-2,91	-2,94	-3,74	-2,55

Table 3 - RMS difference between GPS/BM geoidal heights and height anomalies of the GGMs (max degree) for each country in meters.

	EGM2008	GOCO03S	JYY_GOCE04S	GROGA04S	TIM_R5	DIR_R5	EIGEN6C4	GEOD2014
Argentina	0.30	0.34	0.34	0.34	0.32	0.33	0.29	0.60
Brazil	0.57	0.64	0.64	0.63	0.64	0.64	0.57	0.44
Chile	0.65	0.94	0.64	0.79	0.70	0.68	0.76	0.76
Ecuador	0.80	1.158	1.12	1.125	1.06	1.07	0.72	1.18
Uruguay	0.63	0.65	0.58	0.59	0.63	0.63	0.65	0.67
Venezuela	0.49	0.82	0.85	0.85	0.77	0.76	0.49	0.47

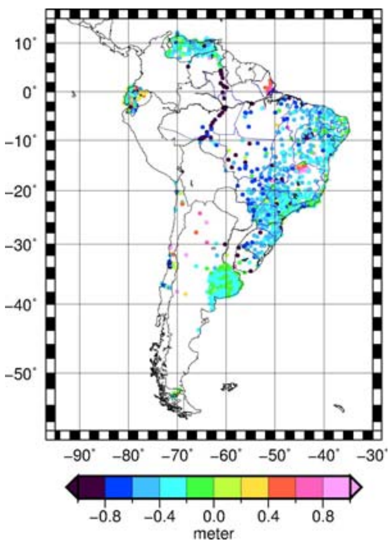

Figure 3 - Distribution of the GPS/ BMs and illustration of the differences between GPS/BM geoidal heights and EIGEN6C4 (max. degree) height anomalies.

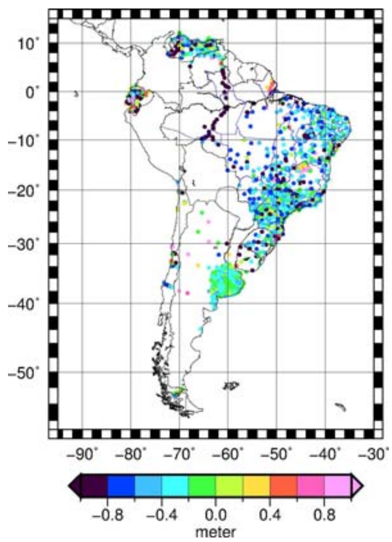

Figure 4 - Distribution of the GPS/ BMs and illustration of the differences between GPS/BM geoidal heights and DIR_R5 (max. degree) height anomalies.

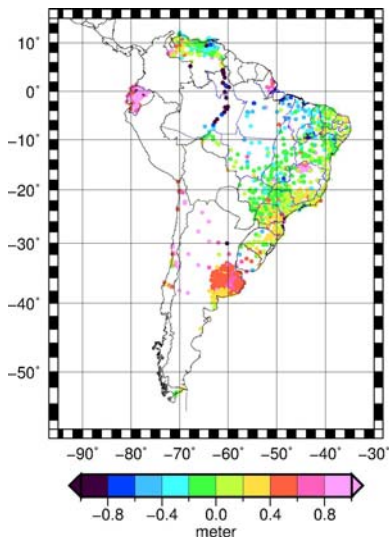

Figure 5 - Distribution of the GPS/ BMs and illustration of the differences between GPS/BM and GEOID2014 geoidal heights.

Table 4 - Statistics for the discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs (max degree) in mGal.

	EGM2008	GOCO03S	JYY_GOCE04S	GROGA04S	TIM_R5	DIR_R5	EIGEN6C4
Mean	0.97	-5.82	-5.72	-5.73	-5.14	-5.19	1.81
σ diff	14.38	25.83	25.53	25.53	24.71	24.51	14.48
RMS diff	14.41	26.48	26.17	26.17	25.24	25.06	14.59
Max.	301.59	282.20	284.27	284.39	285.42	286.53	304.81
Min.	-369.09	-369.18	-360.03	-360.21	-358.51	-351.16	-518.32

Activities undertaken by IBGE related to the Vertical Reference Network (VRN)

In 2011 a considerable effort has been carried out on the re-adjustment of the leveling network. Many special attentions have been dedicated to issues like identifications of BMs, materialization and connection of BM with gravity and coordinates derived from GPS. Revision of the description of the BM with comparison to Google Earth. Temporal analysis of leveling sections from 1945 to 2010, in a total of 74.169. Files reformatting for processing with GHOST. New leveling campaigns supported by GPS for inconsistencies checking. The final result have been the inclusion of 69,590 new BMs in the data base.

Leveling network densification: There are efforts in the densification of the levelling network in the last 3 years in different parts of Brazil, like states of Ceará, São Paulo, Minas Gerais, Pernambuco and Amapá. In the last three years a total of 1,006 have been established and measured with electronic level LEICA.

A continuous attention is addressed to the Brazilian Network of Tides. A total of 5 stations exist along the coast. (Imbituba, Macaé, Salvador, Fortaleza and Santana)

IBGE is maintained a special attention to the gravity surveys for the improvement on the geoid model in Brazil. In 2011 a total of 34,000 gravity points were reprocessed with attention to the height values derived from the new adjustment of the leveling network. A big effort was addressed to gravimetric surveys in São Paulo, Minas Gerais, Santa Catarina, Rio Grande do Norte, Ceará, Mato Grosso do Sul, Goiás, Paraiba and Sergipe states with a total of 5,017 new gravity stations.

A geoid model is in preparation at the moment to be accomplished until October in substitution to MAPGEO1010. It will include airborne gravity data in Amazonas and in Paraiba basin.

The activities related to Geodetic Reference Network included GPS processing of many points and the maintenance of the PPP (Precise Point Positioning) service at IBGE website.

Weekly processing of SIRGAS network and RBMC (*Rede Brasileira de Monitoramento Contínuo;* in English: Brazilian Network for Continuous Monitoring). The maintenance of RBMC is the object of a special attention of IBGE.

Earth Tide Program

University of São Paulo, GEORADAR supported by a few organizations are 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, already measured, Proto Velho, Manaus, under observations at the moment, Brasília, Fortaleza, Salvador, Cuiabá, Campo Grande, Curitiba and Santa Maria, to be observed in the future. For this purpose two gPhone gravity-meters are available. Figure 6 shows the distribution of the stations. Figure 7 shows the results for 5 stations already observed.

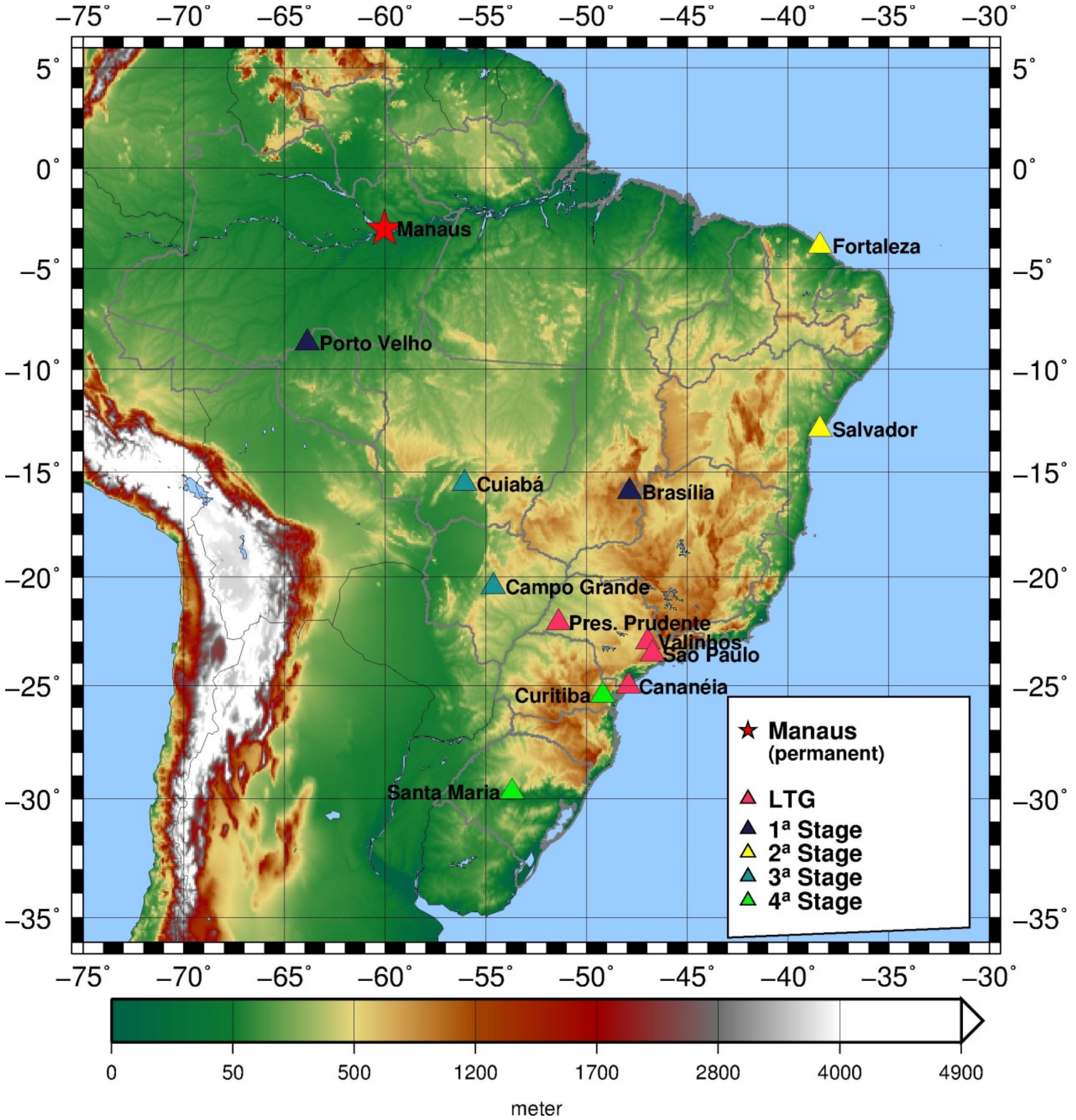

Figure 6 - Distribution of sites to be observed for Earth tides.

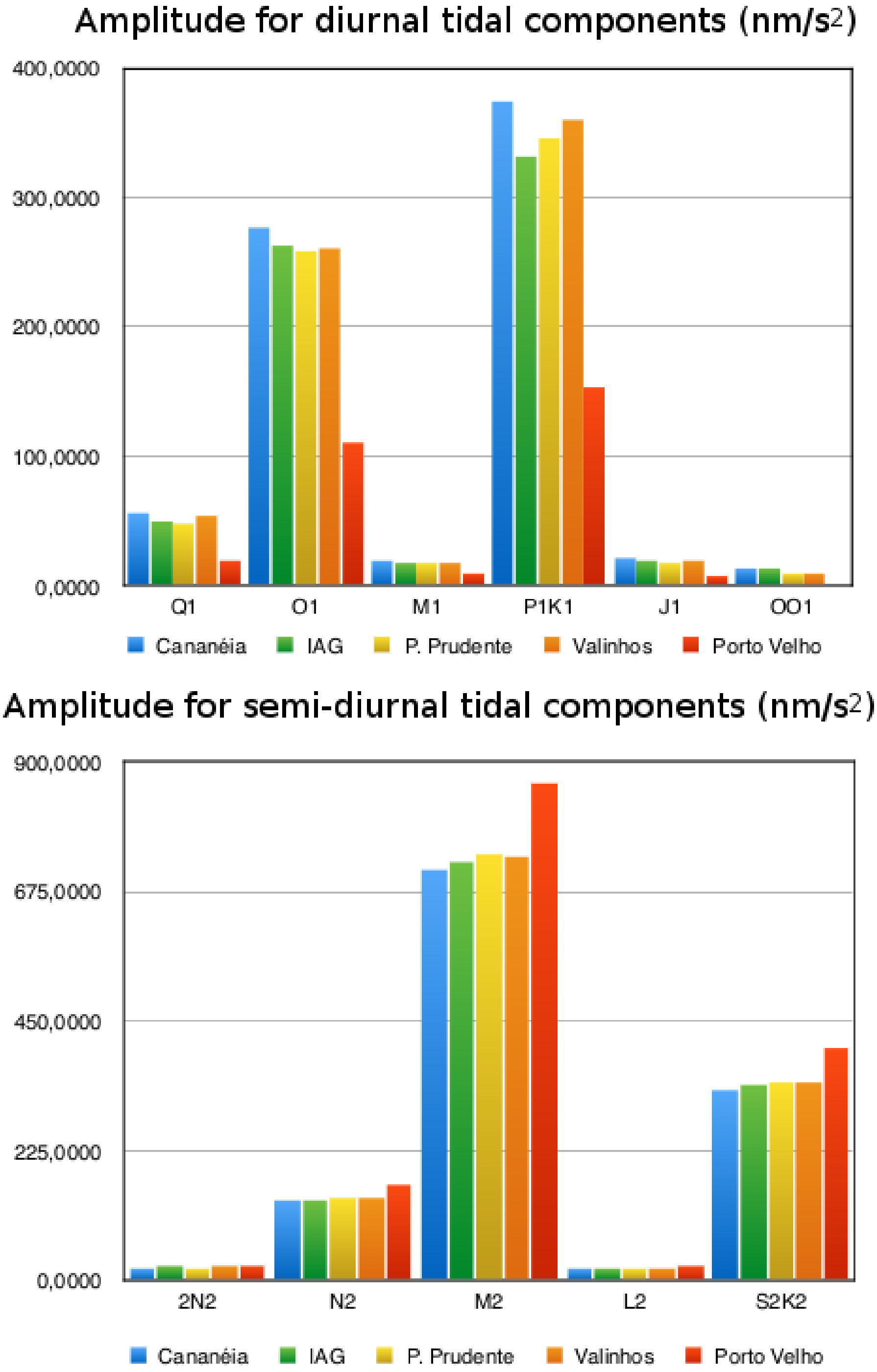

Figure 7 - Results for 5 stations already observed.

Absolute gravity network

The Institute of Geography and Cartography of the state of São Paulo has a gravity meter A-10 under the responsibility of the University of São Paulo (Figure 8). The gravity meter is involved in many different activities in Brazil, Argentina and Venezuela with intentions to undertake measurements in Ecuador, Peru, and possibly other countries. Figure 9 shows the establishment since 2013 of the new (green point) and reoccupied (red points) absolute stations in São Paulo State. The idea is to establish an absolute gravity network in South America.

Figure 8 - Absolute gravitymeter A10-32.

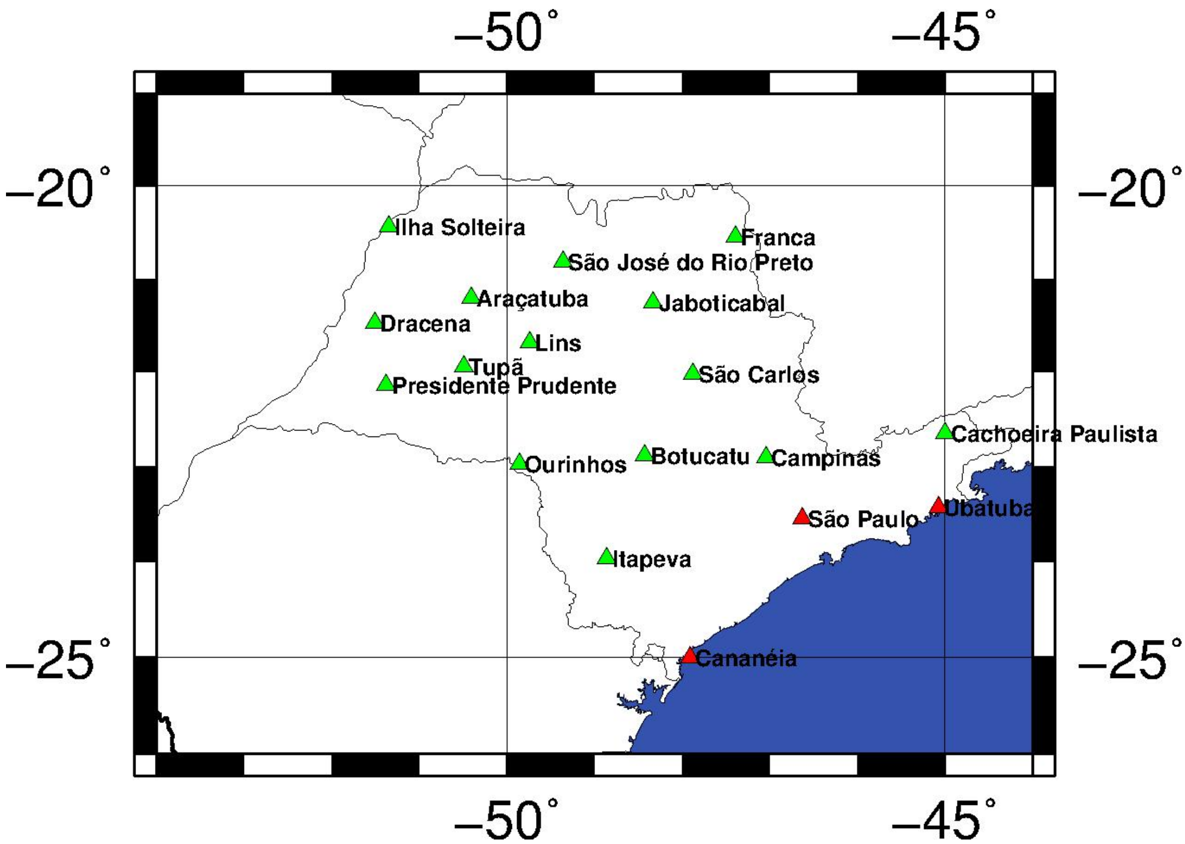

Figure 9 - Absolute gravimetric station in São Paulo State.

In 2011, during a vertical datum workshop organized by the Subcommittee of Geodesy of the National Committee of the International Union of Geodesy and Geophysics (IUGG) held in the National University of Rosario, the determination of a new first-order gravimetric network to replace BACARA (Figure 10), which was measured in 1968, was proposed.

Therefore, in 2012, the Argentinean National Geographic Institute (IGN), together with the National Universities of Rosario, San Juan and La Plata, started the gravimetric surveys along the country. Five relative gravimeters were used (i.e. 3 LaCoste & Romberg and 2 Scintrex CG-5) to measure approximately 85% of the 250 proposed sites (Figure 11), which were co-located with altimetry benchmarks. The computations were performed using GRAVDATA (Drewes, 1978) and GRAVDJ (Forsberg, 1981) software, and applying the Hartmann and Wenzel (1995) tidal potential catalogue. The gravity observations were adjusted to the absolute RAGA network (Figure 12) and the standard error of the final gravity values was less than ± 0.04 mGal.

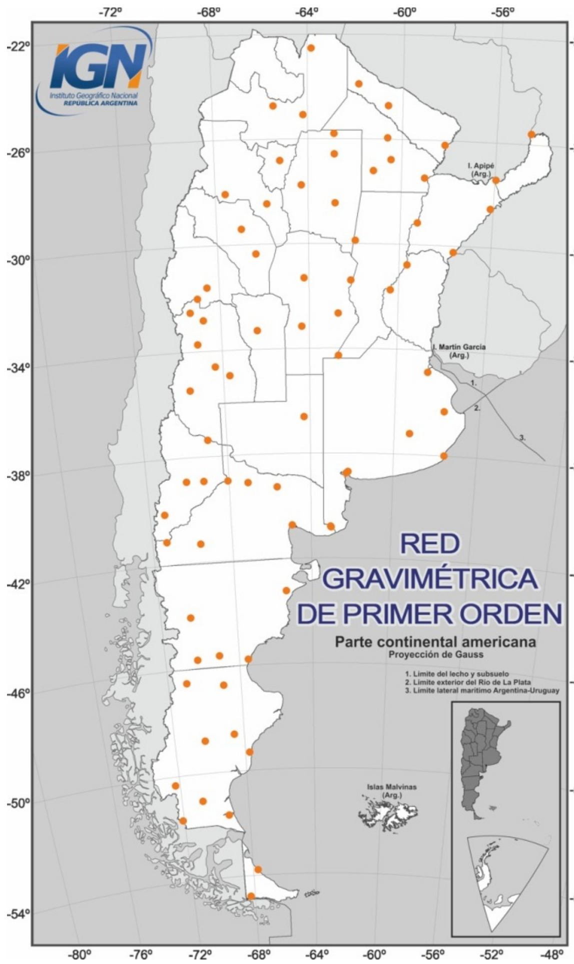

Figure 10: BACARA gravity network

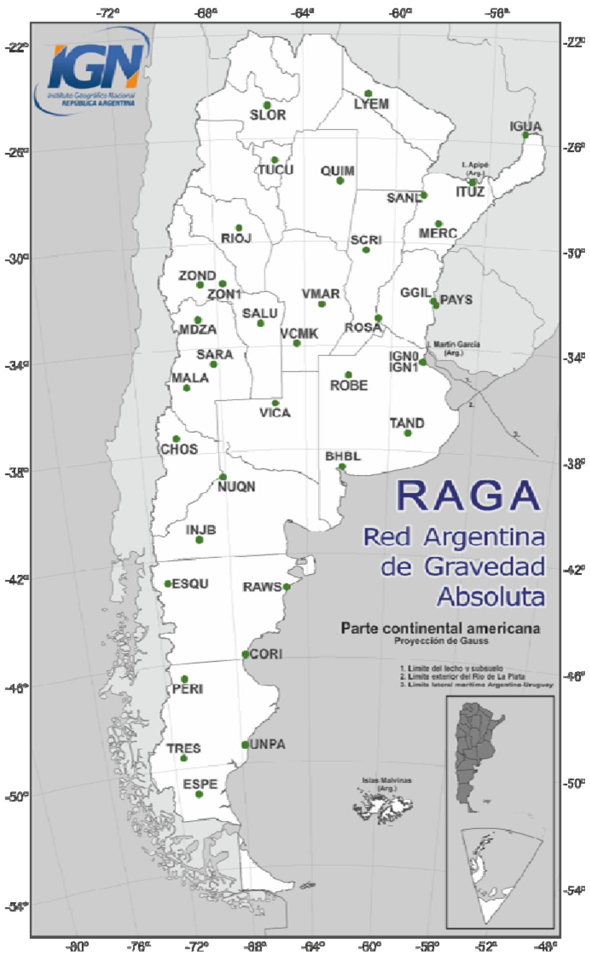

Figure 11: Absolute gravity network

In 2014, the IGN started a new project in order to readjust the second-order gravity network (Figure 13), which is co-located with the first-order leveling network. Therefore, all the original gravimetric surveys, which were carried out since 1950s using different relative gravimeters (i.e. Western, Worden, LaCoste & Romberg and Scintrex), were computed and adjusted to RAGA network using GRAVDATA (Drewes, 1978) and GRAVDJ (Forsberg and

Tscherning, 1981) software. The gravity standard error of the approximately 15,000 sites was estimated at ± 0.1 mgal.

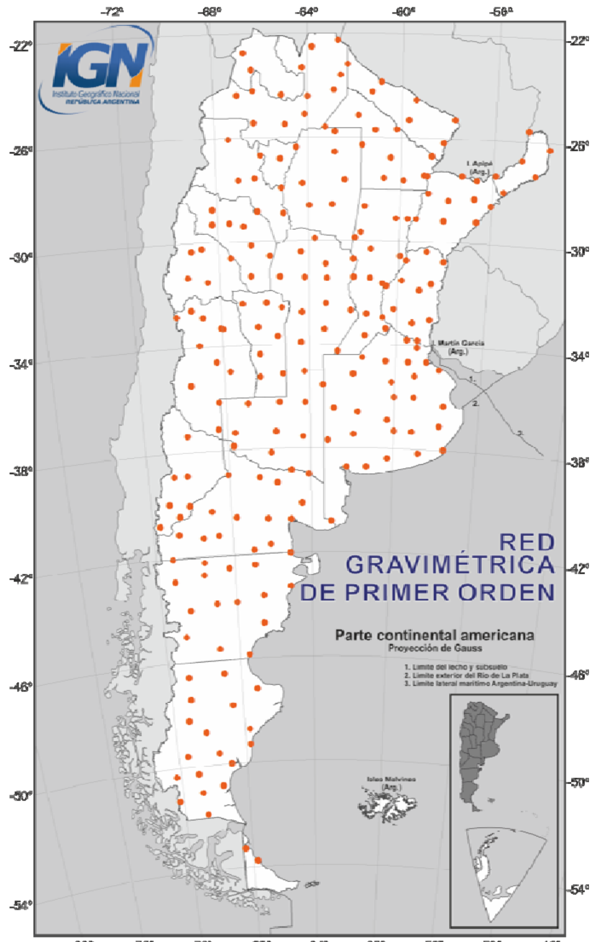

Figure 12: new first-order gravity network

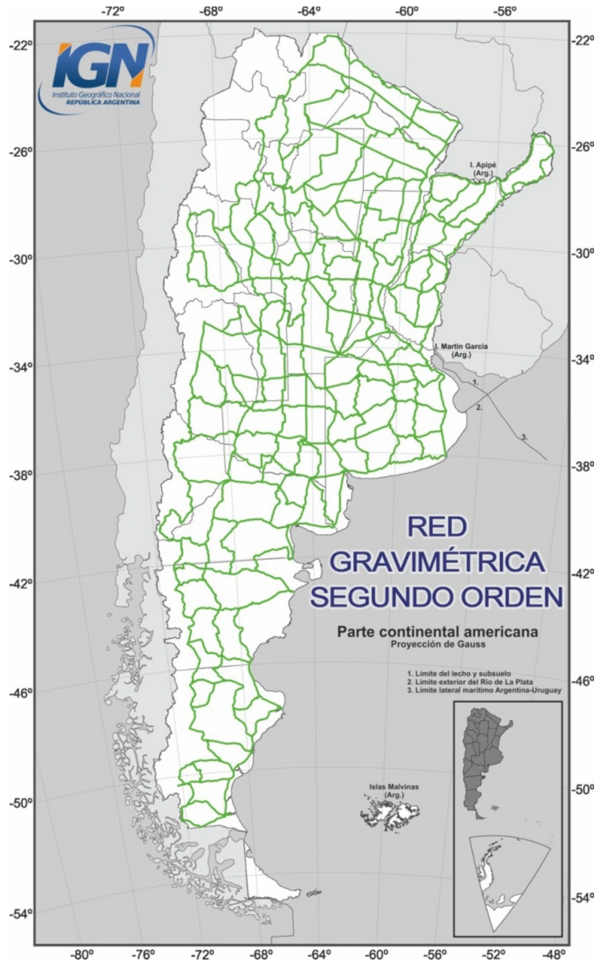

Figure 13: second-order gravity network

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

Chair: David Avalos (Mexico)

Steering Committee

- David Avalos (Chair, INEGI, Mexico)
- Rene Forsberg (DTU, Denmark)
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- Alvaro Alvarez (IGN, Costa Rica)

Activity report

Regional agreements: Prominently, national geodetic agencies in North and Central America work in geoid modeling under the one single parameter defining the vertical datum as the geopotential value W_0=62,636,856.0 m^2s^{-2}.

- The geodetic agencies NRCAN/GSD from Canada and NOAA/NGS from the USA have formally agreed in using this W_0 value as an official reference for their respective national geodetic control. This decision ensures the compatibility of every future realization of the geodetic vertical datum through local or national scale surveying between the two largest countries in the region. At present, Canada uses the geoid model CGG2013 as the realization of the vertical datum based on the W_0 reference value.
- National geographic institutions from Mexico-INEGI, Guatemala-IGN, El Salvador-IGN, Honduras-IP, Nicaragua-INETER, Costa Rica-IGN, Panama-IGNTG and the Dominican Republic-ICM, agreed in creating a regional geoid model for Central America and the Caribbean, based in the same reference geopotential value. This decision came from adopting the W_0 value referred by the parameters in the ITRF, which is coincident to the standard in North America.

For Canada and the USA, the agreement on W_0 is derived from the project named "A geoid-based vertical reference frame for height modernization in North America", in which participated the University of Calgary, the York University, the Permanent Service for Mean Sea Level, the European Space Agency, the NRCAN/GSD, the NOAA/NGS and INEGI.

Geopotential models in use:

Products derived from the GRACE and GOCE satellite missions are continuously assessed and used for geoid modeling in low and medium frequencies. Releases from the processing centers at the ESA, GFZ and the University of Texas are heavily used.

Gravity data and models in high resolution:

Recent airborne gravity surveys conducted on Greenland by the DTU and on the USA by the NGS provide a new source for massive data coverage to increase the accuracy at the medium frequencies of the gravity field spectrum. Under the program called GRAV-D, the NGS combines the low frequency signal from GOCE models with the airborne and the existing terrestrial surveys to create a progressive series of gravity field models to cover the Conterminous USA.

The geodetic divisions in Mexico, the Dominican Republic and El Salvador maintain in progress national surveys of terrestrial gravimetry. These programs aim to obtain homogeneous and accurate high resolution modeling for the near future.

Table 1: Latest geoid models released for official reference:

Country	Model	Coverage	Datum	Release
Greenland	CGG2013	National	MSL	2015
Canada	CGG2013	National	W_0=62,636,856.0 m^2s^{-2}	2013
USA	USGEOID2009	National	MSL	2009
Mexico	GGM10	National	MSL	2011
El Salvador	ESGEOIDE	National	MSL	2011

Note: other countries in the region use EGM2008, EGM96 or MEX97.

Table 2: Geoid models under preparation:

Country	Coverage	Datum	Progress
USA	National	W_0=62,636,856.0 m^2s^{-2}	40%
Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, R. Dominicana	Central America and Caribbean	W_0=62,636,856.0 m^2s^{-2}	80%

Main events for reference in the region Collaboration among the scientific community, private companies, users and government agencies made possible the progress reported here. From within a long series of meetings and communications these four can be highlighted as the major contribution to coordinate independent efforts:

- The first North American Comparison of Absolute Gravimeters, NACAG 2014.

  10 absolute meters from USA and Canada were gathered to make observations and exchange experiences during 5 days on September 2014 at the Table Mountain Geophysical Observatory. The NOAA's National Geodetic Survey (NGS) was host and convener.

- Geoid workshops for Mexico, Central America and the Caribbean.

  A series of 3 workshops held on 2011, 2013 and 2014 took place in Mexico with the participation of representatives from Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama and the Dominican Republic. These events provided a forum to exchange experiences, information, build capacity for geoid modeling and discuss the topic of geoid-based vertical datum. The NGS and the University of New Brunswick, Canada, shared their view and experience on the implementation of new techniques. The Mexico's INEGI acted as host and convener.

- Canadian geoid workshops.

  The NRCAN/GSD convened a wide scientific community from North America and Europe at the Canadian Geophysical Union's yearly meeting. This regular forum promoted a comprehensive understanding on the newest geopotential models as a key component of the strategies to unify the vertical datum.
- Special sessions and conferences of the American Geophysical Union.

  In these forums the concepts and technical approaches of gravity and geoid modeling have been discussed prominently among representatives from North America, contributing to the harmonization of terminology and parameters in such a way that the geoid models from Canada and the USA now possess a high level of compatibility.

Within the period 2011-2015, the academic and governmental community expressed in different forums an interest in gravity field and geoid determination with two fundamental coincidences: further promote an open access to databases on terrestrial gravity, and the unification of vertical reference over the realization of a standard geopotential surface.

Collaboration with other Sub-Commissions

In order to help improving the compatibility between the regional models of the Sub-commissions 2.4c and 2.4d, it was proposed to create a unified dataset of terrestrial gravimetry for Central America and the Caribbean. The terms and conditions to realize this proposal have not been settled.

Sub-Commission 2.4d: Gravity and Geoid in Africa

Chair: Hussein Abd-Elmotaal (Egypt)

Webpage: http://www.minia.edu.eg/Geodesy/AFRgeo/

Terms of Reference

The African Gravity and Geoid regional sub-commission (AGG) belongs to the Commission 2 of the International Association of Geodesy (IAG). The main goal of the African Gravity and Geoid regional 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.

Steering Committee

Chairman: Hussein Abd-Elmotaal (Egypt), Charles Merry (South Africa), Ahmed Abdalla (Sudan), .Sid Ahmed Benahmed Daho (Algeria), J.B.K. Kiema (Kenya), Joseph Awange (Kenya), Ludwig Combrinck (South Africa), Prosper Ulotu (Tanzania)

Delegates

Addisu Hunegnaw (Ethiopia), Adekugbe Joseph (Nigeria), Albert Mhlanga (Swaziland), Francis Aduol (Kenya), .Francis Podmore (Zimbabwe), .Godfrey Habana (Botswana), Hassan Fashir (Sudan), .Ismail Ateya Lukandu (Kenya), Jose Almeirim (Mozambique), Karim Owolabi (Namibia), Peter Nsombo (Zambia), Saburi John (Tanzania), Solofo Rakotondraompiana (Madagascar), Tsegaye Denboba (Ethiopia)

Main activities (2011–2015)

A 2-years project "Detailed Geoid Model for Africa" in collaboration between IAG and IASPEI has been granted by IUGG. In this project, IUGG aimed to help in the acquisition of gravity data for Africa needed for computing the geoid as well as in attending the geodetic international conferences to disseminate the project results. This allowed the determination of a better precise geoid model for Africa as well as it fostered cooperation between African geodesists and helped in providing high-level training in geoid computation to African geodesists. A separate detailed report of this project has been directed to IUGG.

There were several attempts to collect gravimetric point data for the African continent. Contacts were established with the BGI, NGA and GETECH. Until now, this was not very successful.

- Abdalla et al. (2012) have tested the most recent GRACE/GOCE global geopotential models using GPS/levelling data (in Khartoum State) and gravity data of Sudan.
- Abd-Elmotaal (2012) performed gravity interpolation within large gaps, which is the case of the gravity network in Africa, in order to obtain the best suited interpolation process for such cases.
- Abd-Elmotaal and Ashry (2013) have established a 3" × 3" DHM for Egypt using SRTM 3" and other local and regional resources.
- Abd-Elmotaal et al. (2013) have established a very detailed 1" × 1" DHM for Egypt using ASTER-GDEM 1", SRTM 3" and other local and regional resources.

- Abd-Elmotaal and Makhloof (2013) have made a study regarding the gross-error detection in the shipborne data set for oceans surrounding Africa, which will has been presented at the Geodetic Week & INTERGEO 2013, Essen, Germany, October 8-10, 2013.
- Comparison of recent geopotential models for the recovery of the gravity field in Africa has been performed by Abd-Elmotaal and Makhloof (2013), presented at the Geodetic Week & INTERGEO 2013, Essen, Germany, October 8-10, 2013.
- Ben Ahmed Daho works on the investigation the possibility of improving the accuracy of the latest geoid model for Algeria using the new and revolutionary Global Gravitational Model EGM2008 and the satellite altimetry-derived marine gravity anomalies. For this purpose, a new gravimetric geoid model for Algeria has been computed using the land gravity data supplied by the BGI, EGM2008 to degree 2190 as the reference field, Digital Elevation Model derived from SRTM for topographic correction, and DNSC2008GRA altimetry-derived gravity anomalies offshore. According to his numerical results, the new geoid shows an improvement in precision and reliability, fitting the geoidal heights of these GPS/levelling points with more accuracy than the previous geoids. Its standard deviations fit with GPS/levelling data are 12.7cm and 2.5cm before and after fitting using the seven-parameter similarity transformation model. Moreover, the analysis of the results shows that the signals in benchmarks are dominated by errors in the geoid due to the bad gravimetry, while the noise level indicates of the presence of errors in the vertical datum. The available and accuracy of the land gravity data remains insufficient to agree with GPS/Levelling at the sub-centimeter level. This new geoid model will be used to support Levelling by GPS at least for the low order levelling network densification. Improvement the accuracy of the latest geoid model (Benahmed et al., 2009), especially in mountainous areas by considering the effect of lateral density variations. Numerical results show that the differences in the geoid height due to actual density model can reach up to 13 cm, which is not negligible in a precise geoid determination with centimeter accuracy. His results suggest that the effect of topographical density lateral variations is significant enough and ought to be taken into account especially in mountainous regions in the determination of a precise geoid model for Algeria. However, basically because of the lack of GPS/levelling data in mountainous areas and the most of the GPS/levelling points used in this investigation are located in moderate heights areas, one could not see much improvement by evaluation of the corrected gravimetric geoid model versus GPS/levelling.
- Abd-Elmotaal and Kühtreiber (2014a) have investigated the effect of DHM resolution in computing the topographic-isostatic harmonic coefficients within the window technique in order to get the optimum resolution of computing the window topographic-isostatic coefficients.
- Land gravity data for Africa has been collected, and an automated gross-error detection algorithm has been proposed and tested by Abd-Elmotaal and Kühtreiber (2014b).
- Abd-Elmotaal (2014a) has computed a geoid model for Egypt using ultra high-degree tailored geopotential model.
- Abd-Elmotaal (2014b) has computed a geoid model for Egypt using the best estimated response of the earth's crust due to the topographic loads.
- Abd-Elmotaal and Makhloof (2014) have proposed an optimum geoid fitting technique for Egypt.
- Abd-Elmotaal and Makhloof (2014b) have nicely performed a combination between altimetry and shipborne gravity data sets for Africa.
- Abd-Elmotaal et al. (2014) perfomed some experiments with different techniques for combination of gravity field wavelength components for geoid determination in Egypt.

- Abd-Elmotaal (2015a) has computed a gravimetric geoid model for Egypt implementing seismic Moho information.
- Abd-Elmotaal (2015b) performed an assessment study of the GOCE models over Africa.
- A Tailored Reference Geopotential Model for Africa has been compued by Abd-Elmotaal et al. (2015a).
- Establishment of the Gravity Database for the African Geoid, which is the core of the the regional sub-commission for Africa and the most important and time consuming task, has been carried out by Abd-Elmotaal et al. (2015b).

Future Activities

A new geoid model for Africa is going to be presented during the forthcoming IUGG2015, Prague, Czech Republic, June 22 - July 2, 2015 by Abd-Elmotaal et al. The new geoid model for Africa is shown in Figure 1.

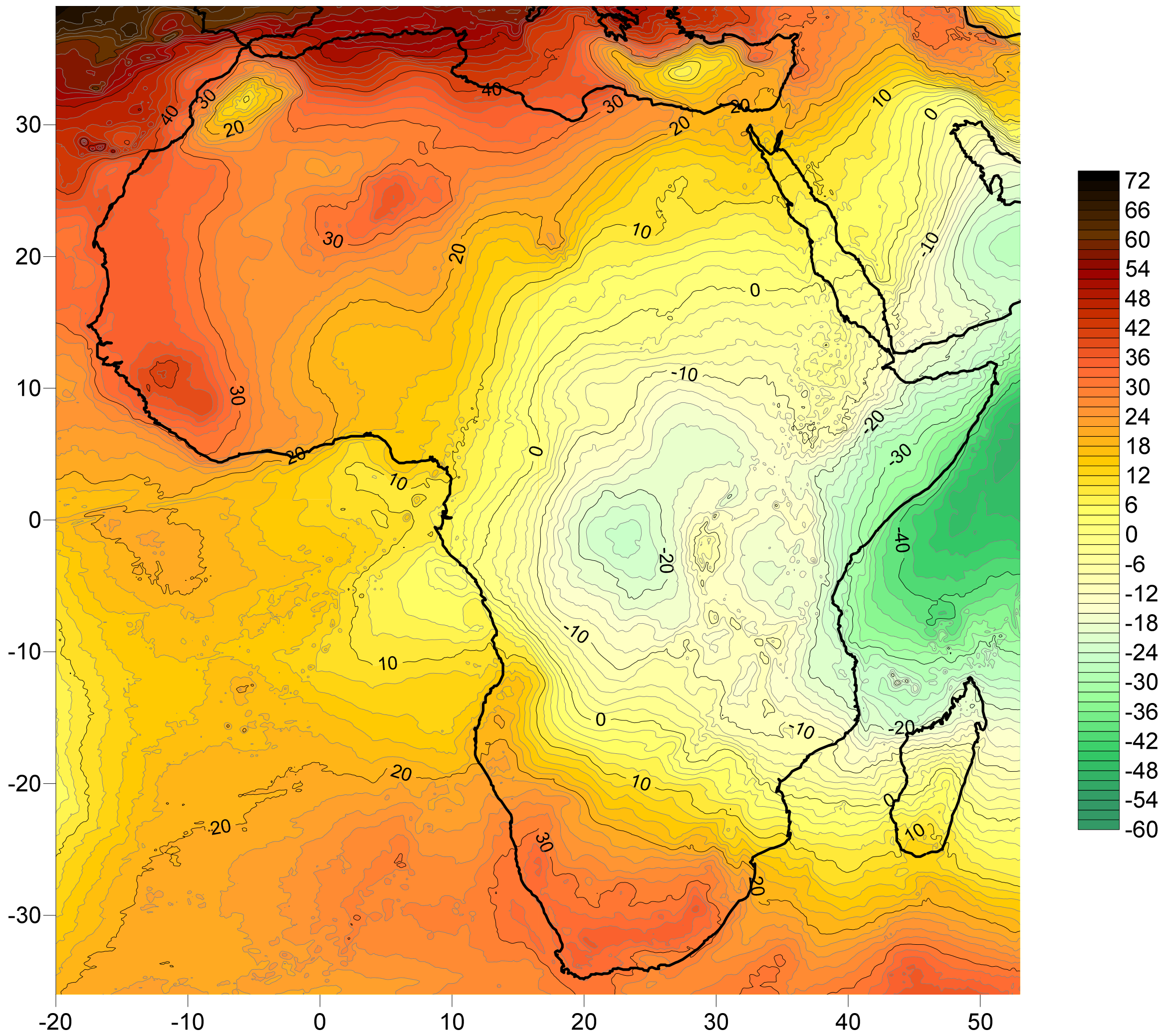

Figure 1: The African geoid model AFRgeo2015 (after Abd-Elmotaal et al., 2015c).

An African 3" × 3" DHM using SRTM 3" and SRTM30+ is under process.

A splinter meeting for the steering committee of the 2.4d regional sub-commission will take place during the forthcoming IUGG2015, Prague, Czech Republic, June 22 - July 2, 2015.

Problems and Request

The gravity and geoid regional sub-commission suffers from the lack of data (gravity, GPS/levelling and height). 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 regional sub-commission would help in solving the problems and would definitely contribute to the quality of its outputs. IAG is thus kindly invited to support that action.

Publications

Abdalla, A., Fashir, H.H., Ali, A., Fairhead, D., (2012) Validation of Recent GOCE/GRACE Geopotential Models Over Khartoum State – Sudan , Journal of Geodetic Sciences, DOI: 10.2478/v10156-011-0035-6.

Abd-Elmotaal, H. (2012) Gravity Interpolation within Large Gaps. 7th International Conference of Applied Geophysics, Cairo, Egypt, February 27, 2012

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Abd-Elmotaal, H. (2014b) Egyptian Geoid using Best Estimated Response of the Earth's Crust due to Topographic Loads. 3rd International Gravity Field Service (IGFS) General Assembly, Shanghai, China, June 30 – July 6, 2014

Abd-Elmotaal, H. (2015a) Gravimetric Geoid for Egypt Implementing Seismic Moho Information. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 12–17, 2015.

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Abd-Elmotaal, H. and Makhloof, A. (2013) Gross-error Detection in the Shipboirne Gravity Data Set for Africa. Geodetic Week & INTERGEO 2013, Essen, Germany, October 8-10, 2013.

Abd-Elmotaal, H. and Makhloof, A. (2013) Comparison of Recent Geopotential Models for the Recovery of the Gravity Field in Africa. Geodetic Week & INTERGEO 2013, Essen, Germany, October 8-10, 2013.

Abd-Elmotaal, H. and Makhloof, A. (2014a) Optimum Geoid Fitting Technique for Egypt. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 27 – May 2, 2014.

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Sub-Commission 2.5e: Gravity and Geoid in Asia-Pacific

Chair: Will Featherstone (Australia)

Summary

This sub-commission (SC) has not been very active and has no results to present. This brief report highlights the difficulties for such a SC and makes a series of recommendations if the IAG wishes to continue it.

Difficulties

- Inactivity of the Chair
- Difficulty for a "westerner" to make the relevant contacts in the Asia-Pacific region (this SC has been chaired by Australians since 2003)
- Depending on one's definition of the Asia-Pacific, this SC could cover as many as 48 countries
- The region is diverse in terms of languages, history, politics and wealth
- Difficulty to convince geodetic agencies to share data, especially in areas of conflict
- A compelling case is needed to present the benefits to each country of sharing gravity and geoid data

Recommendations

- Appoint an active chair from deeper inside the Asia-Pacific region, who will have a better appreciation of the cultures and thus be better placed to make contacts
- Determine the countries considered to be inside the Asia-Pacific region (this would be useful for other SCs)
- Produce an easy-to-read (and for the layperson) document selling the benefits to each country of sharing gravity and geoid data
- Set protocols for data sharing and/or exchange
- Establish contacts in each country
  - Follow up on potential contacts through the Geodesy Working Group of the Permanent Committee for GIS Infrastructure in Asia and the Pacific (PCGIAP). This group comprises the main authorities that deal with geoids and height datums in the region and beyond.
  - A group convened by J. Kwon (South Korea) on height systems and vertical datums in the Asia-Pacific region (APRHSU: Asia-Pacific Regional Height System Unification) may generate more contacts.
  - Establish other contacts in the Asia-Pacific region through FIG Commission 5, which has a strong interest in these matters from the viewpoint of operational geodesy.

Sub-Commission 2.4f: Gravity and Geoid in Antarctica

Chair: Mirko Scheinert (Germany)

Short Review

This group was adopted at the IAG General Assembly in Sapporo 2003. In 2011 it was transferred from a Commission Project to the Sub-Commission 2.4f. 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 interdisciplinary, especially incorporating experts from the fields of geophysics and glaciology. This is also reflected in the group membership (cf. below).

During the last period of (2011-2015) further progress has been made to include new data and to open access to already existing data. The preparation to publish an Antarctic gravity anomaly grid is in the final stage (Scheinert et al., 2015). Results and products will be presented at the IUGG General Assembly in Prague, 2015. 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.

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 bi-annual SCAR meeting in Auckland, New Zealand, 2014. M. Scheinert co-chairs GIANT as well as chairs the GIANT project “Gravity Field”.

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).

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. Several projects are in progress which include aerogravimetry over Antarctica, from the US (e.g. Icebridge), from Germany, Denmark, the UK and other nations, focusing especially to fill the satellite-induced polar data gap (due to GOCE’s inclination of 96.5°). 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. Thereby, it could be of great value to adopt long-range aircraft capable to fly under Antarctic conditions. Respective efforts are underway e.g. in the US or in Germany. In this respect, the chair of AntGG is acting as PI of a German project to utilize the German research aircraft

HALO for an Antarctic airborne geodetic-geophysical survey (ANTHALO). In 2012 HALO could already successfully be utilized for a survey over Italy and adjacent seas to demonstrate the feasibility of aerogravimetry aboard HALO (e.g. Barzaghi et al., 2015).

In view of the long-term scientific rationale of AntGG this group shall be continued as an IAG Sub-Commission of Commission 2.

Selected conferences with participation of AntGG members

- IUGG General Assembly, Melbourne (Australia), June 28 – July 07, 2011;
- IAG Symposium "Gravity, Geoid and Height Systems" (GGHS 2012), Venice, October 9-12, 2012;
- IAG General Assembly, Potsdam, 1-5 September 2013;
- 3rd International Gravity Field Service (IGFS) Assembly, Shanghai, 30 June – 6 July 2014;
- XXXII SCAR Meeting and Open Science Conference, Portland (USA), July 13 – 25, 2012;
- XXXIII SCAR Meeting and Open Science Conference, Auckland, 23-29 August 2014;
- International Symposium on Antarctic Earth Sciences (ISAES XI), Edinburgh (UK), July 10 – 16, 2011;
- AGU Fall Meetings (2011 – 2014) and EGU General Assemblies (2011 – 2015);
- Workshop "Geodesy and Geophysics on flying platforms (with special attention to HALO)", Potsdam (Germany), 08-09 November 2012.

Membership

(active members)

Mirko Scheinert (chair)	TU Dresden, Germany
Don Blankenship	UTIG, USA
Alessandro Capra	Universita di Modena a Reggio Emilia, Italy
Detlef Damaske	BGR Hannover, Germany
Fausto Ferraccioli	British Antarctic Survey, UK
Christoph Förste	GFZ Potsdam, Germany
René Forsberg	DTU Space, Denmark
Larry Hothem	USGS, USA
Wilfried Jokat	AWI Bremerhaven, Germany
Gary Johnston	Geoscience Australia
Steve Kenyon	National Geospatial-Intelligence Agency, USA
German L. Leitchenkov	VNIIOkeangeologia, Russia
Jaakko Mäkinen	Finnish Geodetic Institute, Finland
Yves Rogister	Université Strasbourg, France
Kazuo Shibuya	NIPR, Japan
Michael Studinger	NASA Goddard SFC, USA

(corresponding members)

Matt Amos	LINZ, New Zealand

Selected publications and presentations with relevance to AntGG (2011 – 2015)

Barzaghi, R., A. Albertella, D. Carrion, F. Barthelmes, S. Petrovic, M. Scheinert (2015): Testing Airborne Gravity Data in the Large-Scale Area of Italy and Adjacent Seas, In: *IAG Symposia 143*, Springer International Publishing, Switzerland. doi: 10.1007/1345_2015_45 (accepted for publication).

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Ferraccioli, F.; Forsberg, R.; Jordan, T.; Matsuoka, K.i; Olsen, A.; King, O.; Ghidella, M. (2014): New aero-geophysical views of crustal architecture in the Recovery frontier of East Antarctica. Presentation EGU2014-4374, EGU General Assembly, Vienna, 27 April – 02 May 2014.

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Muto, A., Anandakrishnan, S., and Alley, R. B. (2013), Subglacial bathymetry and sediment layer distribution beneath the Pine Island Glacier ice shelf, West Antarctica, modeled using aerogravity and autonomous underwater vehicle data, *Annals of Glaciology,* 54(64), 27-32, doi: 10.3189/2013AoG64A110

Mieth, M. (2014): Aerogeophysical constraints for the geodynamic evolution of Dronning Maud Land, East Antarctica, PhD Thesis, University of Bremen, hdl.handle.net/10013/epic.44466 (last accessed: 03 Feb 2015).

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Scheinert, M. et al. (2015): New Antarctic Gravity Anomaly Grid for Enhanced Geodetic and Geophysical Studies in Antarctica (in preparation).

Scheinert, M. et al. (2013): From Germany to Antarctica: Airborne geodesy and geophysics and the utilization of the research aircraft HALO. Presentation G13C-05, AGU Fall Meeting, San Francisco, 9-13 December 2013.

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Scheinert, M. (2012): Progress in the measurement and improvement of the gravity field in Antarctica. Pres., XXXII SCAR Meeting and Open Science Conference, Portland (OR), 13-25 July 2012.

Scheinert, M. (2011): Towards an Improved Knowledge of the Gravity Field and Geoid in Antarctica Utilizing Airborne Gravimetry, Presentation G12A-05, AGU Fall Meeting, San Francisco, 5-9 December 2011.

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Sub-Commission 2.5: Satellite Altimetry

Chair: Xiaoli Deng (Australia)

Steering Committee: Xiaoli Deng, Cheinway Hwang, CK Shum, Wolfgang Bosch, David Sandwell, Walter H.F. Smith, Ole B Andersen and Per Knudsen

From 2011-2015 as contributions from IAG sub-commission 2.5, we performed a diverse research into development of altimeter waveform retrackers, improvement of global and regional marine gravity field models, studies of sea-level extremes, improvement of dynamic ocean topography models, applications over ice-covered and river surfaces, modelling and assessing of ocean tides and calibration of altimetry data. Of them, the most significant improvements are made in the new marine gravity field (~2 mGal accuracies) and ocean mean dynamic topography models due to new data sources from GOCE and non-repeated altimetry missions.

Improvement in Waveform Retracking

Waveform retracking is an important means that improves the retrieval of sea surface height (SSH) for all purposes of altimetry applications. To optimize the satellite altimetric sea levels from multiple retracking solutions near the coast, Idris and Deng (2012a, 2012b, 2013 and 2014), developed a new Coastal Altimetry Waveform Retracking Expert System (CAWRES). The system first reprocesses altimeter waveforms using the optimal retracker based on the analysis from a fuzzy expert system, and then minimizes the relative offset in the retrieved sea levels caused by switching from one retracker to another, using a neural network. The sub-waveform retracker by Idris and Deng (2012a) contributes significantly to the system, which fits the Brown (1977) model to the truncated waveform samples that correspond to the returns reflected from the water surface. This innovative system is validated against geoid height and tide-gauge data in two different regions: the Great Barrier Reef in Australia and the Prince William Sound in Alaska USA, for Jason-1 and Jason-2 satellite missions. The results demonstrate that the CAWRES effectively enhances the quality of 20 Hz sea level data near the coast.

To measure marine gravity anomalies at accuracy under 1 mGal, the error in the along-track slopes from the altimeter profiles must be about 1 μrad, or there must be enough repeated tracks to achieve the 1 μrad accuracy. In this regard, Garcia et al. (2013) used a two-pass retracking procedure to improve the accuracy of sea surface slopes determined from multiple altimetric missions. A simple, but approximate, analytic model has been derived for the shape of the CryoSat-2 SAR waveform that can be used in an iterative least-squares algorithm for estimating range. For the conventional waveforms, the two-pass retracking procedure has resulted in a factor of ~1.5 improvement in range precision. The improved range precision and dense coverage from CryoSat-2, Envisat and Jason-1 GM lead to a significant increase in the accuracy of the new marine gravity field (Sandwell et al. 2014). The two-pass retracking method has also been used by Andersen et al. (2014).

Waveform retracking has also been investigated in coastal seas (0.5-7km from the coast), over lakes and land. Tseng et al. (2013) introduced a novel algorithm that modifies coastal waveforms to mitigate spurious waveform peaks and minimizes the error in the determination of the leading edge and associated track offset in the waveform retracking process, thus improving coastal data coverage and accuracy. The algorithm was applied in four study regions in North America, using both Envisat and Jason-2 altimetry 20 Hz waveform data.

The retrieved altimetry data in the 1–7 km coastal zone indicate a 63% of improvement in accuracy compared to the use of the original deep-ocean waveform retracker. Tseng et al. (2013) successfully applied their retracker and a waveform classification in the Qinghai Lake, China, where the water body has distinct seasonal variations between water and ice, causing retracking extremely difficult. Yi et al. (2013) assessed the performance of different waveform retrackers over Lake Baikal in Siberia, Russia, using Jason-1 and Envisat data through a time-series analysis. Retracking techniques are also applied to altimeter data over areas with potential land subsidence for hazard mitigation (e.g., Lee et al., 2013; Gommenginger et al., 2011).

Yang et al. (2012) developed a threshold subwave-form retracker based on a correlation analysis method to improve the precision of altimeter-derived sea surface heights (SSHs) and gravity anomalies. The retracker has been used in the Antarctic Ocean, resulting in an improved precision of gravity anomalies up to 46.6% when compared to shipborne gravity anomalies.

Significant Improvement in Global Marine Gravity Field from Altimetry

With new non-repeat altimeter data sets from CryoSat-2, Jason-1 and Envisat, the impact on global marine gravity field, in particular the Arctic marine gravity field is significant. CryoSat-2 has provided the most dense track coverage after 4 years in orbit, providing a nominal track spacing of about 2.5 km (Sandwell et al. 2014). Jason-1 geodetic mission provided 14 months of dense track coverage, resulting in a track spacing of 7.5 km. Envisat was placed in a new partly drifting-phase repeat orbit (~30 days) and collected 1.5 years of data with dense coverage in high latitudes. These new altimeter data sets have resulted in improvement by a factor 2 to 4 in the global marine gravity field. In Addition, the newer radar technology results in a 1.25-times improvement in range precision that maps directly into gravity-field improvement (Sandwell et al. 2014). These data sources have been exploited for high-resolution and high-accuracy mapping of marine gravity filed globally, as well as in the Arctic Ocean (e.g., Stenseng and Andersen, 2011; Andersen, 2011; Andersen and Sandwell, 2012; Marks et al. 2013; Sandwell et al., 2013, 2014).

Sandwell et al. (2014) produced a latest global marine gravity field with an accuracy of ~2 mGal using these retracked altimeter data sets (Fig.1), from which the most improvement occurs in the wavelength band 12-40 km. This improvement allows investigating the small-scale (~6 km) seafloor structures, which was not allowed by the past marine gravity models. The accuracy of ~2 mGal achieved by Sandwell et al. (2014) is available over all marine areas and large inland bodies of water, providing an important tool for exploring the deep ocean basins. For examples, the new data reveal buried tectonic structures in the Gulf of Mexico and the South Atlantic Ocean, as well as tectonic features of the continent-ocean boundary and the buried faults in the China Sea (Hwang et al. 2014). In addition, this new marine gravity field can be used to significantly improve the estimates of sea-floor depth in oceans without sounding data.

The gravity accuracies of ~2 mGal are achieved also based on the development in computing altimeter slope corrections. The slope correction is applied to altimeter derived sea surface heights to minimise the effect of the sea surface slope. Its effect has been neglected in all previous altimetry ocean studies, but must be considered if accuracies of 1-2 mGal of the marine gravity files are to be achieved. Sandwell et al. (2014) provided a global correction grid that can be scaled to the effective altitude of any radar altimeter.

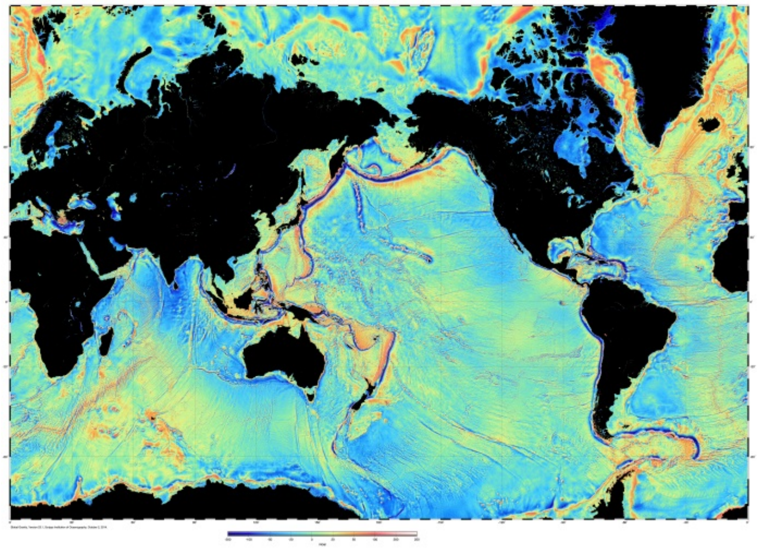

Figure 1. The latest global map of marine gravity - version 23.1 by Sandwell et al. (2014, http://topex.ucsd.edu/grav_outreach/)

Another model was produced by Andersen et al. (2013) and is called the DTU13 global marine gravity field. All available altimeter data sets, including Cryosat-2 SAR mode data, in the Arctic Ocean up to latitude 88°N are used in the model. The DTU marine gravity field is directly based on retracked altimetric sea surface heights. Extensive testing, interpretation and improvement of methods to handle the new class of altimeter data has been investigated (Stenseng and Andersen 2012; Andersen et al. 2014). The results from a new Arctic Ocean wide gravity field has been presented, as well as initial test of derived altimetric bathymetry using the new gravity field data.

Hwang et al. (2014) retracked waveforms from Geosat GM, ERS-1 GM, repeat Geosat/ERM, ERS-1/35d, ERS-2/35d, Jason-1 GM and TOPEX/Poseidon. Using these retracked data sets, together with Cryosat-2 LRM data retracked at the Radar Altimeter Database System (RADS, http://rads.tudelft.nl/rads/rads.shtml), a regional marine gravity field is recovered in the waters off Taiwan and in the South China Sea. The shipborne gravity measurements were collected using small vessels over shallow waters around Taiwan and large research vessels in the South China Sea. The shipborne gravity measurements are used to validate the altimeter-derived gravity anomalies. These shipborne gravity anomalies can be used for any researchers wishing to validate their techniques of gravity derivation from satellite altimetry, over both shallow and deep waters.

As examples, Tables 1 and 2 show the statistics of the differences between altimeter-derived and shipborne marine gravity anomalies around Taiwan and in the South China Sea. Table 1 shows that the sub-waveform threshold retracker (Yang et al. 2011) with 0.2 threshold value is the optimal retracker with small standard deviations around the waters off Taiwan. In Table 2, we experiment with both Inverse Vening Meinesz (IVM) formula and the least-squares collocation to transform altimeter-derived heights to marine gravity anomalies. Both methods perform equally well. Table 2 shows that the regional marine gravity field from the NCTU team has similar accuracies to the gravity fields produced by major institutions SIO and DTU.

Table 1: Standard deviations of differenced SSHs (in m) around Taiwan using different retrackers

Data	Beta-5	Threshold[a]	sub-waveform threshold			
			0.1	0.2	0.3	0.5
Geosat/GM	0.0812	0.0742	0.0647	0.0633	0.0639	0.0745
ERS-1/GM	0.0805	0.0975	0.0523	0.0499	0.0531	0.0710

[a] full waveform and the threshold value equal to 0.5 are used

Table 2: Statistics of differences between altimeter-derived gravity and shipborne gravity at two depth ranges in the South China Sea (unit: mgal)

Gravity Model	Data used	Depth (m)	mean	STD	max	min
Case 1 (IVM)	ERS-1 Geosat (no retracking)	All	-0.2	9.2	71.9	-97.4
		<500m	-0.1	9.9	62.4	-64.8
Case 2 (IVM)	ERS-1 Geosat	All	-0.1	6.3	81.9	-91.9
		<500m	-0.3	7.0	58.6	-57.6
Case 3 (LSC)	ERS-1 Geosat Jason-1 Cryosat-2	All	-0.1	5.9	80.1	-87.9
		<500m	-0.5	6.7	61.9	-56.8
Case 4 (IVM)	ERS-1 Geosat Jason-1 Cryosat-2	All	0	6.0	80.6	-90.4
		<500m	-0.2	6.8	61.3	-57.3
DTU10	ERS-1 Geosat	All	0	6.1	79.9	-84.6
		<500m	-0.4	7.1	54.3	-58.6
Sandwell V23.1	ERS-1 Geosat Envisat Jason-1 Cryosat-2	All	-0.5	6.0	82.7	-83.0
		<500m	0.6	7.7	57.7	-61.1

[a] Altimeter-derived gravity from the National Chiao Tung University team

Hwang et al. (2014) constructed the 1′×1′ grids of free-air and Bouguer gravity anomalies around Taiwan with well-defined error estimates from multiple platforms and sensors. The grids are compiled from land, airborne and shipborne gravity measurements, and altimetry derived gravity over the oceans. All data sets were well processed and outlier-edited. They were combined by the band-limited least-squares collocation in a one-step procedure. The new grids show unprecedented tectonic features that can revise earlier results, and can be used in a broad range of applications.

Significant Improvement in Dynamic Ocean Topography and ocean circulation

The more detailed and accurate ocean mean dynamic topography (MDT) has been computed using a high resolution GOCE (Gravity field and steady-state Ocean Circulation Explorer) gravity model and a new mean sea surface (MSS) derived from satellite altimetric mission since 1992 (Knudsen et al 2011; Albertella et al. 2012). These new MDTs make it possible to calculate geostrophic velocities to a higher accuracy and spatial resolution. Knudsen et al (2011) constructed a global MDT using two months of GOCE data and DTU10MSS, which clearly displays the gross features of the ocean's steady-state circulation. Albertella et al. (2012) computed a MDT using 12 months of GOCE data, which achieves the error estimate ~7 cm s^{-1} in the Southern Ocean. Meanwhile, Janjic et al. (2012) investigated the impact of combining GRACE and GOCE gravity data on circulation estimates. Their study focused on optimal data processing and filtering techniques to obtain more accurate dynamic ocean topography details.

Instead of a long-term mean topography the processing strategy of Bosch et al. (2013) aims to estimate the instantaneous dynamic topography (iDOT) on individual altimeter profiles. This is possible after a careful cross-calibration of the altimeter missions of interest by consistently filtering and subtracting sea surface heights and geoid height derived by the GOCE-based GOCO03S gravity field model. With a filter length of only 70 km the iDOT-profiles approach Eddy resolution and avoid the long-term smoothing of a MDT in western boundary currents.

Studies of Extreme Sea Levels

Tide gauge and satellite altimetry has vastly different spatial and temporal sampling. However the data can be integrated to take advantage of the high temporal sampling of the tide gauges with the high spatial sampling of the satellite. Our investigation demonstrates the importance of optimal tide modeling using the response method and careful use of the dynamic atmosphere correction delivered by the MOG2D model (Cheng and Andersen 2012; Andersen and Scharroo 2011; Idris et al. 2014). Data from TOPEX/Poseidon and Jason1/2 altimetry missions and tide gauges recorders over the past 20 years around both European and Australian coasts general exhibit temporal correlation of more than 90% for nearly all tide gauge stations. These data were combined using the multivariate regression method (Cheng et al. 2012; Deng et al. 2012 and 2015) and the Multi Adaptive Regression Splines approach (Gharineiat and Deng 2015). The results have been used to investigate several large tropical cyclones, such as cyclones Larry and Yasi. These severe cyclones hit the Queensland coasts in March 2006 and February 2011, respectively, causing both loss of lives and huge devastation. The results suggest the existence of ability to capture surge (and cyclones) and sea level along the Northwest European and Australian coastlines (Cheng and Andersen 2012; Deng et al. 2012 and 2015; Gharineiat and Deng 2015). The results of this study open the way for further research into monitoring of extreme sea level events.

Altimetry applications over ice sheets and rivers

Our studies involved in research into altimetry application over ice sheets and rivers. Wang et al. (2014) constructed, for the first time using, the freeboard map of the giant iceberg generated by the collapsed Mertz Ice Tongue (MIT) in February 2010 using a time-series ICESat/GLAS data. The precision of the freeboard extraction is approximately ±0.50 m. They found that the freeboard varied from 23m to 59m with the mean of 41 m. With assumption of hydrostatic equilibrium, the minimum, maximum and average ice thickness were calculated as 210 m, 550m and 383m, respectively. The total ice loss is ~8.96 × 1011 tons over an area, 34 km in width and 75 km in length, or ~2560± 5 km2. These parameters extracted from remote sensing and altimetry data will provide additional information for studies of the evolution of iceberg, especially in iceberg tracking system.

Lee et al. (2012) investigated ice-sheet elevation change rates over mountain glaciers using altimeter data. The study demonstrated the feasibility to estimate elevation change rates over the Bering Glacier System in Alaska for the period of 1992–2010 using TOPEX/Poseidon and Envisat radar altimeter measurements. Surge events are observed between 1993–1995 and 2008–2011 by the altimeter time series. They also observe the accelerated elevation decreases in 2002–2007, after slightly negative or near nil elevation changes in 1996–2001, which are related to the temperature and snow depth variations. The method can be applied to other wide (>7 km) glaciers worldwide, and provide new insights into the behaviour of glaciers responding to climate change.

Yang et al. (2014) used a new fixed full-matrix method (FFM) method to compute height changes at crossovers of satellite altimeter ground tracks over ice sheets. Assisted by the ICE-Sat-derived height changes, they determine the optimal threshold correlation coefficient (TCC) for a best correction for the backscatter effect on Envisat height changes. The TCC value of 0.92 yields an optimal result for FFM. With this value, FFM yields Envisat derived height change rates in East Antarctica mostly falling between −3 and 3 cm/year, and matching the ICESat result to 0.94 cm/year.

A study by Guo et al. (2013) analysed the spatial and temporal distribution of the backscatter coefficient (i.e. sigma0) at altimeter Ku and C bands over Xinjiang, Western China, using the TOPEX/Poseidon dataset from January 1993 to December 2004. The results show that the sigma0 is influenced by the water distribution over land and the time evolution of sigma0 has clear seasonal changes.

Over rivers, research into accurate retrieval of water levels, comparison between altimeter retrieved and hierologically modelled water levels and investigation of altimeter derived water level bias have been conducted. The study areas include Indonesian small rivers (width <1 km), Bangladesh riverine deltas and Amazon basin rivers (Sulistioadi et al. 2015; Siddique-E-Akbor et al. 2011; Calmant et al. 2013). Of them, Indonesian small rivers and Bangladesh riverine deltas are places, where altimetry applications subject to scientific challenge due to small reflecting area covered by satellite and large spatial and temporal sampling gaps. The studies explored the ability of satellite altimetry to monitor small water bodies in Indonesia and the complex hydrology of riverine deltas. Calmant et al. (2013) estimates the bias of the Envisat ICE-1 retracked altimetry over rivers is 1.044 ± 0.212 m, revealing a significant departure from other Envisat calibrations or from the Jason-2 ICE-1 calibration.

Multi-mission altimetry has been used to study in combination with remote sensing data and GRACE observations the inter-annual water storage changes in the Aral sea (Singh et al. 2012, 2013). Schwatke et al. (2015a) elaborated a dedicated Kalman filter approach for estimating water level time series over inland water using multi-mission satellite altimetry. The potential of SARAL/Altika for inland water applications was investigated by Schwatke et al. (2015b).

Studies of ocean tides

Altimetry studied of ocean tides involve in modelling a combined ocean tide model using GRACE and altimetry measurements (Mayer-Gürr et al. 2012) and assessing global (and regional) barotropic ocean tide models (Fok et al. 2013; Wang et al. 2013; Stammer et al. 2014). Mayer-Gürr et al. (2012) used altimetry and GRACE observations, both having the signature of ocean tides, to construct a combined estimation of a global ocean tide model EOT08ag. The differential contributions of GRACE to EOT08ag remain small and are mainly concentrated to the Arctic Ocean, an area with little or poor altimetry data. No significant improvement from GRACE was found over the altimetry-only tide model, except for a few areas above 60°N. Overall the improvements of the combination remain small and appear to stay below the current GRACE baseline accuracy. The successor model EOT11a (Savcenko and Bosch, 2012), based exclusively on empirical analysis of satellite altimetry data has been selected for the Release 05 processing standard of the German GRACE Science team.

In the process of developing a real-time data-assimilating coastal ocean forecasting system for Prince William Sound, Alaska, tidal signal was added to a three-domain nested Regional Ocean Modeling System (ROMS) model for the region. Wang et al. (2013) validated the ROMS tidal solution against the data from coastal tide gauges, satellite altimeters, high-frequency coastal radars, and Acoustic Doppler Current Profiler (ADCP) current surveys. The error of barotropic tides, as measured by the total root mean square discrepancy of eight major tidal constituents is 5.3 cm, or 5.6% of the tidal sea surface height variability in the open ocean. Along the coastal region, the total discrepancy is 9.6 cm, or 8.2% of the tidal sea surface height variability. Model tidal currents agree reasonably well with the observations. The influence of tides on the circulation was also investigated using numerical experiments. Their results indicate that tides play a significant role in shaping the mean circulation of the region.

The accuracy of state-of-the-art global barotropic tide models was assessed by Stammer et al. (2014) using bottom pressure data, coastal tide gauges, satellite altimetry, various geodetic data on Antarctic ice shelves, and independent tracked satellite orbit perturbations. The root-sum-square differences between tide observations and the best models for eight major constituents are ~0.9, ~5.0, and ~6.5 cm for pelagic, shelf, and coastal conditions, respectively. Large intermodel discrepancies occur in high latitudes, but testing in those regions is impeded by the paucity of high-quality in situ tide records. For the M2 constituent, errors in purely hydrodynamic models are now almost comparable to the 1980-era Schwiderski empirical solution, indicating marked advancement in dynamical modelling. The assessment of ocean tides also extended to the ice-covered polar oceans and near coastal regions by Fok et al. (2013).

Based on pressure tide gauge observations at three sites off the Atlantic coast of Tierra del Fuego main island, Richter et al. (2012) derived the time series spanning one to seven months of bottom pressure and sea-level variations. The results reveal the major driving mechanisms and difference between the in situ observations and six recent global ocean tide models, official tide tables, and sea-surface heights derived from satellite altimetry data. In the time domain the tidal signal represented by the models deviates typically by a few decimetres from that extracted from our records. Absolute altimeter biases were determined for the Jason-2, Jason-1 extended mission, and Envisat satellite altimeters. Relative sea- level variations are represented by the altimetry data with accuracy of the order of 5cm.

Altimetry calibration

Since satellite altimetry has observed global and regional evolution of the sea level over 20 years of data records, it is important to have its long-term data records from a sequence of different, partly overlapping altimeter systems carefully cross-calibrated among altimeter missions and calibrated by in-situ sites. Dettmering and Bosch (2013) and Bosch et al. (2014) globally realised the cross-calibration through adjusting an extremely large set of single- and dual-satellite crossover differences performed between all contemporaneous altimeter systems. The total set of crossover differences creates a highly redundant network and enables a robust estimate of radial errors with a dense and rather complete sampling for all altimeter systems analysed. The cross-calibration approach has been also applied to study radial errors, range biases and sensor drifts for new altimeter missions like CryoSat-2 (Dettmering and Bosch 2011, 2014; Horvath et al. 2013) and SARAL-Altika (Dettmering et al. 2015).
Andersen and Cheng (2013) investigated long term changes in the TOPEX/Jason range corrections at four altimetry calibration sites: Bass Strait, Corsica, Gavdos and platform Harvest. The results show that there are no significant linear trends in the sum of range corrections at the calibrations sites in case of the local scales (within 50 km around the selected site) and regional scales (within 300 km). However, the geophysical corrections related to atmospheric pressure loading and high frequency sea level variations (dynamic atmosphere correction) should be used with caution, as the dynamic atmosphere correction shows a regional trend close to 1 mm/year at Mediterranean calibration sites (Corsica and Gavdos).

Future Contributions

After 2015 IUGG, we will continue our research in satellite altimetry with development of new generation of satellite altimetry missions, such as CryoSat-2 and Sentinel-3 (secluded to be launch in 2015). Based on expected future data acquisitions, further improvements may come from development of advanced techniques to process altimeter SAR mode data and LRM data in coastal area through optimal waveform retracking. With accumulated CryoSat-2 non-repeat data and recent progress in improvement of altimeter range precision, we expect a further improvement of the high-accuracy and high–resolution marine gravity field. We also continue our studies in modelling dynamic ocean topography and ocean tides, especially in near Polar Regions, in monitoring and modelling of sea-level rise and extremes, in monitoring of water level heights over rivers, lakes and ice sheets.

Some Publications between 2011-2015:

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Sub-Commission 2.6: Gravity and Mass Displacements

Chair: Shuanggen Jin (China)

Website: http://202.127.29.4/geodesy/IAG_SC2.6/

Activities

SC 2.6 initiated several working groups and study groups: JWG 2.5; JWG 2.6; JWG 2.7; JWG 2.8; JSG 3.1; JSG 0.8. See separate reports of these entities.

SC 2.6 organized a Special Issue of Journal of Geodynamics on "Earth System Observing and Modelling from Space Geodesy"

> This special issue of *Journal of Geodynamics* on "Earth System Observing and Modelling from Space Geodesy" focuses on assessing current technological capabilities and presenting recent results of space geodetic observations and understanding the physical processes and coupling in the Earth system, and future impacts on climate. Topics include data retrieval of space geodetic techniques, reference frame, atmospheric-ionospheric sounding and disturbance, gravity field, crustal deformation and earthquake geodesy, GIA, Earth rotation, hydrological cycle, ocean circulation, sea level change, and ice sheet mass balance as well as their coupling in the Earth system. This special issue consists not only of papers given at the International Symposium on Space Geodesy and Earth System but also includes other contributions on this topic that were submitted in response to an open call for contributions. All related papers are welcome to submit to Special issue of Journal of Geodynamics on "Earth System Observing and Modelling from Space Geodesy" via http://ees.elsevier.com/geod. To ensure that all manuscripts are correctly identified for inclusion into the special issue, authors must select "SI: Geodetic Earth System" when they reach the "Article Type" step in the submission process. **Guest editors:** Prof. Shuanggen Jin, Shanghai Astronomical Observatory, CAS, Shanghai, China; A/Prof. Tonie van Dam, University of Luxembourg, Luxembourg; Dr. Shimon Wdowinski, University of Miami, Miami, USA.

Academic Activities

- **1-4 June 2015**, Shuanggen Jin co-organized the 2nd International Association of Planetary Sciences (IAPS) General Assembly (IAPS2015) as Co-Chair, Kazan, Russia.
- **30 June-6 July 2014**, Shuanggen Jin co-organized The 3rd International Gravity Field Service (IGFS) General Assembly (IGFS2014) as Co-Chair of Scientific Organizing Committee and Chair of Local Organizing Committee, Shanghai, China.

- **1-11 September 2013**, Shuanggen Jin attended International Association of Geodesy (IAG) Scientific Assembly (IAG2013) with two oral talks and five session chairs in Potsdam, Germany and visited University of Beira Interior (UBI) and University of Lisbon with one talk, Lisbon, Portugal.
- **1-4 July 2013**, Shuanggen Jin organized International Symposium on Planetary Sciences (IAPS2013) as Chair of Symposium, Shanghai, China.

- **12-13 May 2013**, Prof. Rene Forsberg visited Shanghai Astronomical Observatory, CAS and gave a talk on "GRACE, GOCE and Polar Geodesy", Shanghai, China.

- **12 December 2012**, Shuanggen Jin, Per Knudsen and Ole Andersen co-organized SHAO-DTU Workshop on Space Geodesy and discussed future possible collaboration, Shanghai, China.

- **18-21 August 2012**, Shuanggen Jin organized International Symposium on Space Geodesy and Earth System (SGES2012) as Chair of Symposium, Shanghai, China.

- **21-25 August 2012**, Shuanggen Jin organized International Summer School on Space Geodesy and Earth System and gave a half-day lecture on GNSS and Gravity Geodesy, Shanghai, China.
- **13-17 August 2012**, Shuanggen Jin attended the AOGS-AGU (WPGM) Joint Assembly with convening two sessions and giving one talk, Singapore.
- **08-16 August 2011**, Shuanggen Jin convened one Session at Asia Oceania Geosciences Society (AOGS 2011) with one talk, Taiwan.
- **10-18 November 2011**, Shuanggen Jin was invited to visit and give several talks at Taiwan National Chiao Tung University, National Cheng Kung University, National Central University and Institute of Earth Sciences, Academia Sinica, Taiwan.

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Avsar, N.B., S.H. Kutoglu, B. Erol, and S.G. Jin, Sea level changes in the Black Sea from Satellite Altimetry and Tide Gauge observations, The 26th International Union of Geodesy and Geophysics (IUGG) General Assembly, 22 June -2 July 2015, Prague, Czech.

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Joint Project 2.1: Geodetic Planetology

Chairs: Oliver Baur (Austria), Shin-Chan Han (USA)

The Joint Project "Geodetic Planetology" (JP-GP) has mainly been established to build a bridge between the geodesy-related efforts in planetary sciences and the activities within the IAG. As outlined in the terms of reference: "Within the 4-year horizon 2011-2015, the JP-GP will start to initiate and promote geodetic research of extra-terrestrial bodies. Furthermore, in terms of sustainable follow-on activities, the project envisages the establishment of an Inter-Commission Committee on Geodetic Planetology for the next period 2015-2019."

As mentioned in the Midterm Report, during the first two years of the joint project it turned out that enormous effort (with very limited success) is required to motivate scientists to actively support and contribute to the project activities. This holds true for the collaboration with both the European and the US geodesy-related planetary sciences communities. The situation did not change during the second JP-GP period, and therefore the conclusion has to be drawn that the joint project failed to meet its objectives. Against this background, the chairs consider neither prolongation of the current activities beyond 2015 nor the establishment of an Inter-Commission Committee on Geodetic Planetology.

Activities

Meetings

Conference sessions dedicated to geodetic planetology and (co-)organized by the project chairs:

Conference	Session	# presentations oral/poster
International Symposium on Gravity, Geoid and Height Systems (GGHS), Venice, Italy	Gravity Field of Planetary Bodies	4 / 1
International Symposium on Planetary Sciences (IAPS), Shanghai, China	Science and Exploration of the Moon	12 / 1

Results

The Gravity Recovery And Interior Laboratory (GRAIL) mission can be considered as the 'highlight' in geodetic planetology of the last few years. The satellite data allow estimating the lunar gravity field with unprecedented accuracy and resolution, which in turn is a key quantity to improve our knowledge about the interior structure and thermal evolution of the Moon. GRAIL lunar gravity field recovery is mainly done by planetary scientists in the US. Owing to GRACE heritage, efforts within the IAG are underway since recent years.

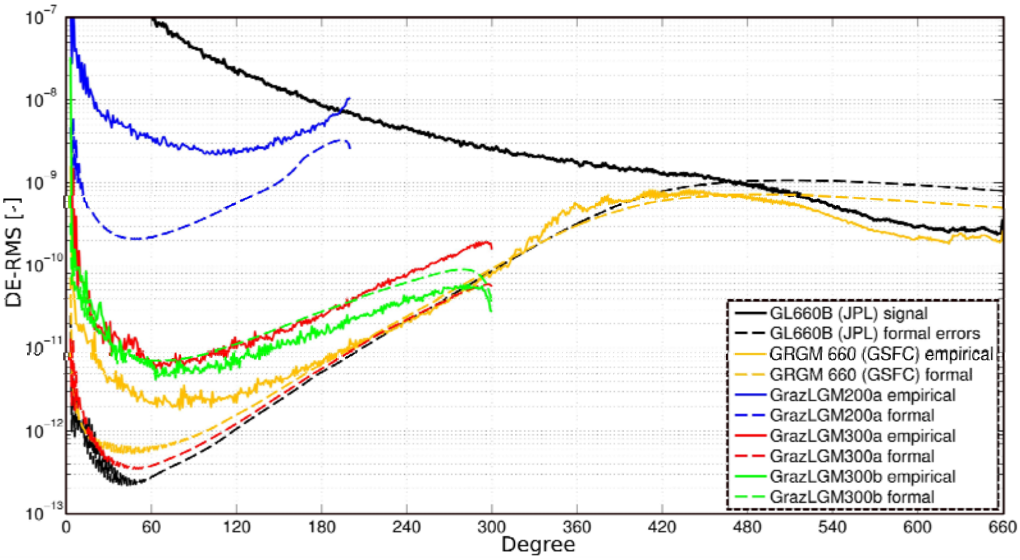

Figure 1. RMS values per spherical harmonic degree for different GRAIL gravity field solutions based on data collected during the primary mission phase (March 1 to May 29, 2012); figure taken from Krauss S., Klinger B., Baur O., Mayer-Gürr T. (2015) Development of the lunar gravity field model GrazLGM300b in the framework of project GRAZIL, EGU General Assembly, Vienna, Austria, 12.-17.04.2015

Joint Working Group 2.1: Techniques and Metrology in Absolute Gravimetry

Chair: Vojtech Palinkas (Czech Republic)

Primary Objectives

The IAG Joint Working Group 2.1 (JWG 2.1) focuses on the technical and metrological aspects in absolute gravimetry and the realization an appropriate system of comparisons of absolute gravimeters to fulfil requirements especially in geodesy. JWG 2.1 works in cooperation with the "Joint Working Group 2.2: Absolute Gravimetry and Absolute Gravity Reference System" (JWG 2.2) and the "Working Group on Gravimetry of Consultative Committee for Mass and Related Quantities of International Committee of Weights and Measures" (CCM-WGG).

Activities and results (2011-2015)

This section presents the report of the JWG 2.1 activities since its creation in 2011. During the period 2011-2015 the JWG 2.1 established its term of reference, held one official meeting, contributed on preparation of a document "CCM – IAG Strategy for Metrology in Absolute Gravimetry" and contributed on realization of two comparisons of absolute gravimeters.

Meeting in Vienna

The discussion Meeting on Absolute Gravimetry, organized as a joint meeting of JWG 2.1 and JWG 2.2, was held in Vienna in February 2012. The meeting covered the major topics related to the work of JWG 2.1 and had following consequences:

- *Treatment of systematic effects in absolute gravity determination:* The scientific results of three systematic effects (self-attraction, diffraction, and finite speed of light) were presented by several authors related to papers of Biolcatti et al. (2012), Palinkas et. al. (2012), Rothleitner and Svitlov (2012), Rothleitner and Francis (2011), Nagornyi et al. (2011). Important results of this meeting are recommendations concerning implementations of corrections to absolute measurements, which were consequently followed by processing of comparisons in 2009 (Jiang et al. 2012), 2011 (Francis et al. 2013) and 2013 (Francis et al. 2015).
- *Determination of reference instrumental height.* Unclearness connected with the position where the gravity is determined as invariant of the vertical gravity gradient, causes several troubles with practical determination and application of measured gravity acceleration. The concept of the effective position of the free-fall was reintroduced at the meeting. Two publications (Rothleitner and Svitlov 2012, Palinkas et. al. 2012) are related to this topic. The processing of the comparison in 2013 (Francis et al. 2015) have used correctly the effective position of the free-fall for transferring g to the comparison reference height.
- The function of the "comparison site requirements" document was discussed. The text was distributed to the members of JWG 2.1 and CCM-WGG. The final document was consequently prepared, named "*Guide to evaluation of the sites for comparison of absolute gravimeters*", and approved by the CCM-WGG.
- The working groups JWG 2.1 and JWG 2.2 agreed with the present periodicity of comparisons, four-yearly ICAGs with intermediate RCAGs two years after the ICAG. Moreover, the capability of the reference stations equipped with a superconducting gravimeter was demonstrated. The reference stations should play a key role for validation of absolute

gravimeters used in geodesy. These recommendations were reflected in the Strategy document discussed below.

Comparisons of absolute gravimeters

In November 2011 and November 2013 key comparisons (EURAMET.M.G-K1 and CCM.G-K2) of absolute gravimeters have been organized in Walferdange by the University of Luxembourg (O. Francis) and METAS (H. Baumann). Gravimeters without metrological status have participated under the pilot studies accompanied with the key comparisons. Altogether 22 resp. 25 absolute gravimeters participated at comparisons. For the first time the influence of the geophysical gravity changes during the comparison has been implemented to the results of comparison (Francis et al. 2013). Both comparisons showed ability to define the reference values with uncertainty of about 1.5 μGal.

Cooperation with CCM-WGG

Nine members of JWG 2.1 are also members of CCM-WGG. Both groups have several common goals, especially those connected with comparisons of absolute gravimeters. Activities as organization of comparisons, discussion concerning methodology of data processing etc. have been arranged in the period 2011-2015 within CCM-WGG meetings (Istanbul 2012, Paris 2013, Paris 2015), because the comparisons have official metrological status at present.

Strategy document

A common strategy document of IAG and CCM for metrology in absolute gravimetry has been prepared by the cooperation of IAG JWGs and CCM-WGG. The IAG Executive Committee accepted the current document "CCM-IAG Strategy for Metrology in Absolute Gravity" as relevant and important, for the IAG in the establishment of a global gravity reference system and a contribution to the Global Geodetic Observing System (GGOS).

The document presents the basic ideas for the cooperation and coordination of activities of institutions in metrology and geosciences for the establishment of the metrology system in absolute gravimetry based on the comparisons and calibrations of absolute gravimeters. It proposes best practices to maintain the metrological traceability for selected comparisons levels. This spans from the level of the CIPM key comparisons and regional key comparisons to the level of additional comparisons. Furthermore, the role of reference stations (monitored e.g. by combined measurements of absolute and superconducting gravimeter) is defined in the traceability chain. It is understood as a very important contribution especially for the geodetic community, because for the first time a formal agreement is reached on the ways to ensure the traceability of absolute gravity measurements to SI units at the uncertainty level of a few parts in 10^{-9}.

Upcoming activities

In November 2015, regional comparison of absolute gravimeters will be held in Walferdange. The comparison is organized by the University of Luxembourg (O. Francis) and VÚGTK/RIGTC (V. Palinkas). It is planned to reach agreement in processing of comparisons in terms of testing different approaches for constraining the adjustment and including correlations between gravimeters.

Joint meeting of IAG JWGs and CCM-WGG will be organized in Brussels in February 2016.

Publications

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Joint Working Group 2.2: Absolute Gravimetry and Absolute Gravity Reference Systems

Chair: Herbert Wilmes (Germany)

Within the IAG, JWG 2.2 is closely connected with the IAG Sub-Commission 2.1 "Gravimetry and Gravity Networks" which promotes the scientific investigations of gravimetry, gravity networks and terrestrial, airborne, shipboard and planetary gravity measurements.

The International Gravity Field Service IGFS coordinates the support of the geodetic and geophysical community with gravity field related data, software and information. The IAG's scientific community demands more detailed information on the Earth's gravity field and its changes. Precise terrestrial absolute gravity (AG) observations are an important contribution to the monitoring and understanding of mass transports in atmosphere, hydrology or the cryosphere and to understand better the questions of global climate change, sea level rise and geodynamical processes.

It is the basic purpose of this working group to contribute to the realization of a global absolute gravity reference system which integrates all absolute gravimeters and is stable enough to monitor the temporal gravity changes for terrestrial applications.

The importance of absolute gravimetry has increased with growing accuracy, new instruments and the distribution of measurements worldwide. The concept of gravity measurements has changed from AG determinations on a few principal network stations to repeated absolute gravity observations in global networks. In many stations collocated geometric observations are available which enables investigations of geophysical processes and provides the opportunity to distinguish between mass- and height-related changes. This is a contribution to the Global Geodetic Observing System (GGOS) which integrates the geodetic techniques, models and approaches to ensure a long-term, precise monitoring of the Earth's shape, the Earth's gravity field and the Earth's rotational motion. Consistent and precise absolute gravity measurements from a global network are a valuable contribution to the GGOS infrastructure.

The intended realization of a precise and stable reference system relies upon the close co-operation of IAG with the institutions responsible for legal metrology and is represented by the International Bureau for Weights and Measures (BIPM) and the International Committee for Weights and Measures (CIPM), respectively. Comparisons of absolute gravimeters were conducted since 1981 under the leadership of BIPM. A new quality of the comparisons was introduced with the adoption of the mutual recognition arrangement in metrology (http://www.bipm.org/en/cipm-mra/) in 2009. Consequently, international comparisons of absolute gravimeters changed to key comparisons (KC) which are carried out under CIPM with the support of the Consultative Committee for Mass and Related Quantities, Working Group on Gravimetry (CCM-WGG). In a close cooperation of this working group together with members of the "IAG Sub-Commission 2.1" and the two Joint Working Groups, JWG 2.1 and JWG 2.2, a new strategy document was prepared: "CCM – IAG Strategy for Metrology in Absolute Gravimetry, Role of CCM and IAG". This document defines the cooperation between metrology and the geoscientific community. It explains and fixes the procedures of the comparisons and specifies the rules how to connect additional absolute gravimeters and stations to the metrological reference. Best practices are included in this document which span from the level of the centralized four-annual key comparisons of the Consultative Committee for Weights and Measures (CIPM) to the level of distributed and intermediate comparisons. The discussion spread over several meetings and involved intensive e-mail communication.

The agreed strategy paper was then submitted to the IAG Executive Committee and was accepted in 2015. It defines the metrological basis for the establishment of a consistent global absolute gravity reference system.

The conclusion of this agreement is that the set of compared absolute gravimeters forms the realization of the absolute gravity standard. If we want to obtain the highest resolution with the absolute gravity measurements, we need to apply the instrumental offsets (or degree of equivalence) determined during the comparison, presently in the order of a few µGal. The observation with a compared absolute gravimeter transfers this standard to the new observation site.

Due to tides, polar motion and air pressure variations, the gravity acceleration never is a constant value; and even if we apply correction models for these effects, we still observe variations due to e. g. hydrology which so far cannot be satisfactorily modelled.

For the realization of the global absolute gravity reference system, a secondary component is important which observes and documents the gravity variations continuously: This is a network of gravity reference and comparison sites which are equipped with a superconducting gravimeter (SG) and where repeated AG measurements with a compared absolute gravimeter are carried out. The measurements of absolute gravimeters and SG are combined to a drift-corrected reference function in the global absolute gravity reference system. For geoscientific investigations of highest accuracy and multiple instruments it is important that additional AG instruments can be connected with the absolute reference system, and additional instruments can be checked against the reference function.

SG stations of such a global network can be found in the Global Geodynamics Project (GGP), where a global network of stations using SG is maintained and the gravity variations are studied. Presently GGP prepares a new IAG service, and for this purpose has asked the community with absolute gravimeters to provide repeated observations at the SG sites for the drift correction and calibration of the SG sensors. Therefore, the planned cooperation finds mutual benefit.

Such a network of gravity reference and comparison stations enables the global distribution and is a permanent access to the absolute gravity reference. Instrumental checks are possible for AG instruments after intensive field campaigns or repair works. It seems important that at least a few national stake holder institutions guaranty the operation of a basic number of absolute gravity reference and comparison stations.

At present, still the International Gravity Standardization Network 1971 (IGSN71) is the valid gravitational reference system of the IAG. Correction models and parameters have not been updated for this system, so that gravity data referring to this system can only be defined with an accuracy level of ± 100 µGal which by far is not sufficient for the determination of temporal gravity changes.

De-facto, the AG measurements at the few µGal accuracy level have already replaced this gravity reference IGSN71. But the international community needs an official and an up to date gravity standard.

A registry is required for such a system of "key comparison" AG instruments and connected SG reference stations with a worldwide distribution. The comparison results must be documented for each absolute gravimeter, together with the combined time series of repeated AG measurements and the SG time series. This function can be covered by an extension of the existing AGrav database. The AGrav database goes back to an earlier development within this working group. The database is operational since several years and became a reliable component of the International Gravimetric Bureau (BGI) permanent services. The database provides an overview of existing AG stations, observations, instruments and institutions, and facilitates cooperation.

For the IAG general assembly in Prague, it is planned to submit a resolution with following content. The (draft) text is provided as Appendix.

In 2012 a “Discussion Meeting on Absolute Gravimetry” was held as a joint meeting of the two IAG working groups, JWG 2.1 “Techniques and Metrology in Absolute Gravimetry” and JWG 2.2 “Absolute Gravimetry and Absolute Gravity Reference System”. The meeting with more than 30 participants was hosted by the Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna, Austria.

Major topics of this meeting were the treatment of systematic effects in absolute gravity determination, the development of the technical protocol for the international and regional comparisons of absolute gravimeters, the realization of the International Gravity Reference System, the use of reference gravity stations, and the status and future development of the AGrav database.

The participants thank the Bundesamt für Eich-und Vermessungswesen (BEV) for the great hospitality during hosting this discussion meeting and for the invitation to visit the Conrad observatory on Trafelberg.

The AGrav database now holds data from 50 absolute gravimeters, 1117 gravity stations and 3200 observational epochs (status April 2015). The planned transformation of the gravity reference system from IGSN71 to a Global Absolute Gravity Reference System strongly requires the continuation of this work.

Members

- Chair: Herbert Wilmes (Germany)
- Martine Amalvict (France)
- Nicholas Dando (Australia)
- Reinhard Falk (Germany)
- Jan Krynski (Poland)
- Jaakko Mäkinen (Finland)
- Vojtech Palinkas (Czech Republic)
- Victoria Smith (UK)
- Ludger Timmen (Germany)
- Leonid Vitushkin (Russia)
- Jonas Ågren (Sweden)
- Henri Baumann (Switzerland)
- Mark Eckl (USA) †
- Domenico Iacovone (Italy)
- Jacques Liard (Canada)
- Urs Marti (Switzerland)
- Diethardt Ruess (Austria)
- Gabriel Strykowski (Denmark)
- Michel van Camp (Belgium)
- Hartmut Wziontek (Germany)

Corresponding Members

- Mauro Andrade de Sousa (Brazil)
- In-Mook Choi (Korea)
- Yoichi Fukuda (Japan)
- Olga Gitlein (Germany)
- Alessandro Germak (Italy)
- Janis Kaminskis (Latvia)
- Jakub Kostelecky (Czech Republic)
- Tomasz Olszak (Poland)
- Rene Reudink (Netherlands)
- V.M. Tiwari (India)
- Roger Bayer (France)
- Andreas Engfeldt (Sweden)
- Jose Manuel Serna Puente (Spain)
- Mirjam Bilker Koivula (Finland)
- Jacques Hinderer (France)
- Steve Kenyon (USA)
- Dennis McLaughlin (USA)
- Bjorn Ragnvald Pettersen (Norway)
- Heping Sun (China)

Joint Working Group 2.3: Assessment of GOCE Geopotential Models

Chair: Jianliang Huang (Canada)

Highlights of Members' Assessments and Activities

Abd-Elmotaal, Hussein has tested different recent GOCE geopotential models to produce reduced isostatic gravity anomalies for Africa. The reduction of the gravity anomalies follows the window remove-restore technique employing the Airy floating hypothesis. The results show that the GOCE-GRACE-LAGEOS combined geopotential model EIGEN-6C4 gives the smallest standard deviation of the Airy window isostatic anomalies for Africa. The GOCE satellite-only model GO CONS GCF 2 DIR R5 gives the smallest range of the Airy window isostatic anomalies for Africa, with only 1 mgal higher in the standard deviation compared to that of the EIGEN-6C4 model.

Benahmed Daho, Sid focused on the evaluation of the performances of the latest GOCE-based GGMs models. The terrestrial gravity data over Algeria supplied by BGI and new set of GPS/leveling-derived geoid heights were used as ground-truth data sets for the new GOCE-based GGMs evaluation. Analysis of the root mean square (RMS) residuals between the terrestrial data sets and spectrally enhanced GGM functionals showed that the GOCE-based models improved knowledge in the spectral bands ~160 to ~180 with respect to GRACE. Furthermore, when analyzing the results obtained with the high-quality GPS/levelling data, it can be concluded that the global geoid accuracy is at the level of 9 cm at degree and order 180. It is about to 5 to 6 cm if we take into account the error level of the GPS/levelling data. This indicates that the objectives of mission have not been reached yet.

Carrion, Daniela et al. (2015) suggest that the GOCE satellite mission has significantly improved the results obtained with the previous satellite missions CHAMP and GRACE. Using GOCE data satellite Global Geopotential Models were developed using three different approaches, namely the direct, the time-wise and the space-wise approaches. The last releases of these models are complete to degree and order 300 (direct approach) and 280 (time-wise and space-wise approaches). In their study, the different releases of the three estimation methodologies are compared with observed gravity and GPS/levelling data in the Mediterranean area. Particularly, the Italian and the Greek databases are considered. Comparisons are also carried out with respect to EGM2008 in order to check for possible improvements in the medium frequencies. The comparisons show that significant improvements are obtained when Greek data are considered while the same doesn't occur with the Italian data.

Cheng, Minkang and John C. Ries suggest that the orbit fit tests show that all recent GOCE and GRACE-based models perform similarly at the longer wavelengths. The GOCO_TIM models did not include SLR or GRACE data, yet they perform here as well as models that did. The results indicate that there is little to distinguish between the available mean gravity field models, suggesting that the time variable gravity is now likely to be the dominant source of long-wavelength gravity model error. It is well known that the value of C20 has a significant long-term trend, and the SLR data is essential in monitoring this trend for the most precise applications

Denker, Heiner and Christian Voigt suggest that the agreement between the latest GOCE models (5th generation) and terrestrial data is about 2-3 cm for height anomalies, 1 mGal for gravity anomalies, and 0.3" for vertical deflections, respectively, being fully compatible with the relevant error estimates. The combination solutions based on GOCE and terrestrial data perform in many cases similar to corresponding calculations relying on EGM2008, which is due to the high quality of the European data sets utilized in the EGM2008 development; however, in several areas with known weaknesses in the terrestrial gravity data (e.g., Bulgaria, Romania, etc.), the inclusion of the GOCE models instead of EGM2008 leads to significant improvements in terms of GPS/leveling fits, especially regarding the 5th generation GOCE models.

Foerste, Christoph, as a member of the European GOCE Gravity Consortium EGG-C and ESA's GOCE High Level Processing Facility GOCE-HPF, routinely assesses and evaluates all global GOCE gravity field models including GOCE models which were jointly generated by GFZ Potsdam and CNES/GRGS Toulouse.

Godah, Walyeldeen et al. have provided an accuracy assessment of 1st – 5th release GOCE-based GGMs developed with the use of the direct solution and the time-wise solution strategies over the area of Poland. Free-air gravity anomalies and height anomalies computed from those GGMs have been compared with the corresponding ones obtained from the EGM08. Moreover, height anomalies determined from GOCE-based GGMs were compared with the corresponding ones obtained from three different GNSS/levelling data sets with the use of the spectral enhancement method. Taking into the consideration the accuracy of the EGM08 and GNSS/levelling data used, the evaluation of gravity functionals determined from GOCE-based GGMs at d/o 200 indicates that the models developed with the use of whole set of GOCE mission data, i.e. 5th release, could provide free-air gravity anomalies and height anomalies with accuracy of 1 mGal and 1 – 2 cm, respectively. It can lead to the conclusion that the goal of GOCE mission has been achieved.

Gruber, Thomas has performed continuous validation of GOCE gravity field models per release in order to identify the impact of additional GOCE data on model performances. The true GOCE global model errors in terms of geoid heights and gravity anomalies were estimated by means of comparison with independent information. From these analyses it turned out that the ultimate GOCE mission goals of 1-2 cm geoid heights and 1 mGal gravity anomalies at 100 km spatial resolution have been achieved and partially even were outperformed. Results of the GOCE data analysis and the derived global models were presented at all major conferences and dedicated gravity field meetings.

Hirt, Christian et al. have used topographic mass models to evaluate five generations of GOCE gravity models, both globally and regionally. As model representing Earth's topography, ice-sheet and waterbody masses they used the new RET2014 rock-equivalent topography model by Curtin University (Perth). The gravitational potential of the RET2014 model is computed in spherical harmonics and in ellipsoidal approximation (ellipsoidal topographic potential, cf. Claessens and Hirt 2013, JGR Solid Earth, 118, 5991). They compare gravity from GOCE and from the RET2014 topography, whereby similar signal characteristics are taken as a sign of quality for the GOCE gravity fields. The topographic evaluation shows a steadily improved agreement of the five model generations with topography implied gravity, and increase in GOCE model resolution. For the fifth-generation GOCE gravity fields, full resolution is indicated to harmonic degree ~220 (90 km scales), and partially resolved gravity features are found to degree ~270 (time-wise approach, TIM) and degree ~290-300 (direct approach, DIR), As such, the 5th-generation GOCE models capture parts of the gravity field signal down to ~70 km spatial scales. This is a very significant improvement in satellite-only static gravity field knowledge compared to the pre-GOCE-era. The comparisons show that models from the DIR approach improved relative to those from the TIM approach from the

2nd to the 5th generation, with DIR offering the best short-scale performance (from degree 240 and beyond).

Huang, Jianliang and Marc Véronneau indicate that the GOCE R5 models provide better precision than the GOCE release 4 (R4) models beyond degree and order 180. The accuracy of the GOCE R5 models is estimated to be better than 4-5 cm up to spherical harmonic degree ~200. The astronomic deflections in Canada are not accurate enough to measure improvements in the GOCE R5 models with respect to the GOCE R4 models. For the validation of GGM against terrestrial gravity data over land in Canada, EIGEN-6C4, which includes a GOCE R5 model, is assessed in contrast to EGM2008. Their analysis infers that the GOCE contribution in EIGEN-6C4 is more accurate than the corresponding wavelength components in EGM2008, which includes the Canadian terrestrial gravity data.

Hwang, C. and H. J. Hsu used gravity data and GPS-levelling data in Taiwan to assess the GOCE-Tim3 and –Tim4 models, which are independent of all terrestrial data. The omission error is reduced by using the EGM2008 high degree terms and they remove the residual terrain effect. They show that GOCE-TIM4 has a reliable degree to 220, compared with degree 180 for GOCE-TIM3. GOCE-TIM4 uses ~26.5 months of mission data, whereas GOCE-TIM3 uses only ~12 months of data. In conclusion, the best harmonic expansion degree for the GOCE-TIM4 model is 220.

Jekeli, Christopher et al. have determined for the Bolivian Andes that the new global gravity models derived from GOCE may be used directly to study lithospheric structure. A numerical comparison of the spherical harmonic models to conventional three-dimensional modelling based on topographic data and newly acquired surface gravity data in Bolivia confirmed their suitability for lithospheric interpretation. Specifically, the relatively high and uniform resolution of the satellite gravitational model (better than 83 km) produces detailed maps of the isostatic anomaly that clearly delineate the flexure of the Brazilian shield that is thrust under the Sub-Andes. Inferred values of the thickness of Airy-type roots and the flexural rigidity of the elastic lithosphere agree reasonably with published results based on seismic and surface gravity data. In addition, the GOCE model generates high resolution isostatic anomaly maps that offer additional structural detail not seen as clearly from previous seismic and gravity investigations in this region.

Klokocnik, Jaroslav et al. have compared the global combined high-resolution gravity field models EGM 2008 and EIGEN-6C3stat by means of gravity anomalies and the radial component of the Marussi tensor. The role of the GOCE gradiometry data is detected. GNSS/leveling provides independent data source to evaluate any gravity field model. They apply such data to test EGM 2008 (without GOCE measurements) and EIGEN-6C3stat (already with them). The GNSS/levelling data set is dense (1024 points) and precise (ellipsoidal height error below 2 cm) but is available only over the territory of the Czech Republic with this density; this test has in turn a limited validity. The RMS of height differences between GNSS/leveling and EGM 2008 or GNSS/leveling and EIGEN-6C3stat is 3.3 cm or 4.1cm, respectively.

Li, Jian-Cheng and Xin-Yu Xu have used a total of 649 GPS/Leveling points and 799897 2′×2′ gridded mean gravity anomalies in mainland China for the evaluation of the recently released Earth Gravitational Models (EGMs) including the GOCE only models (GO_CONS_GCF_2_TIM_R3 (GO_TIM_R3), GRACE only models ITG-Grace2010s, combined satellite gravity field models (GO_CONS_GCF_2_DIR_R3 (GO_DIR_R3), GOCO03S, DGM-1S, EIGEN-5S, EIGEN-6S), and combined gravity field models (EIGEN-

51C, EIGEN-6C, GIF48, EGM2008) from satellite observations and ground gravity data sets. The statistical results show that in mainland China the most precise model is EIGEN-6C with the standard deviation (STD) ±0.183 m of the quasi-geoid height differences compared with the GPS/Leveling data and the STD ±22.5 mGal of the gravity anomaly differences compared with the gridded mean gravity anomalies from observations. For EGM2008, they are ±0.240 m and ±24.0 mGal respectively. Among the satellite only gravity models from GRACE, GOCE and LAGEOS observations, GO_TIM_R3 is the best one in mainland China, and the STDs of the corresponding quasi-geoid differences and the gravity anomaly differences are ±0.459 m and ±31.3 mGal respectively, which are nearly at the same levels as the ones for the models EIGEN-6S, GOCO03S and GO_DIR_R3. This shows that the GOCE mission can recover more medium-short wavelength gravity signals in mainland China than former satellite gravity missions.

Matos, Ana Cristina Oliveira Cancoro de et al. report that the statistics of the differences between the tested geopotential models and GPS/BM show that the best agreement is obtained with DIRR5, TIMR5 and EIGEN6C4 for South America. The gravity disturbances derived from EIGEN6C4 show the best agreement when compared with terrestrial gravity anomalies. Most of the existing inconsistencies of this GGM are in mountainous regions. The general conclusion is that the recent geopotential models with GOCE information, in particular DIRR5, TIMR5 and EIGEN6C4, represent an important improvement on the knowledge of the gravitational potential.

Novák, Pavel et al. compared gravitational gradients observed by the GOCE gradiometer to gradients forward modelled from mass components/layers of the CRUST2.0 model and to gradients computed from ground and satellite altimetry-derived gravity data. Within the ESA's STSE project GOCE-GDC, main results of these studies were reported to ESA in the end of August 2013.

Pavlis, Nikolaos N has been doing various comparisons with the GOCE models, as those become available. He plans to continue performing these tests and comparisons in the future, and will show the results at some meeting, or for possible publication.

Saari, T. and M. Bilker-Koivula have compared altogether 16 GOCE models, 12 GRACE models and 6 combined GOCE+GRACE models with GPS-levelling data and gravity observations in Finland. The latest satellite-only models were compared against high resolution global geoid models EGM96 and EGM2008. Generally, all of the latest GOCE only and GOCE+GRACE models give standard deviations of the height anomaly differences of around 15 cm and of free-air gravity anomaly differences of around 10 mgal over Finland, when coefficients up to 240 or maximum are used. The results are comparable with the results of the high resolution models. The best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

Šprlák, M. et al. have validated global gravitational field models based on the time-wise and the direct approach in Norway. All five releases are compared to height anomalies, free-air gravity anomalies, and deflections of the vertical over the continental part of Norway. The spectral enhancement method is applied to overcome the spectral inconsistency between the gravitational models and the terrestrial data. The three terrestrial datasets indicate comparable performance of the latest GOCE models with respect to EGM2008 up to degree and order 220 in the studied local area.

Tocho, C. and G.S. Vergos have evaluated different GOCE-only and GOCE/GRACE GGMs using 567 available GPS/Levelling points and terrestrial free-air gravity anomalies in Argentina. The results show that EGM2008 is better than all GGMs, used for evaluation in this study, in terms of the standard deviation of the geoid heights are concerned. This superiority is marginal and statistically insignificant, being at the 3-2 mm level. GOCE/GRACE GGMs are significantly better than EGM2008 in terms of the range of the differences with the GPS/Levelling data, since they reduce the 1.964 m of the EGM2008 range by as much as 0.21 m for DIR_R5.

Vergos, G.S., et al. have evaluated various releases of GOCE and GOCE/GRACE GGMs over a network of 1542 collocation GPS/Leveling benchmarks, ~300,000 free-air gravity anomalies and 99 deflections of the vertical points in Greece. From the results acquired, the improvement of incorporating more GOCE data in the GGMs was evident, as progressing from release 1 to release 5. Being limited up to d/o 180-200 for the first releases it reaches d/o 245 for DIR-R5, with significant improvement in the spectral range between d/o 185-230. The latest releases of the GOCE/GRACE GGMs are better as much as 3.2 cm in terms of the std and 12.6 cm in terms of the range, compared to EGM2008. The latest versions of the GOCE/GRACE GGMs manage to provide a 1 cm relative accuracy for baselines larger than 40-50 km, which is quite encouraging for their use in medium-wavelength geoid related studies.

Vatrt, Viliam et al. conclude: 1) The global precision of EIGEN-6C (±0.203 m and ±11.22 mGal) was practically the same as EGM08 (±0.210 m and ±10.94 mGal). 2) The global precision of GOCO03S (±0.350 m and ±18.5 mGal) was lower than both others geopotential models. 3) The observed Geopotential Model Testing technology distortions can be used for improvements of the EIGEN-6C, GOCO03S and EGM08 geopotential models.

Selected Publications

Alothman, A., J. Bouman, Th Gruber, V. Lieb,. M. Alsubaei, A. Alomar, M. Fuchs, M. Schmidt (2015) Validation of Regional Geoid Models for Saudi Arabia Using GPS/Levelling Data and GOCE Models; in: Marti, U. (eds.) Proceedings of the IAG Symposium GGHS2012, October 9-12, 2012, Venice, Italy, Nr. 141, Springer, ISBN (Print) 978-3-319-10836-0, ISBN (Online) 978-3-319-10837-7, ISSN 0939-9585, DOI: 10.1007/978-3-319-10837-7, 2015

Gerlach, C., M. Šprlák, K. Bentel, B. R. Pettersen (2013) Observation, Validation, Modeling - Historical Lines and Recent Results in Norwegian Gravity Field Research. Kart og Plan, 73, pp. 128-151

Gruber, T., Visser, P. Ackermann, C, Hosse, M (2011) Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons. Journal of Geodesy 85:845-860, DOI 10.1007/s00190-011-0486-7

Guimarães, G., A. Matos and D. Blitzkow (2012) An evaluation of recent GOCE geopotential models in Brazil. Journal of Geodetic Science 2:144–155, DOI 10.2478/v10156-011-0033-8

Guimarães, G., D. Blitzkow, A. Matos (2013) Densificação Gravimétrica no Estado de São Paulo Visando um Modelo Geoidal Consistente. Revista Brasileira de Geofísica ISSN 0102-261X

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Hirt, C., T. Gruber and W. Featherstone (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights. Journal of Geodesy, 85:723–740, DOI 10.1007/s00190-011-0482-y

Hirt, C., M. Kuhn, W. Featherstone and F. Göttl (2012) Topographic/isostatic evaluation of new-generation GOCE gravity field models. Journal of Geophysical Research - Solid Earth 117(B05407), DOI 10.1029/2011JB008878

Huang, J. and M. Véronneau (2014) A Stokesian approach for the comparative analysis of satellite gravity models and terrestrial gravity data. In U. Marti (ed.), Gravity, Geoid and Height Systems, International Association of Geodesy Symposia IAGS 141, DOI 10.1007/978-3-319-10837-7_13

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Li, J., X. Zou, X. Xu, W. Shen (2014) Evaluation of Recent GRACE and GOCE Satellite Gravity Models and Combined Models Using GPS/Leveling and Gravity Data in China. In U. Marti (ed.), Gravity, Geoid and Height Systems, International Association of Geodesy Symposia 141, DOI 10.1007/978-3-319-10837-7_9

Matos, A., D. Blitzkow; G. Guimaraes, M. Lobianco, S. Costa (2012) Validação do MAPGEO2010 e Comparação com Modelos do Geopotencial Recentes. Boletim de Ciências Geodésicas (on-line), v.18, p.101 - 122

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Rexer, M., C. Hirt, R. Pail, and S. Claessens (2013) Evaluation of the third- and fourth-generation GOCE Earth gravity field models with Australian terrestrial gravity data in spherical harmonics, Journal of Geodesy 88(4), 319-333, DOI 10.1007/s00190-013-0680-x

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Tocho, C., G. S. Vergos, and M. C. Pacino (2014) Evaluation of GOCE/GRACE Derived Global Geopotential Models over Argentina with Collocated GPS/Levelling Observations In U. Marti (ed.), Gravity, Geoid and Height Systems, International Association of Geodesy Symposia 141, DOI 10.1007/978-3-319-10837-7_10

Vergos, G. S., V. N. Grigoriadis, I. N. Tziavos, and C. Kotsakis (2014) Evaluation of GOCE/GRACE Global Geopotential Models over Greece with Collocated GPS/Levelling Observations and Local Gravity Data. In U. Marti (ed.), Gravity, Geoid and Height Systems, International Association of Geodesy Symposia 141, DOI 10.1007/978-3-319-10837-7_11

Voigt, C., H. Denker (2014) Regional validation and combination of GOCE gravity field models and terrestrial data. In: Flechtner, F., et al. (eds), Observation of the System Earth from Space - CHAMP, GRACE, GOCE and Future Missions, Advanced Technologies in Earth Sciences, 139-145, DOI 10.1007/978-3-642-32135-1_18

Joint Working Group 2.4: Multiple Geodetic Observations and Interpretations over Tibet, Xinjiang and Siberia

Chairs: Cheinway Hwang (Taiwan), Wenbin Shen (China)

This joint working group is dedicated to studies of geodynamic process and climate change over the Tibet, Xinjiang and Siberia (TibXS), using geodetic tools ranging from satellite altimetry to satellite gravimetry. Additional techniques, such as GPS, terrestrial gravimetry, and interferometry SAR are also used. The members, as listed in the geodesists' handbook 2012, are all very active in this JWG, with activities ranging from personnel exchange, to attending the annual meetings, and to publishing papers in special issues of this JWG (see below).

From 2011 to 2015, we held annual meetings to exchange research results and ideas, and propose directions of study over TibXS, as the major activity of JWG2.4. We have published two special issues in the journal of Terrestrial, Atmospheric and Oceanic Sciences (TAO), with papers solicited from the meetings (with enhancements) and from outside. Highlights of the meetings and special issues are:

- TibXS2011 meeting (22-26 July, 2011) (http://space.cv.nctu.edu.tw/altimetryworkshop/TibXS2011/TibXS2011.htm) This meeting was held in Xining, Qinghai Province of China, with more than 60 participants. Several landmark papers on GRACE determination of mass change over TibXS were presented. The TAO special issue, "Geodynamic process and Climate Change in TibXS" was launched to publish 13 papers on research results mainly from GRACE, satellite altimetry and terrestrial gravimetry (TAO, Vol. 22, No.2, April, 2011).
- TibXS 2012 meeting (26-30, August, 2012) (http://space.cv.nctu.edu.tw/altimetryworkshop/TibXS2011/TibXS2011.htm):

  Held in Chengdu, Sichuan Province of China, the meeting is another important activity of JWG2.4. The second TAO special issue was published (TAO, Vol. 24, No. 4, August 2013). The highlights of the activities reported in the papers are:

  (1) An updated Moho depth model and a new geoid model over Tibet from recent GRACE/GOCE gravity models and CRUST2.0 crust model.

  (2) Improved methods of retracking altimeter waveforms and improved method of lake level determination and prediction; TibXS hydrology variability and climate variability from height and backscatter observations of TOPEX.

  (3) Crustal movements in China and tsunami simulations related to the Tohoku-Oki earthquake of March 11, 2011, Japan.

  (4) Changes in ice mass and in seasonal ocean tide over arctic islands and subarctic oceans (near Siberia) from GRACE and satellite altimetry.

  (5) A distinct crustal structure of Tibet compared to PREM, using GOCE and GPS data.

  (6) A new SG is installed at Lhasa, Tibet. The preliminary result reported in this special issue both contrasts or confirms the model predictions, depending on the subjects. A long-term SG record here is needed to enhance the current determinations of tidal amplitude factors and the SG calibration function.
- TibXS 2013 meeting (July 28 to Aug 1, 2013)
- The 2013 annual meeting was held in YiNing, Xinjiang, China (http://space.cv.nctu.edu.tw/altimetryworkshop/TibXS2013/TibXS2013.htm).
- TibXS 2014 meeting (July 28 to Aug 1, 2013)

- The 2014 meeting was held in Guiyang, Guizhou, China. (http://space.cv.nctu.edu.tw/altimetryworkshop/TibXS2014/TibXS2014.htm)

The 2013 and 2014 meetings again focused on broad issues of TibXS. Specific issues are hydrological change over river basins, lake level variation, vertical deformation, mountain glacier change and influence of atmospheric circulation on TibXS climate. A third special issue of TAO is being proposed to publish papers on studies related to TibXS.

All these meetings are kindly supported by Wuhan University (financially) and supported by IAG Commissions 2 and 3.IAG (spiritually). In July 2015, we will hold a 2-day meeting in Lhasa, Tibet and organize a tour to high altitude lakes and possibly glaciers for inspirations of studies. The TibXS 2015 meeting will be held in Kunming, the capital of Yunnan Province, in south-western China. We also propose a session in the AGU 2015 Fall meeting "Present-Day Climatic and Geophysical Processes in the Tibetan Plateau from Multiple Satellite Geodetic Observations" to promote geodetic and geophysical studies in the TibXS region. Because of the availability of multi-platform and decadal data sets, including GNSS, GRACE, GOCE, altimetry, InSAR, we expect synergistic investigations in his session that can lead to new insights and potential separations of competing geophysical, cryospheric and hydrologic processes previously limited by data scarcity.

Due to the vast area and the remoteness of TibXS, in situ data here are quite limited in spatial coverage and temporal coverage. We also believe the discussions in the annual meetings and the papers in the special issues of TAO will provide important references for strategic plans of in situ observations over TibXS. In fact, we have launched campaigns to collect gravity and GPS data. In turn, such observations are critical to substantiating and validating current and future geodetic results. We will continue the effort to promote geodetic and geophysical studies in such a climate-sensitive and geodynamic-active region as TiBXS.

Joint Working Group 2.5: Physics and Dynamics of the Earth's Interior from Gravimetry

The Working group was closed in 2013

Joint Working Group 2.6: Ice Melting and Ocean Circulation from Gravimetry

Chair: Bert Wouters (UK/USA)

Active members: Jennifer Bonin, Carmen Boening, Don Chambers, Annette Eicker, Martin Horwarth, Felix Landerer, Scott Luthcke, Jürgen Kusche, Roelof Rietbroek, Riccardo Riva, Ingo Sasgen, Jens Schroeter, Clark Wilson, Bert Wouters.

Goals and priorities of JWG 2.6

The goal of JWG 2.6 is to promote the use of gravimetry data to address the contribution of ice melting to the global and regional sea level and to study changes in the ocean circulation, complementary to existing projects such as the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE). Given the wide range of the members areas of expertise and knowledge, the strength of this group lies in combining different experts and aspects i.e. in networking and in providing advice, setting up guidelines and best practices and communication/outreach of results to scientists in other fields (i.e., non-geodesists).

Past meetings of JWG 2.6

- *European Geosciences Union* General Assembly *2012*. Vienna (Austria) April 22–27, 2012
- *European Geosciences Union* General Assembly *2013*. Vienna (Austria) April 7–12, 2013
- Next Generation gravity field mission workshop 2014. Herrsching (Germany) September 26-26, 2014

Completed and running projects of JWG 2.6

- Several members of JWG 2.6 were involved in the Next Generation Gravity Field Mission project, which aims to provide consolidated science requirements for a future GRACE-like mission. The Ocean and Ice subgroups were lead by members of JWG 2.6 (Wouters and Horwath).
- In order to advertise and promote the use of satellite gravimetry for earth observation purposes, members of the JWG 2.6 worked on an overview article of the GRACE mission. The paper discusses the basic principles of the mission, the data it provides and gives a comprehensive overview of the scientific merits. Aimed at a wide audience, it was published in *Reports on Progress in Physic* (2013 Impact factor: 15.6):

  B Wouters, J A Bonin, D P Chambers, R E M Riva, I Sasgen and J Wahr, *2014, GRACE, time-varying gravity, Earth system dynamics and climate change,* Rep. Prog. Phys. 77 116801 doi:10.1088/0034-4885/77/11/116801
- GRACE observations are becoming increasingly popular to estimate the mass balance of glaciers and ice caps (GICS). JWG 2.6 members are currently looking into the options to set up an IMBIE-like intercomparison project for GICS and are trying to secure funding to cover the management costs of such a project.
- There is a chance that the current GRACE mission will come to an end before the launch of the GRACE follow-on mission in 2017. JWG 2.6 members have been and are still actively involved in the development of methods to fill up a possible gap with the follow-on mission, e.g. using satellite laser ranging (SLR). Within the framework of the e.motion project a model of time variable gravity has been developed which may act as a test bed for such methods. Felix Landerer is PI of the new NASA MEaSUREs project 'Earth Surface

Mass Changes' (essentially the Tellus website and all its data products), which is looking into this issue and will provide data products (like EOF-based reconstruction using lower order SLR etc.). Jennifer Bonin is recently received funding to work on a similar project.

Joint Working Group 2.7: Land Hydrology from Gravimetry

Chair: Annette Eicker (Germany)

General information

Working group members:

- Annette Eicker (University of Bonn, Germany), eicker@geod.uni-bonn.de
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- Petra Döll (University of Frankfurt), P.Doell@em.uni-frankfurt.de
- Andreas Güntner (GFZ Potsdam), guentner@gfz-potsdam.de
- Laurent Longuevergne (University of Rennes), laurent.longuevergne@univ-rennes1.fr
- Matt Rodell (Goddard Space Flight Center, NASA), matthew.rodell@nasa.gov
- Himanshu Save (University of Texas), save@csr.utexas.edu
- Bridget Scanlon (University of Texas), bridget.scanlon@beg.utexas.edu
- Ben Zaitchik (Johns Hopkins University Baltimore), zaitchik@jhu.edu

Activities

The primary joint work of IAG JWG 2.7 in the last 4 years was the contribution to an initiative established to derive consolidated science requirements of different user communities for a next generation satellite gravity mission. The initiative and its results will be described in Section 2.1. Apart from this, all working group members have been actively engaged in research activities concerning the working group topic (Section 2.2), splinter meetings presented an opportunity for personal interaction (Section 2.3) and a working group webpage was set up to facilitate communication (Section 2.4).

Science Requirements for a Next Generation Satellite Mission

General remarks:

The main work of JWG 2.7 during the last years was the definition of hydrological science requirements for a next generation gravity satellite mission (NGGM, i.e. beyond GRACE-FO) within the framework of a joint initiative of the International Union of Geodesy and Geophysics (IUGG), the Global Geodetic Observing System (GGOS) Working Group on Satellite Missions, and the IAG Sub-Commissions 2.3 and 2.6. The effort resulted in consolidated science requirements agreed upon by all relevant satellite gravity user communities (hydrology, oceanography, glaciology, and solid Earth research) during a workshop held in Herrsching, Germany in fall 2014. The results are summarized in a document which will serve as strong voice of the user communities towards the space agencies (NASA, ESA) for realizing a corresponding mission. The science requirement document will be published in the IUGG publication series and a corresponding journal publication is currently under preparation. The hydrology sub-group of this initiative was covered primarily by JWG 2.7 incorporating additional experts to include a large part of the hydrological user community. This resulted in the following sub-group members:

Experts panel

Annette Eicker (University of Bonn, chair), *Laurent Longuevergne* (Université de Rennes 1, chair), *Gianpaolo Balsamo* (ECMWF), *Melanie Becker* (LEGOS Toulouse), *Decharme*

Bertrand (Meteo France), John D. Bolten (NASA), Jean-Paul Boy (University of Strasbourg), *Henryk Dobslaw* (GFZ Potsdam), *Petra Döll* (University of Frankfurt), *James Famiglietti* (UC Irvine; JPL), *Wei Feng* (Chinese Academy of Sciences), Nick van de Giesen (TU Delft), *Andreas Güntner* (GFZ Potsdam), Harald Kunstmann (Karlsruhe Institute of Technology), *Jürgen Kusche* (University of Bonn), *Anno Löcher* (University of Bonn), *Christian Ohlwein* (Hans-Ertel-Centre for Weather Research), Yadu Pokhrel (Michigan State University), *Matt Rodell* (NASA), *Himanshu Save* (University of Texas), *Bridget Scanlon* (University of Texas), Sonia Seneviratne (ETH Zurich), Frederique Seyler (Université Paul Sabatier, Toulouse), *Qiuhong Tang* (Chinese Academy of Sciences), *Albert van Dijk* (Australian National University), *Hua Xie* (International Food Policy Research Institute, Washington), *Pat Yeh* (National University of Singapore), *Ben Zaitchik* (Johns Hopkins University Baltimore).

Main results:

The hydrological part of the science requirement document first discusses hydrology-related scientific and societal challenges, then quantifies the added value of different mission scenarios for hydrological applications and finally results in hydrology-specific user requirements.

Societal and scientific challenges

As main *societal challenges* for upcoming years, a sustainable exploitation of water resources (water management), early warning for extreme events and risk management (especially for floods and droughts), and the understanding of climate change impacts on the water cycle were identified by the expert panel. Several *scientific questions* will have to be addressed in order to meet those societal requirements, the experts group particularly identified the following: The monitoring of changes in water storages on different spatial and temporal scales will remain a challenging task, especially in those storage compartments that are not well constrained by observations (e.g. groundwater, snow). Reducing the uncertainties of the individual quantities in the terrestrial and atmospheric water balance will be required to converge towards water budget closure. Especially the water fluxes are provided with large uncertainties and these will require better constraints. Other important hydrological challenges will be involved with the evaluation and control of water management procedures and policies. These procedures, such as the impoundment of reservoirs cause gravity changes on very small temporal and spatial scales (but aggregate to larger scales) and will require near real-time observations that are available after a few days. Other examples for near real-time applications are the prediction of extreme events such as flooding. Focusing on longer time scales, the identification of climate change signatures and anthropogenic impacts on the hydrological cycle will present an important research question. As many of these research fields can only be addressed by exploring the joint benefits of both observational data sets and improved hydrological modelling, it will be one of the major scientific challenges in the upcoming decades to drive and constrain the development of predictive hydrological models for water management and climate adaption studies.

New hydrological applications of satellite gravimetry

The potential for new hydrological applications of satellite gravimetry data results primarily from overcoming the limitations of current missions (i.e. limited spatial and temporal resolution) and from ensuring continuity of the mass variation time series. The following new investigation areas were identified by the working group:

a) Water storage changes in medium to small river basins & closing the terrestrial water balance
b) Analyzing the atmospheric water balance
c) Land surface - atmosphere feedbacks
d) Quantifying the impact of land cover and land management change
e) Near-real time analysis of hydrological extremes and episodic events
f) Quantifying snow melt and mountain glacier contribution
g) Study surface water - groundwater interactions and inter-basin groundwater flow
h) Impacts of permafrost thawing on water storage compartments
i) Validation of seasonal and decadal climate predictions
j) Signal separation/disaggregation of total water storage dynamics
k) Data combination
l) Data assimilation and improving the predictive skills of models
m) Establishing satellite gravimetry as a sustained observation system

For those new application fields, the added value of an improved temporal and spatial resolution of satellite gravity observations was discussed using the example of two different imaginary mission scenarios: Scenario 1 (accuracy of a monthly solution: 5mm equivalent water height at 400km resolution) and Scenario 2 (0.5mm@400km).

Theme-specific science requirements for hydrology

The group was given the task to define both a "threshold requirement" (i.e. a significant improvement with respect to the current situation clearly justifying the realization of such a mission) and a "target requirement" (i.e. a significant leap forward, that enables to address completely new scientific and societal questions).The discussion within the working group revealed that depending on the particular societal and scientific question and challenge to be solved, different requirements for a future satellite gravity mission need to be defined. While large parts of the hydrological community consider an increase in spatial resolution to be the most important requirement for a new mission, there is nevertheless considerable interest also in near real-time applicability of gravity data with a temporal resolution of a few days and/or a reduced latency of a few days.

The group came up with the following science requirements to address the societal challenges mentioned above:

Water management: Improved spatial resolution is a clear necessity to work at the scale of river basin and aquifer management.

- Threshold: Scenario 1
- Target: Scenario 2

Early warning for risk management of extreme events: While spatial resolution is important, low latency data would allow for contributing to near-real time operational forecasting systems. Daily to weekly data is also vital for short-term predictions.

- Threshold: Scenario 1 with better temporal resolution, latency of a few days
- Target: Scenario 2 with better temporal resolution, latency of a few days

Understanding global change impacts on the water cycle: To analyze long-term effects of climate change and to separate natural from anthropogenically driven changes, the most important aspect is a continuous time series in combination with an increased spatial resolution.

- Threshold: extended time series
- Target: Scenario 1

Consolidated science requirements

Summarizing the results of the different thematic sub-groups, consolidated science requirements were agreed upon by the members of the initiative during a workshop held in Herrsching in fall 2014. This consolidated view of the different user communities defines Scenario 1 as threshold requirement and Scenario 2 as target requirement for a next generation satellite gravity mission.

Research activities of working group members

During the previous four years, all of the working group members have been involved in various research areas associated with "Land hydrology from gravimetry". Activities comprised tailored GRACE data analysis and signal interpretation, hydrological model development, model validation and calibration, as well as assimilation of GRACE data into hydrological and land surface models. Further research interests include water resource analysis and ground water monitoring, and the use of local, superconducting gravity observations to monitor local water storage variations. Additionally, assistance has been provided by working group members to the hydrological community via preparation of easy-to-use GRACE products and pedagogy on the use of GRACE data. The specific contributions of the working group members include, but are not limited to, the following research fields:

Several group members have worked on the understanding of the hydrological cycle using GRACE data. An incomplete list of examples includes the analysis of water storage variations in Central Asia based on GRACE and multiple model and observation data sets (Andreas Güntner), the retrieval of large-scale hydrological signals in Africa (Jean-Paul Boy), the interpretation of GRACE water storage estimates in regions with significant reservoir and lake storage (Laurent Longuevergne), and the assessment of inter-annual variability of terrestrial water storage and groundwater, including human and climate induced trends (Matt Rodell, Bridget Scanlon).

Besides the interpretation of observations, improving hydrological modeling has been an important issue. Petra Döll and Andreas Güntner have advanced the development of the global hydrological model WaterGAP and used GRACE water storage estimates to validate model output. Petra Döll has introduced anthropogenic water abstractions into the model and, in cooperation with Annette Eicker, has focused on the question to what extent the human water use can be identified by combining WaterGAP and GRACE information.

The integration of observations into hydrological modeling has become more and more important in recent years. Andreas Güntner and Laurent Longuevergne have worked on the development of multi-criterial calibration approaches using GRACE and other observation data sets. Several members of the working group have dedicated their work to the assimilation of GRACE data into hydrological models. Ben Zaitchik applied GRACE data assimilation to hydrologic monitoring and water resource analysis in North America, Europe, the Middle East and North Africa. The studies show that assimilation of GRACE observations improves simulation of hydrologic states and fluxes, including groundwater levels in unconfined aquifers and river discharge. Annette Eicker (in collaboration with Petra Döll) has developed an approach to simultaneously calibrate model parameters and assimilate model states. The approach exploits the full GRACE spatial resolution by using a gridded data product and accounts for the complex spatial GRACE error correlation pattern by rigorous error propagation from the monthly GRACE solutions. Matt Rodell has worked on the development of an operational data assimilation platform to integrate GRACE and other data into a land surface model and apply it for drought monitoring.

Members of the group have worked on producing improved GRACE gravity field models to be used for hydrological (and other) applications. Himanshu Save has applied a regularization procedure within the inversion process to produced regularized GRACE gravity fields that have significantly fewer stripes. They fit the K-band data as well as the unconstrained gravity solutions but do not require additional filtering. The signal attenuation due to regularization for most of the river basins is within the noise level of GRACE. Annette Eicker has used a gravity field representation by radial basis functions to compute regional gravity field models optimally tailored to the signal content in specific regional areas with the goal to extract as much information out of the GRACE data as possible. In the same context of the exploration of the GRACE data content, Laurent Longuevergne has been concerned with identifying signatures of masses having a size below the GRACE resolution.

The topic of the working group does not only focus on satellite information, but group members (Andreas Güntner, Jean-Paul Boy) have been involved in the analysis of ground-based gravity measurements. Andreas Güntner has monitored local water storage variations by hydro-meteorological observation systems in the vicinity of superconducting gravimeters (Wettzell, Concepción, Sutherland) and has analyzed the data of superconducting gravimeters to identify and interpret hydrological information. He has furthermore worked on the development of superconducting gravimeters as hydrological monitoring devices.

Webpage:

A website was set up to coordinate and document the group activities: http://www.igg.uni-bonn.de/apmg/index.php?id=535

It includes the terms of references, contact information of the working group members, reports of the working group activities and a complete list of publications originating from the years 2011-2015.

Meetings

During the working group period the following working group splinter meetings took place:

- Joint splinter meeting of working groups 2.6 and 2.7, EGU Vienna April 2013
- Splinter meeting of NGGM working group, AGU San Francisco, December 2013
- Splinter meeting of NGGM working group, EGU Vienna, April 2014
- NGGM Coordinator Meeting, Munich July 2014
- NGGM Workshop, Herrsching, September 2014
- NGGM Coordinator Meeting, Munich, January 2015

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Joint Working Group 2.8: Modelling and Inversion of Gravity-Solid Earth Coupling

Chair: Carla Braitenberg (Italy)

The activities were decided in the regular meetings of the Working Group and reported in the circulars. The circulars are deposited in the home-page of the WG described below.

Definition of activities for Working Group

The activities accomplished by the working group (WG) have been the following:

1. Create a platform in which density models can be tested through geodynamic models. This needs the interaction of the geodynamic modeller with the geophysical modeller, and allows a consistency check of the density models from the point of view of observations of the potential field and of geodynamics. Viceversa the geodynamic models producing density variations are checked against consistency with density models constrained by further geophysical observations.
2. Create a reference database covering the subject of gravity-solid earth coupling (mass loading, under-plating, isostatic Moho, crustal thickness, lithospheric thickness, dynamic topography versus mass loading).
3. Create a database on methodology of gravity forward and inversion calculations, spherical calculations
4. Create a kit of software tools that have been tested and verified by the WG and that will be shared among the members of the working group. It shall cover the different aspects of the goals of the WG. If several software-programs are made available they can be benchmarked against each other.
5. Set up a social networking page for the members of the WG.
6. Meetings of the WG at conferences to which enough members of the WG were present.

The WG has collected a variety of tools that allow to tackle and improve the understanding of solid earth-gravity coupling processes. In particular the efforts have been summarized in a home-page that contains an overview of the relevant papers on a few key topics necessary for fulfilling the scientific task. Secondly the page houses a useful collection of software tools that have been used and tested by members of the WG, and that are recommended as useful tools for gravity forward and inverse modelling. The efforts of the WG have been considered useful to several colleagues who have accessed the homepage to retrieve information and contact persons regarding gravity modelling.

Four meetings have been held, detailed in Table 1, and the homepage has been set up, as described in the next section.

Table 1: The meetings of the Workgroup were held at various conferences relevant to potential fields.

Convention	Title	Date
Splinter meeting at EGU2012, SPM1.30.	First Meeting of the Joint Working Group JWG2.8 (IAG) Modeling and Inversion of Gravity-Solid Earth	26 Apr, 2012, 19:00–20:00
Splinter meeting at the Symposium Gravity, Geoid and Height Systems GGHS2012, 09-12 October 2012, San Servolo Island, Venice, Italy	Second Meeting of the Joint Working Group JWG2.8 (IAG) Modeling and Inversion of Gravity-Solid Earth	10 October 2012
Splinter meeting at EGU2013, SPM1.30.	Third Meeting of the Joint Working Group JWG2.8 (IAG) Modeling and Inversion of Gravity-Solid Earth	11 Apr, 2013 12:15–13:15
Splinter meeting at EGU2015, SPM1.38.	Fourth Meeting: Joint Working Group on Gravity Modeling and Inversion JWG2.8 (IAG)	14 Apr, 2015 12:15–13:15

Working Group Discussion page

We have set up a discussion page for the Working group, located here: http://www.lithoflex.org/IAGc2

The scope of the homepage and the responsibility from side of the members for the different topics were defined in the GGHS2012 meeting in Venice.

As decided at the Venice meeting the page contains an exhaustive overview of the most important and relevant papers on a few key topics necessary for fulfilling the scientific task. Secondly the page houses a useful collection of software tools that have been tested by members of the WG, and which are recommended as useful tools for gravity forward and inverse modeling. The WG homepage has given the opportunity to exchange news and information regarding gravity modelling.

Throughout the years of the WG the page has been updated. The accredited members of the WG are able to edit the pages after registering and can post messages. News include an interesting paper, or a recent publication, or a topic of discussion.

The homepage allows the WG-members to discuss the topics of the WG at ease.

The pages dedicated to relevant publications have been divided among the WG-members as follows:

Properties of rocks

Density, velocity, correlation between density and seismic velocity, mineral composition, dependence on pressure and temperature. Jörg Ebbing (Norway), Javier Fullea (Spain), Richard Lane (Australia)

Gravity forward modeling

Spatial-domain techniques (Flat vs. spherical. Prisms, tesseroids), and spectral-domain techniques (spherical harmonic expansion), Resp. Leonardo Uieda (Brazil), Rezene Mahatsente (Germany), Thomas Grombein (Germany), Christian Hirt (Australia)

GOCE and other satellites

Application of GOCE satellite gravimetry in solid Earth investigations, GOCE mission overviews, GOCE gradients and gravity recovery, and GOCE model quality, Christian Hirt (Australia), Carla Braitenberg (Italy).

Gravity Associations

Gravity associations, gravity discussion groups (all members)

Inverse gravity modeling

Flat, spherical, spectral approach, Surface harmonics (Valeria Barbosa (Brazil), Riccardo Barzaghi (Italy)

Isostatic modeling

Different techniques on isostatic modeling.
John Kirby (Australia)

Topographic Corrections

Methods for calculation of mass effect of topography; cartesian and spherical coordinates
Orlando Alvarez (Argentina) , Nils Köther (Germany)

The Opening page is shown in Figure 1.

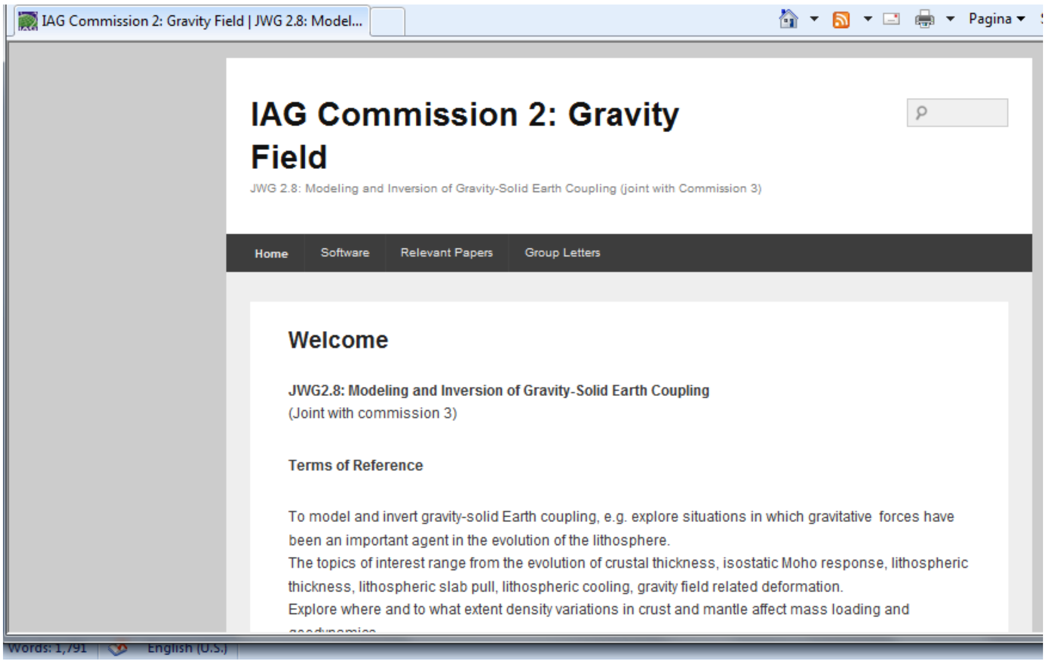


Figure 1: Welcome page of the IAG 2.8 homepage, which includes a depository of software, relevant-publications-list and the possibility of making discussions.

Software tools

We have included a set of software tools useful in gravity inverse and forward modeling. The software has been tested by WG members, so as to achieve a control on reliability. The software should have the following requisites:

- It runs on Windows or Linux.
- It is freely distributed
- It must include a documentation with description of routines and usage, and a set of testing files, that allows all routines to be tested by the user.
- The person or group of persons that provide the software also demonstrate that the SW has been validated on a standard dataset.
- The SW will be distributed by its owner, the IAG WG accepts the SW as having been validated by the standards set up by the WG.

We have collected some benchmark models. They include a lithospheric model of the North Atlantic margin created by Jörg Ebbing and a model of the Grotta Gigante cave, a Karstic cave in NE-Italy.

The home-page also houses a collection of commercial software considered to be useful in this scientific context.

Annex 1

Urs Marti, President of the International Association of Geodesy (IAG) Commission 2 «Gravity Field»
Philippe Richard, President of the Consultative Committee for Mass and related quantities (CCM)
Alessandro Germak, Chairman of the CCM working group on gravimetry (WGG)
Leonid Vitushkin, President of IAG SC 2.1
Vojtech Pálinkáš, Chairman of IAG JWG 2.1
Herbert Wilmes, Chairman of IAG JWG 2.2

11 March 2014

CCM – IAG Strategy for Metrology in Absolute Gravimetry

Role of CCM and IAG

Introduction

The President of the Consultative Committee for Mass and related quantities (CCM)[1] and the President of the International Association of Geodesy (IAG)[2] Commission 2 «Gravity Field»[3] met on March 21, 2013 with the objective to better coordinate the work at the level of both organizations. It was decided to prepare a common strategic document to be used by their respective Working Groups (WG), Sub-commission (SC) and Joint Working Groups (JWG) to clarify future activities and to develop an action plan.

The main objective is to define and to harmonize the activities in order to ensure traceability to the SI[4] for gravity measurements at the highest level for metrology and geodesy within the framework of the CIPM[5] Mutual Recognition Arrangement (CIPM MRA[6]).

General principles

Vision

The CCM and IAG want to ensure scientific excellence and measurement of the gravity acceleration traceable to the SI at the level of uncertainty of few microgals (1 µGal = 1 x 10^{-8} m/s^2) or better according to the principles of the CIPM MRA, for metrology (in particular for the realization of the new definition of the kilogram) and geodetic science (in particular for time variable gravity and

[1] http://www.bipm.org/en/committees/cc/ccm/
[2] http://www.iag-aig.org/
[3] http://www.iag-aig.org/index.php?tpl=text&id_c=7&id_t=553
[4] http://www.bipm.org/en/si/
[5] http://www.bipm.org/en/committees/cipm/
[6] http://www.bipm.org/en/cipm-mra/

gravity networks). The present strategy shall support the Global Geodetic Observing System (GGOS)[7], International Gravity Field Service (IGFS)[8], IAG Commission 2 "Gravity Field" and CCM activities.

Role and mission of CCM

In addition to all matters related to the comparisons of mass standards with the international prototype of the kilogram and the considerations that affect the definition and realization of the unit of mass, the **CCM is responsible for the establishment of international equivalence between national laboratories** for mass and a number of related quantities, such as gravity acceleration, and advises the CIPM on these matters.

Briefly: realization and dissemination (at the highest accuracy level) of the unit and international equivalence of primary standards validated through appropriate comparisons.

Role and mission of IAG Commission 2, IGFS and GGOS

The main role of IAG Commission 2 "Gravity Field" is the **accurate determination of the gravity field** and its temporal variations promoting, supporting and stimulating the advancement of knowledge, technology and international cooperation in the geodetic domain associated with Earth's gravity field.

The main goal of IGFS is to coordinate the servicing of the geodetic and geophysical community with gravity data, software and information.

The main goal of GGOS is to work with the IAG components to provide the geodetic infrastructures necessary for monitoring the Earth system and for global change research.

Briefly: practical application of gravity measurements in compliance with the IERS conventions[9] for the accurate determination of the gravity field in geodesy.

Level of collaboration

The scopes of CCM and IAG in the field of absolute gravimetry are complementary. The objective of this strategy is to harmonize the activities.

The CCM provides traceability to the SI for gravimetry. IAG represents one of the main stakeholders and user community in the field of gravimetry. The second main stakeholder is the metrology community.

Finally, mutual sharing of information is ensured through regular meetings at the management level between the CCM President and the President of IAG Commission 2. The technical contact at the operational level is established by systematically inviting observers from the other community to the working group meetings as well as by contact between the chairperson of the CCM WGG (see §3.1) and the chairperson of the IAG SC 2.1 (see §3.2).

[7] http://www.ggos.org/
[8] http://www.igfs.net/
[9] http://www.iers.org/nn_11216/SharedDocs/Publikationen/EN/IERS/Publications/tn/TechnNote36/tn36,templateId=raw,property=publicationFile.pdf/tn36.pdf

Terms of Reference

CCM WGG

The Terms of Reference of the CCM Working Group on Gravimetry (WGG)[10] are:
- to propose key comparisons to the CCM;
- to maintain contact to international organizations and stakeholders active in absolute gravimetry;
- to support stakeholders to ensure and promote the traceability of gravity measurement to the SI;
- to follow the main research activities in absolute gravimetry.

Remark: The main objective is the establishment of equivalence for absolute gravimeters belonging to National Metrology Institutes (NMIs) or Designated Institutes (DIs) in full accordance with the rules of the CIPM MRA.

Correct traceability according to the CIPM MRA ensures equivalent measurement results necessary for applications in metrology and geodesy.

IAG Sub-Commission 2.1

The main objective of the IAG SC 2.1 "Gravimetry and gravity networks"[11] is to promote scientific studies of methods and instruments for terrestrial, airborne, shipborne and satellite gravity measurement and establishment of gravity networks.

The Joint Working Group 2.1[12] (Techniques and Metrology in Absolute Gravimetry) can support the CCM WGG for the organisation of Key Comparisons (KC) (see §4.1.1, §4.1.2 and §4.1.3) and can organise additional comparisons (see §4.1.4) as defined by the geodetic needs.

The Joint Working Group 2.2[13] (Absolute Gravimetry and Absolute Gravity Reference System) makes use of all comparison data available to ensure traceable gravity values and maintains stable reference gravity stations for the practical work in geodesy.

The traceability chain in gravimetry

There are two distinct traceability paths for the measurements performed by absolute gravimeters:
A) Independent traceability to the SI units of time and frequency.
B) Calibration by comparison (against a reference).

Some schematic traceability chains are given in Fig. 1.

Independent traceability to the SI units of time and frequency

The absolute gravimeter has independent traceability to the SI unit of time (frequency) through the calibration of the frequencies of the laser and reference clock.

The uncertainty of the absolute gravimeter (Calibration Measurement Capability - CMC) is calculated combining the contributions of uncertainty associated with these references, together with all other contributions of uncertainty.

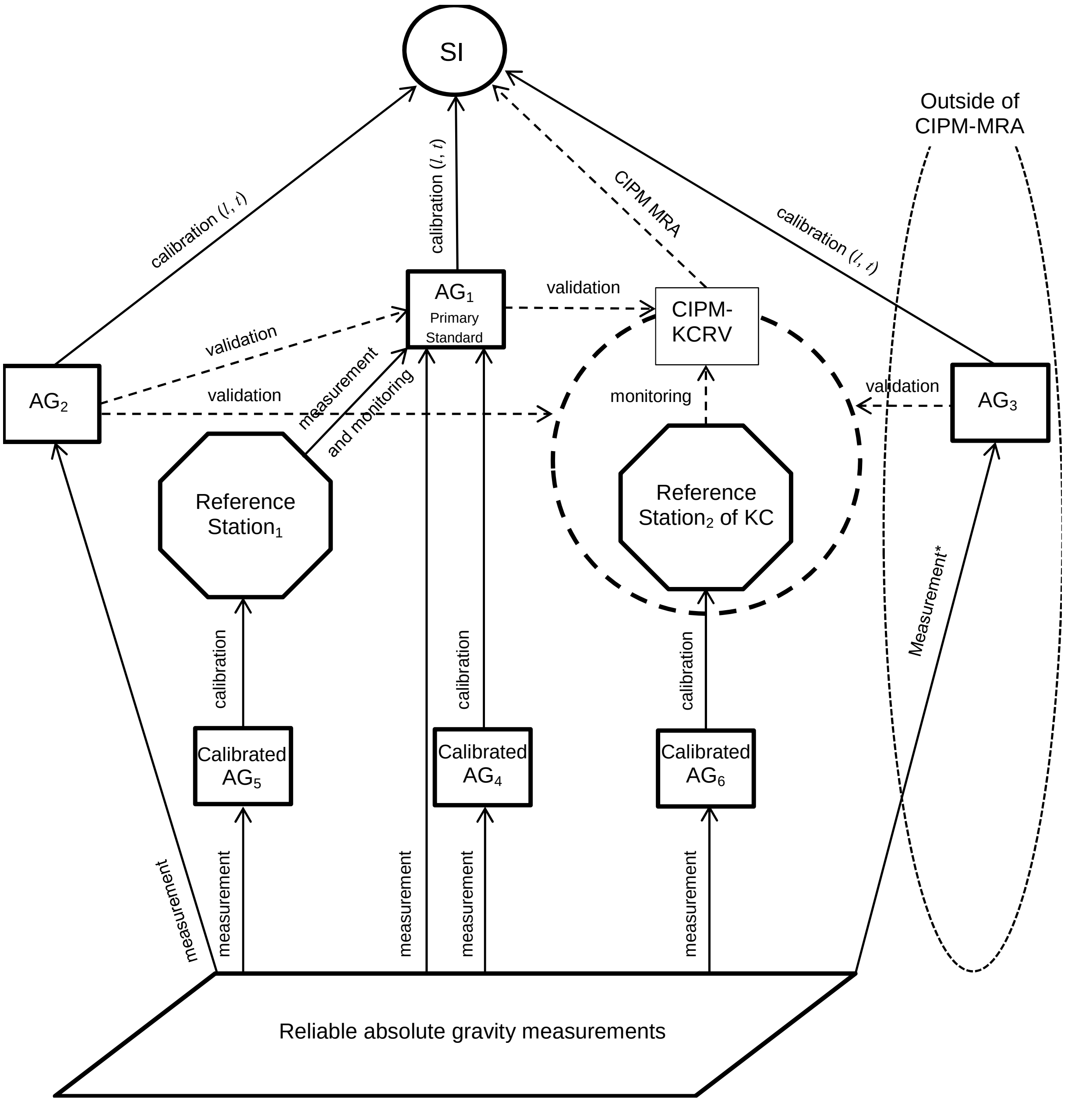
It is necessary also to perform comparisons between the absolute gravimeter and an appropriate reference in order to validate the associated uncertainty. References are absolute gravimeters as

[10] http://www.bipm.org/en/committees/cc/ccm/working_groups.html#wgg
[11] http://www.iag-commission2.ch/SC21.pdf
[12] http://www.iag-commission2.ch/WG21.pdf
[13] http://www.iag-commission2.ch/WG22.pdf

primary standards maintained by NMIs or DIs with declared Calibration Measurement Capabilities (CMCs)[14] in the CIPM MRA or a gravity value of a reference station characterized with the highest accuracy (see §4.2). The results need to be analysed as a comparison rather than a calibration. The analysis just needs to demonstrate whether or not the results are metrologically equivalent[15,16].

Absolute gravimeters of NMIs or DIs, recognized as primary standards, that have CMCs declared in the CIPM MRA shall participate in Key Comparisons (KC) in order to confirm their CMCs.

[14] http://kcdb.bipm.org/AppendixC/default.asp
[15] K Beissner, 2002, Metrologia 39, 59. *On a measure of consistency in comparison measurements*
[16] A G Steele and R J Douglas, 2006, Metrologia 43, S235. *Extending E_n for measurement science*



AG_1:	Absolute Gravimeter (Primary Standard) with independent traceability to SI units (through calibration of laser and clock) (§4.1) validated with the KCRV of a KC (§4.1.1 - §4.1.3).
AG_2:	Absolute Gravimeter with independent traceability to SI units (§4.1) validated in comparison with a Primary Standard Absolute Gravimeter or with the CIPM-KCRV (§4.1.1 - §4.1.3).
AG_3:	Absolute Gravimeter with independent traceability to SI units (§4.1) validated with KCRV of an additional comparison outside the scope of CIPM MRA (§4.1.4).
AG_4:	Absolute Gravimeter calibrated against a reference gravimeter (AG_1) (§4.2.1).
AG_5:	Absolute Gravimeter calibrated against a gravity value of the Reference Station$_1$ (measured by AG_1 and carefully monitored) (§4.2.2).
AG_6:	Absolute Gravimeter calibrated against a gravity value of a Reference Station$_2$ (measured during a KC and carefully monitored) (§4.2.2).

Measurement In this case, measurements carried out by AG_3 cannot establish any measurement certificate for ensuring the traceability to the SI.*

Figure 1:Scheme of the traceability chain in gravimetry, according to §§4.1 – 4.2.

CIPM Key Comparisons (CIPM KC)

The main objective of a CIPM key comparison[17] is the **validation,** at the CIPM level, of the declared CMCs published in the Key Comparison Database (KCDB)[18] of the BIPM[19]. These comparisons serve as a technical basis for the CIPM MRA. See also Fig. 2 (CIPM KC).

Periodicity: according to the CCM strategy.

Responsibility[20]: CCM (approval) and the pilot laboratory (organization).

Participants: NMIs and DIs listed in Appendix A of the CIPM MRA, with preference given to NMIs and DIs of States Parties of the Metre Convention. If the total number of participants is limited for technical or budget reasons[21], participants are selected among CCM members preferably with declared CMCs and other WGG members in order to represent all regions and independent techniques.

Terminology: CCM.G-K1, CCM.G-K2,[21]

Remark: the terminology "International comparison of absolute gravimeters" (ICAG) related to the comparison system established before the CIPM MRA is replaced by the CIPM terminology for KCs.

Regional Key comparisons (RMO KC)

The main objective of a regional key comparison is the **validation** of the CMCs published in the KCDB of the BIPM through links to the CIPM KC. This is especially important for participants who could not be accommodated in the CIPM KC.

The RMO KCs must be linked to the corresponding CIPM key comparisons by means of common participants. This is mandatory to demonstrate global equivalence. To achieve this, it is recommended that at least two of the participants in the preceding CIPM KC participate also in the RMO KC[21]. See also Fig. 2 (RMO KC). Therefore the RMO must adopt essentially the same protocol as the CIPM KC and must consider carefully how to link their results to the CIPM KC[21].

Periodicity: subsequent to CIPM KCs.

Responsibility: The RMO, the CCM (approval) and the pilot laboratory (organization).

Participants: NMIs and DIs of the Regional Metrology Organizations (RMO)[21].

Terminology: EURAMET.M.G-K1, APMP.M.G-S1,[21]

Remark: the terminology Regional comparison of absolute gravimeters (RCAG) related to the comparison system before the CIPM MRA is replaced by the CIPM terminology for KCs.

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[17] http://www.bipm.org/en/cipm-mra/key_comparisons/

[18] http://kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp

[19] http://www.bipm.org/

[20] CIPM MRA-D-05. *Measurement comparisons in the CIPM MRA*, Version 1.4. (http://www.bipm.org/utils/common/CIPM_MRA/CIPM_MRA-D-05.pdf) and Technical supplement to the arrangement (CIPM revision 2003) (http://www.bipm.org/utils/en/pdf/mra_techsuppl2003.pdf)

[21] http://kcdb.bipm.org/appendixB/KCDB_ApB_search_result.asp?search=1&met_idy=6&bra_idy=50&cmt_idy=0&ett_idy_org=0&epo_idy=0&cou_cod=0

Subsequent bilateral key comparisons

The main objective of a bilateral key comparison is the **validation** of the declared CMCs published in the KCDB of the BIPM through links to the CIPM KC or RMO KC. These comparisons serve as a technical basis for the CIPM MRA. See also Fig. 2 (Bilateral KC)

Periodicity: on demand of a participant.
Responsibility: CCM (approval) and the pilot laboratory (organization).

Participants: two, one of them shall have participated in the preceding CIPM or RMO KC.

Terminology: The results of subsequent key comparisons may be assigned by a separate identifier. This identifier will usually be the name of the previous comparison plus a suffix[22].

The approval process for CIPM KCs carried out within the CCM and subsequent RMO KCs is described in CCM Guidelines[23].

Additional comparisons

Additional comparisons outside the scope of the CIPM MRA could be organized by anyone at any time; the participation is open.

In order to guarantee traceability to the SI, the additional comparison must be linked to the corresponding CIPM or RMO KC by means of joint participants. This is mandatory to demonstrate global equivalence. To achieve this, it is recommended that at least two of the participants in the preceding CIPM or RMO KC participate also in the additional comparison. See also Fig. 2 (additional comparison).

Additional comparisons could be organized simultaneously with CIPM or RMO KCs if the pilot laboratory agrees. In this case, the results of the participants outside the CIPM MRA are not included in the final KC report. A separate report should be established and put into the IAG-AGrav database[24].

[22] Bilateral Key Comparisons are no longer assigned the special identifier "BK" for registration in the KCDB. This allows potential additional participants to join in the comparison without the need to modify the identifier.

[23] http://www.bipm.org/utils/en/pdf/CCM_Guidelines_on_Final_Reports.pdf

[24] http://agrav.bkg.bund.de/agrav-meta/ and http://bgi.omp.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data

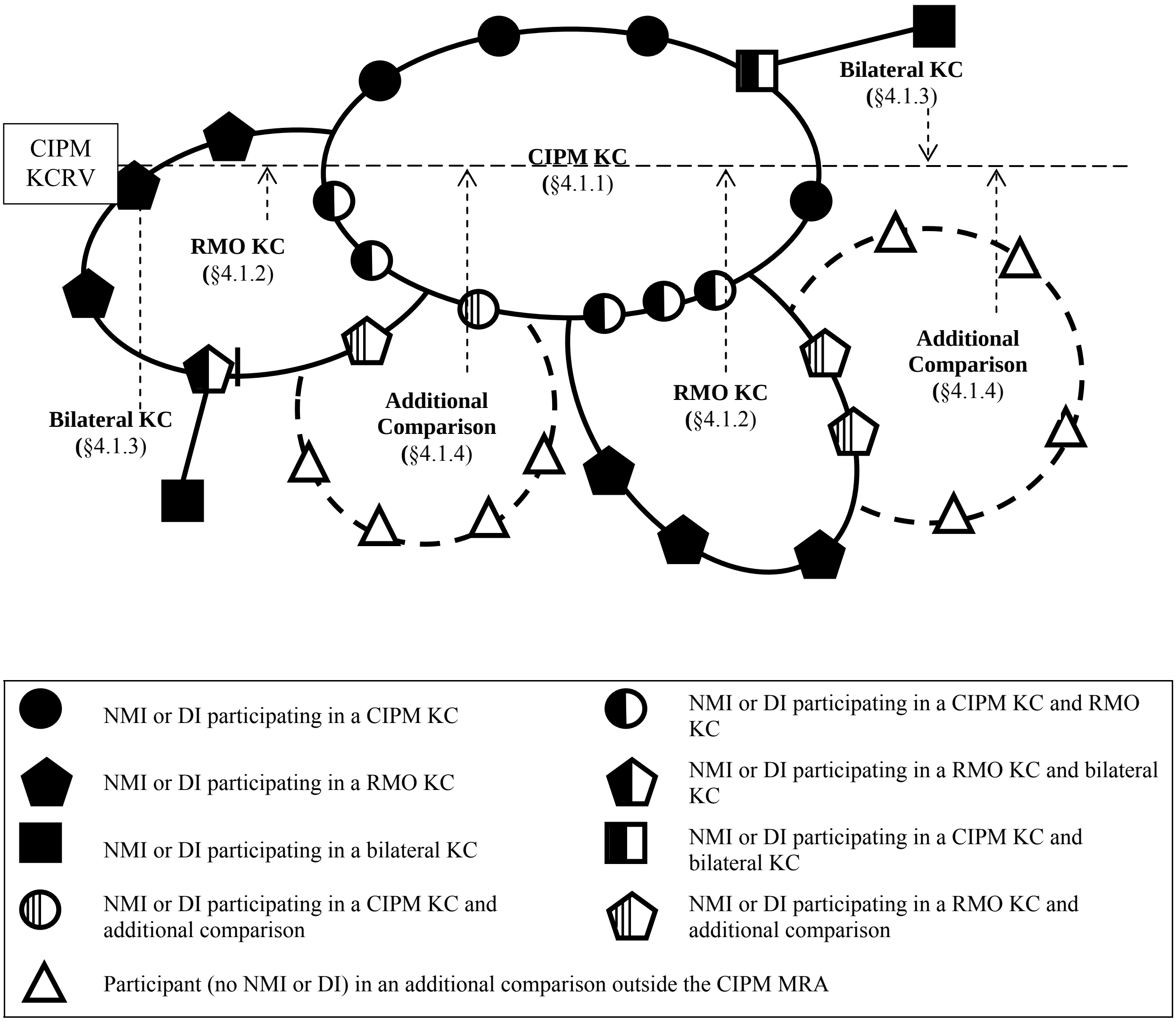

Figure 2: Scheme of some example of structure for Key Comparisons and other comparisons, according to §§4.1.1 - 4.1.4. To be noted that all comparisons have the same reference value, that is the CIPM-KCRV (through the links between comparisons).

Calibration by the comparison

The absolute gravimeter derives its traceability directly from a comparison with the gravimeter of a NMI or a DI having declared CMCs in the CIPM MRA or using a gravity value of a reference station (characterized and monitored by appropriate methods).

The recommended method to determine the uncertainty of the calibrated absolute gravimeter includes, in this case, the corresponding contributions of uncertainty[25] and the bias[26] obtained in the comparison.

Comparison against a reference gravimeter

It is a typical calibration where the Device-Under-Test (DUT) is compared to the reference instrument. In our case, the DUT is the absolute gravimeter of a customer and the reference instrument (absolute gravimeter as primary national standard) of a NMI or a DI with declared CMCs.

[25] uncertainty of the primary standard, method of calibration, etc..

[26] JCGM 200:2012. *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms.* http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

Comparison against a gravity value of a reference station

The DUT is calibrated using the value of a reference station that has been characterized with the highest accuracy (for example during a KC) and that is carefully monitored since then (for example with combined measurements of absolute and superconducting gravimeter). In this case, the uncertainty of the DUT has to include also the uncertainty of estimated gravity variations at a reference station.

Measurement certificate for the characterization of a gravity site

The need of traceability to the SI for gravity measurement in metrology, geodesy etc. is defined by the customer and is closely related to its scientific objectives and to quality management. If traceability to the SI is needed, NMIs or DIs, as well an accredited laboratory in this field, with declared CMCs can measure gravity acceleration at a specified station and establish a measurement certificate.

Summary

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Scheduling of comparisons

The equivalence of results within the declared CMCs must be guaranteed according to the following typical scheduling:

Year 1 CIPM KC (according to section 4.1.1)

Year 1 + x RMO KCs (according to section 4.1.2)

Year 1 + y Next CIPM KC

The periodicity x is defined by the RMOs based on a recommendation of the RMO TC and the periodicity y is defined by the CCM on the recommendation of the CCM WGG.
Traceability to the SI according to the routes defined in §§4.1, 4.2 and 4.3 can be performed at any time according to the specific needs of the customers (for example for the validation of the instrument stability).

Common action plan

Short term

IAG

- Align the Terms of Reference of the Commission 2, its SC and JWGs with the present document.
- This document will be published in the appropriate websites and publications
- The CCM – IAG Strategy for gravimetry shall be presented at the next possible occasions (IAG meetings and conferences).
- IAG encourages stakeholders in geodesy community to intensify cooperation with their NMIs to reach the status of DIs.
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CCM

- This document will be published in the CCM WGG website (open access).
- CCM encourages NMIs to intensify cooperation with stakeholders in geodesy community in order to be designated as DIs.
- CCM encourages the NMIs and DIs to increase the number of declared CMCs in gravimetry (presently only four). It is highly desirable that a minimum number of 8 NMIs or DIs have declared CMC before the end of 2014.
- CCM encourages to reduce the declared measurement uncertainty (according to the GUM[27]) of the majority of CMC entries according to the state of art (5 µGal or below).
- The CCM – IAG Strategy for gravimetry will be presented at the next possible occasions (KCs, CCM WGG meetings, and conferences).

Medium term (IAG and CCM)

- Plan future KCs and other comparisons according to the principles and responsibilities described in this document in order to efficiently fulfil the need of both metrology and geodesy.

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[27] JCGM 100:2008 *Evaluation of measurement data – Guide to the expression of uncertainty in measurement.*http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf