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Introduction

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

Since 2001 there are also midterm reports published on the occasion of the IAG Scientific Assemblies in between the General Assemblies. Usually they are presented before the Assembly to the IAG Executive Committee (EC) and are discussed in the EC meetings in order to receive and give advices for the future work. The present Volume 39 contains the quadrennial reports of all IAG components for the period 2011 to 2015 and is presented at the IUGG General Assembly in Prague, Czech Republic, June 22 – July 2, 2015.

The editors thank all the authors for their work. A feedback of the readers is welcome. The digital versions of this volume as well as the previous ones since 1999 may be found in the IAG Office homepage (http://iag.dgfi.tum.de). Printed versions are available on request.

Hermann Drewes
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Commission 1 – Reference Frames

http://iag.uni.lu

President: Tonie van Dam (Luxemburg)
Vice President: Gary Johnston (Australia)

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Overview

This commission deals with the theoretical aspects of 1) defining reference systems for geodetic and scientific applications; 2) the practical applications of reference frame realizations; and 2) applied research in reference frame development.

The main objectives of Commission 1 are:
- Definition, establishment, maintenance and improvement of the geodetic reference frames;
- Advanced terrestrial and space observation technique development for the above purposes;
- International collaboration for the definition and deployment of networks of terrestrially-based space geodetic observatories;
- Theory and coordination of astrometric observation for reference frame purposes.
- Collaboration with space geodesy/reference frame related international services, agencies and organizations; and
- Promote the definition and establishment of vertical reference systems at global level, considering the advances in the regional sub-commissions.

Introduction

The main activities of Commission 1 during the period 2011-2015 include the following:

- A dedicated web site was established immediately after the IUGG General Assembly in Melbourne, where the new Commission members were approved by the IAG Executive Committee. The Web site (http://iag.uni.lu) contains all the information related to the activities and objectives of the commission, its sub-commissions, projects and Working Groups. The Web site is regularly updated directly by the president; Sub-commissions and sub-components prefer to have control over their own websites; links to those websites can be found at the Commission 1 website.
- The terms of reference for the new Commission 1 were compiled and submitted
- Mid-term report compiled and submitted
- Commission 1 Symposium, REFAG, 13-17 October, 2014
- Organization of the IUGG Commission 1 sessions

Main highlights of the activities of Commission 1 Sub-components

Sub-commission 1.1: Coordination of Space Techniques

The activities of SC-1.1 where significant progress has been made since 2011 are the following:

- Establishment of a non-exhaustive list of existing formats at the IAG services and GPS time series providers
- The development of innovative combination aspects such as, e.g., GPS and VLBI measurements based on the same high-accuracy clock, VLBI observations to GNSS satellites, and the combination of atmospheric information (troposphere and ionosphere) of more than one technique.
- Validation of the GGFC fluid models
- An analysis of combining Synthetic Aperture Radar (InSAR), LIDAR and optical image analysis methods.

Sub-commission 1.2: Global Reference Frames

Highlights of the activities of SC-1.2 include the following:

- The estimation of a plate motion model consistent with ITRF2008
- Workshop on Site Surveys and Co-location, Paris, May 2013
- ITRF2014 under development but will be released in 2015
- Comparison of DTRF2008 and ITRF2008 in order to assess the accuracy of the reference frames; The agreement is between 7 and 10 mm and between 0.2 and 2.0 mm/a for the station positions and velocities, respectively, depending on the technique and if only core stations are considered (Seitz et al. 2013)
- A Kalman filter and smoother algorithm has been developed and coupled to the CATREF software, KALREF (JPL)
- GRASP is a proposed satellite mission that will carry very precise sensor systems for all the key geodetic techniques used to define and monitor the TRF. It would allow us to achieve the requirements established by the *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*

- The publication of IGS08 a new IGS reference frame based on ITRF2008 (Rebischung et al., 2012)
- Collilieux et al. (2014) established that the accuracy of the ITRF2008 in terms of origin rate is likely to be less than 0.5 mm/yr on the three components while the scale rate error is smaller than 0.3 mm/yr
- The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) decided in July 2013 to formulate and facilitate a draft resolution for a Global Geodetic Reference Frame

Sub-commission 1.3: Regional Reference Frames

The main activities of SC-1.3 are the following:

- Increase of the number of GNSS permanent stations within the 6 regional sub-commissions;
- The preparation for the future Galileo system and the development of the EPN towards a multi-system GNSS network started
- The number of continuously operating GNSS stations that support the SIRGAS Reference Frame is still growing. It is composed by about 300 stations, 140 of which with GLONASS capability, and 60 with real time data transfer;
- The densification of the ITRF and IGS network is made by weekly combinations of 5 regional weekly solutions using different GPS processing software;
- The increase of the number of stations of the CORS network (approximately 480 stations from 28 countries), whose data are processed by three Analysis Centres (ACs). The increase of the number of institutions contributing to APREF in several domains (analysis, archive and stations). The availability of a weekly combined regional solution, in SINEX format and a cumulative solution, which includes velocity estimates.
- The realization of SCAR GPS Campaigns in 2012 and 2013. The data of 40 Antarctic sites are collected in the SCAR GPS database since 1995.

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

- Together with the Working Group Chairs, Johannes Böhm, summarized the main challenges to be addressed in determining the terrestrial and celestial references in the proceedings paper for the IVS General Meeting 2012 in Madrid, Spain (Böhm et al., 2012).
- Böhm et al. (2011) compared the influence of two different a priori gradient models on the terrestrial reference frame as determined from VLBI observations
- Heinkelmann and Tesmer (2013) assess systematic effects between VLBI terrestrial and celestial reference frame solutions caused by different analysis options
- Malkin (2013) outlines several problems related to the realization of the international celestial and terrestrial reference frames at the millimetre level
- Krásná et al. (2013) reaffirm results firstly shown by MacMillan and Ma (1997) that if tropospheric gradients are neglected, the TRF will experience a scale change of 0.65 ppb compared to a TRF with estimated gradients
- Liu et al. (2012) show that the effect of the Galactic aberration strongly depends on the distribution of the sources that are used to realize the ICRS
- Malkin (2011) as well as Krásná and Böhm (2014) investigate the impact of seasonal station motions on EOP and reference frames
- Seitz et al. (2011) show the first results of a consistent computation of CRF, TRF, and the EOP series linking both frames

- Seitz et al. (2012) deal with the consistent realization of ITRF and ICRF by combining normal equations from VLBI, SLR, and GNSS
- Plank et al. (2013) discuss and simulate VLBI observations to satellites at different altitudes

Joint Working Group 1.1: Tie vectors and local ties to support integration of techniques

JWG 1.1 organized a workshop on site surveys and co-location sites, May 2013 in Paris. One of the most important outcomes of the workshop is a list of recommendations that were identified in an open discussion with all the participants. The document sets out tasks with deadlines and assigns an individual to lead each task. The main tasks were outlined as follows:

- Define a clear nomenclature and terminology to be adopted for local tie discussions;
- Define the models to be adopted in the local tie survey data reduction;
- Propose a survey priority list for the next ITRF2013 computation;
- Recommend a surveying frequency;
- Create a local survey data archive; and
- Prepare of a draft document containing the site survey guidelines and specifications.

Joint Working Group 1.2: Modelling environmental loading effects for reference frame realizations

The activity of the working group has been dominated by the IERS campaign "for space geodetic solutions corrected for non-tidal atmospheric loading", an action item defined at the Unified Analysis Workshop 2011. A call for participation was sent to the analysis technique coordinators of every service in the beginning of 2012. A 6-year loading data set has been generated at The Global Geophysical Fluid Center (GFC) to be used a priori in the data processing of the space geodetic technique observations. Analysis Centers from the four technique services have submitted 12 individual solutions from GNSS, Satellite Laser Ranging (SLR, Very Long Baseline Interferometry (VLBI) and Doppler Orbitography Integrated by satellite (DORIS). These solutions have been analyzed to determine:

- The effect of non-tidal atmospheric loading on the TRF datum and the Earth Orientation Parameters (EOPs);
- The effect of non-tidal atmospheric loading on individual averaged coordinates and velocities; and
- The level of agreement between a priori corrections and a posteriori corrections.

Preliminary results were presented at the EGU in 2013. They are of particular importance for ITRF2014. This effort goes beyond just addressing the bullets above. The main success of this exercise is that it has catalyzed an open dialogue between modeling experts and technique ACs. A splinter meeting has been organized on Wednesday 10th of April 2013 at the EGU and another is planned in 2014.

Joint Working Group 1.3: Understanding the relationship of terrestrial reference frames for GIA and sea-level studies

- Studies concentrated on the evaluation of static- and time variable effects in orbit determination (e.g., Rudenko et al., 2014a) and in effects of reference frame (ex)changes (e.g., Couhert et al., 2014)
- Important contributions for the understanding of reference frame issues in sea level research are summarized in Collilieux and Altamimi (2013) and in the External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2 (Collilieux et al., 2014).

Joint Working Group 1.4: Strategies for epoch reference frames

The following research results of this JWG include

- Datum realization for epoch reference frames can be improved by using an SLR solution which includes at least LARES in addition to LAGEOS1 and 2,
- The time series of weekly epoch reference frames approximate the complete station motion (linear and non-linear part) very well,
- The neglect of non-linear station motions in long-term reference frames affects the consistently estimated EOP-series by annual and semi-annual signals (Bloßfeld et al. 2014),
- Epoch reference frames do not provide such a high long-term stability as long-term reference frames. With regard to the geodetic datum four-weeks solutions show the highest stability. But non-linear station motions are characterized by short-term effects, which can be approximated better with a weekly or even shorter resolution,
- The integration of 10 spherical SLR satellites in the SLR solution and the combination of the techniques allow for a simultaneous estimation of TRF, EOP and gravity field coefficients in epoch reference frame solutions with high accuracy,
- The weekly combination at the observation level of GNSS and SLR (via satellite co-location) leads to very promising results, which allow the transfer of the SLR-derived centre-of-mass of the Earth to GNSS station network with very high accuracy and for a validation of the local ties at ground sites.

Sub-Commission 1.1: Coordination of Space Techniques

Chair: Tom Herring (USA)

The space geodetic observation techniques, including Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, GALILEO, and COMPASS, and the DORIS system, as well as altimetry, InSAR, LIDAR, and the gravity missions, contribute significantly to the knowledge about and the understanding of the three major pillars of geodesy: the Earth's geometry (point coordinates and deformation), Earth orientation and rotation, and the gravity field as well as its time variations. These three fields interact in various ways and they all contribute to the description of processes in the Earth System. Each of the space geodetic techniques contributes in a different and unique way to these three pillars and, therefore, their contributions are critical to the Global Geodetic Observing System (GGOS).

Sub-Commission 1.1 coordinates efforts that are common to more than one space geodetic technique, such as models, standards and formats. It shall study combination methods and approaches concerning links between techniques co-located at fundamental sites, links between techniques co-located onboard satellites, common modeling and parameterization standards, and perform analyses from the combination of a single parameter type up to a rigorous combination on the normal equation (or variance- covariance matrices) as well as at the observation level. The list of interesting parameters includes site coordinates (e.g. time series of combined solutions), Earth orientation parameters, satellite orbits (combined orbits from SLR, GPS, DORIS, altimetry), atmospheric refraction (troposphere and ionosphere), gravity field coefficients, geocenter coordinates, and others. One important goal of SC1.1 will be the development of a much better understanding of the interactions between the parameters describing geometry, Earth rotation, and the gravity field as well as developing methods to validate combination results, e.g., by comparing them with independent geophysical information.

To the extent possible SC1.1 should also encourage research groups to develop new observation techniques connecting or complementing the existing set of measurements.
Sub-Commission 1.1 has the task to coordinate the activities in the field of the space geodetic techniques in close cooperation with GGOS, all of the IAG Services, and with COSPAR.

Objectives

The principal objectives of the scientific work of Sub- Commission 1.1 in collaboration with GGOS are the following:

- Study systematic effects of and between space geodetic techniques.
- Develop common modeling standards and processing strategies.
- Comparison and combination of orbits derived from different space geodetic techniques.
- Explore and develop innovative combination aspects such as, e.g., GPS and VLBI measurements based on the same high-accuracy clock, VLBI observations to GNSS satellites, and the combination of atmospheric information (troposphere and ionosphere) of more than one technique.
- Establish methods to validate the combination results (e.g., with global geophysical fluids data).
- Explore, theoretically and practically, the interactions between the gravity field parameters, EOPs, and reference frames (site coordinates and velocities plus extended models),

improve the consistency between these parameter groups, and assess, how a correct combination could be performed.

- Study combination aspects of new geodetic methods such as Synthetic Aperture Radar (InSAR), LIDAR and optical image analysis methods.
- Additional objectives of Sub-Commission 1.1 are:
- Promotion of international scientific cooperation.
- Coordination of common efforts of the space geodetic techniques concerning standards and formats (together with the IERS and GGOS).
- Organization of workshops and sessions at meetings to promote research. - Establish bridges and common activities between SC1.1 and the IAG Services.

Links to Services

Sub-Commission 1.1 will establish close links to the relevant services for reference frames, namely Global Geodetic Observing System (GGOS), International Earth Rotation and Reference Systems Service (IERS), International GPS Service (IGS), International Laser Ranging Service (ILRS), International VLBI Service for Geodesy and Astrometry (IVS), and International DORIS Service (IDS) and the International gravity services.

Working Groups:

WG 1.1.1: Creation of common geodetic coordinate time series

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Members

- Bernd Richter (BKG) GGOS portal manager
- Thomas Herring (MIT) IERS Analysis Coordinator
- Xavier Collilieux (IGN) ITRS Combination Center
- Manuela Seitz (DGFI) ITRS Combination Center
- Laurent Soudarin (CLS) IDS representative
- Paul Rebischung (IGN) IGS representative
- Erricos Pavlis (Univ. of Maryland, Baltimore County) ILRS representative
- Alexis Nothnagel (Uni. Bonn) IVS representative
- Médéric Gravelle (Uni. La Rochelle) user (SONEL)
- Yehuda Bock (Scripps Institution of Oceanography) user (SOPAC GPS webservice)
- Simon Williams (Proudman Oceanographic Laboratory) user (CATS software)
- Xiaoping Wu (JPL) user

Summary of the activity of the WG since its creation

The first meeting of the WG was organized in San Francisco at AGU, on 6-Dec, 2012. Despite the very short time of meeting, we had rich discussions on some important issues concerning the data: time scale, reference system, coordinate system… The metadata are of prime importance in the format because they will give the necessary information to identify the time series and to make them easily used. They were briefly discussed. S. Bachman, representing GGOS informed us of the existence of ISO standards for Geospatial metadata, and of the metadata search engine included in the GGOS portal.

The second meeting of the WG was held in Vienna at EGU, on 10-April, 2012 with a few participants because of travel restrictions for our NASA colleagues and the meeting of GGOS Bureau of Networks and Communications at TUW at the same time. A list of existing formats at IAG services and GPS time series providers were presented. Several issues concerning the time series were discussed (epoch, time tag, accuracy, correlations,…).

The activity of the WG was presented in the session "Unification of product formats" at the IERS retreat held in Paris in May 2013. The purpose of the session was to discuss the benefits of common formats for the IERS data products, especially for EOP estimates and position time series. It was expressed that there is a clear need to have a standardized format to allow easy comparison. There were not any particular recommendation concerning position time series, just that the WG must continue developing a common format and investigate methods for web access to these files (including graphical presentations). Meeting summary and presentations are online at: http://www.iers.org/nn_128276/IERS/EN/Organization/ Workshops/Retreat2013.html

A third meeting took place in Vienna, on 15-April, 2015, at EGU. Based on a non-exhaustive list of existing formats at IAG services and GPS time series provider, metadata and data have been examined. The next step is to define the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system.

Analysis of time series formats from IDS (STCD), PBO/UNAVCO, NGL, ULR, SOPAC

The WG has established a non-exhaustive list of existing formats at IAG services and GPS time series provider. I examined the time series formats developed by the (a) IDS (STCD format), (b) PBO/UNAVCO, (c) NGL, (d) ULR, (e) SOPAC (see the references in Appendix). These formats have been developed for the own needs of each of these institutions. Examples

There are (at least) three different formats at NGL:

- txyz2 for xyz time series,
- tenv for east, north, up time series,
- tenv3 an upgraded version of tenv using a decomposition of the north, east and vertical coordinates in integer and fractional parts to, if I understand correctly, (1) keep the values in the format in case of important drifts (e.g. AMU2 moving 10 meters per year) or jumps more than 10 meters, (2) make plotting easier (simply plot the fractional parts), (3) detect problems from integer parts.

Note that PBO/UNAVCO has developed formats for various products: GPS station position (POS file), GPS velocity (VEL file), GPS phase RMS (RMS file), ...

The format developed by SOPAC is the most complete.

Type of format:

The first four (IDS, PBO, NGL, ULR) are text format while the latter (SOPAC) is a XML format (XML for Geodesy project).

- IDS STCD format: metadata are given in the header divided in blocks derived from the SINEX format; data are in formatted columns separated by blanks; metadata block and data block are easily identifiable.
- PBO: metadata are given in the first part of the file; data are in formatted columns separated by blanks; metadata block and data block are not clearly separated.
- NGL: this format does not include metadata; data are in formatted columns separated by blanks
- ULR: metadata lines start with an "#";data are in formatted columns separated by blanks

SOPAC: metadata and data are encoded in XML language

Content:

Data

Main characteristics of the fields:

- IDS: position differences XYZ and NEU; one date system; no correlation
- PBO: positions XYZ and position differences XYZ and NEU; 2 date systems; correlations
- NGL: positions differences NEU; 4 date systems; correlations
- ULR: position differences NEU; one date system; no correlation
- SOPAC: positions XYZ and NEU + delta position NEU; 2 date systems; correlations; quality index

	IDS	PBO/UNAVCO	NGL tenv	ULR	SOPAC
Station name	-	-	4-character ID	-	-
time	Decimal MJD (f7.1)	Date "yyyymmdd" and time "hhmmss" + decimal MJD (f10.4)	Date (a) + decimal year (f9.4)+ MJD (i5) + GPS week and day	Decimal year (f9.4)	Date "yyyymmdd" and time "hhmmss" + decimal MJD (f11.4)
X	-	m (f14.5)	-	-	m (f15.5)
Y	-	m (f14.5)	-	-	m (f15.5)
Z	-	m (f14.5)	-	-	m (f15.5)
dX	mm (f6.1)	-	-	-	-
dY	mm (f6.1)	-	-	-	-
dZ	mm (f6.1)	-	-	-	-
sX	mm (f5.1)	m (f7.5)	-	-	m (f9.5)
sY	mm (f5.1)	m (f7.5)	-	-	m (f9.5)
sZ	mm (f5.1)	m (f7.5)	-	-	m (f9.5)
cXY	-	(f6.3)	-	-	(f7.3)
cXZ	-	(f6.3)	-	-	(f7.3)
cYZ	-	(f6.3)	-	-	(f7.3)

North	-	decimal deg (f14.10)	(b)	-	decimal deg (f19.10)
East	-	decimal deg (f14.10)	(b)	-	decimal deg (f16.10)
Up	-	m (f10.5)	(b)	-	m (f11.5)
dN	mm (f6.1)	m (f8.5)	m (f9.6)	m (f7.4)	m (f12.5)
dE	mm (f6.1)	m (f8.5)	m (f9.6)	m (f7.4)	m (f10.5)
dU	mm (f6.1)	m (f8.5)	m (f9.6)	m (f7.4)	m (f10.5)
sN	mm (f5.1)	m (f7.5)	m (f8.6)	m (f6.4)	m (f11.5)
sE	mm (f5.1)	m (f7.5)	m (f8.6)	m (f6.4)	m (f9.5)
sU	mm (f5.1)	m (f7.5)	m (f8.6)	m (f6.4)	m (f9.5)
cNE	-	(f6.3)	(f9.6)	-	(f11.3)
cNU	-	(f6.3)	(f9.6)	-	(f9.3)
cEU	-	(f6.3)	(f9.6)	-	(f9.3)
Antenna height	-	-	m (f6.4)	-	-
Other (c)	-	Solution type	-	-	quality

(a) YYMMMdd ex: 10JUL28

(b) for tenv3, in addition to fractional portions, integer portions of the coordinates are used: longitude (degrees) of reference meridian and integer portion of eastings (m) (from ref. Meridian), integer portion of northings (m) (from equator), integer portion of vertical (m).

(c) in PBO format, this extra column indicates the type of orbit product used to generate the time series (rapid, final, ...). It seems to be the same usage by SOPAC.

Common fields: time, dN, dE, dU, sN, sE, sU.

Positions

- X,Y,Z is probably better than dX, dY, dZ.
- X, Y, Z is unambiguous. dX, dY, dZ depend on the XYZ reference position. Bias between two dX, dY, dZ time series may be introduced when XYZ reference positions differ.
- 7-parameters transformation can easily be applied on X, Y, Z series.
- From X,Y,Z + sigmas and correlations, one can obtained NEU + sigmas and correlations on different ellipsoids.
- XYZ: for a precision of 0.01 mm (+/-6400000.12345) → f14.5 (f15.5 too large)
- XYZ: for a precision of 0.01 mm (+/-6400000.12345) → f14.5 (f15.5 too large)

Date system:

- IDS and ULR use only one date system, decimal MJD and decimal year respectively, which are "easy-to-plot" system.
- PBO and SOPAC use two date systems: date and time for humans, decimal MJD for plotting tools.
- NGL uses four date systems: date YYMMMdd (ex: 96JAN02) + decimal year (ex: 1996.0027) + integer MJD (ex: 50084) + GPS week and day (ex: 834 3).

Comments:

- There is no date system that can be easily understood by human beings and easily used to plot time series. One or several date systems are applied according to the intended use.

- Use of several date systems can introduce errors as the correspondence between the systems must be ensured. Moreover, information redundancy increases the size of files.
- We previously note that decimal years are not recommended at they can cause problems because of leap years (/365.00, /365.25,or /366.00 ?)
- In my opinion, events in a time series such as discontinuities are detectable only when plotted (except in case of large discontinuities and spurious values). This means that a plot tool is used that can often convert date systems to each other. If so, a human readable date system is not absolutely required for the data.

Propositions:

- in metada, start and end epoch expressed in human readable system (e.g. yyyymmdd hhmmss) AND corresponding easy-to-plot system; in data, only easy-to-plot system

-an alternative to MJD date system is the POSIX timestamp (or Unix time http://en.wikipedia.org/wiki/Unix_time) defined as the number of seconds that have elapsed since 00:00:00 UTC, Thursday, 1 January 1970. For instance, 1405555272 corresponds to 2014-07-17T00:01:12Z.

Advantages:

- integer value (no problem of rounding)
- a unique 10-digit format (no 11th digit before year 2287) for time series up to one-second precision. (11 digits are necessary to develop MJD up to the second)
- widely used in Unix system (command: date +%s)

Drawbacks:

-it is neither a linear representation of time nor a true representation of UTC due to its handling of leap seconds. When a leap second occurs, a discontinuity occurs in the Unix time number. At the time the leap second is added, the Unix number is doubled.

23:59:59 → posix time = S

23:59:60 → posix time = S

00:00:00 →posix time = S+1

representation of time prior to 1970.

- an alternate way to represent date "yyyymmdd" and time "hhmmss" is the ISO 8601 standard yyyy-MM-ddTHH:mm:ss.sss (see Annex). SOPAC uses it in the metadata block.

<u>Field format:</u>

- IDS: data content, data format and units defined in header
- PBO: data content and units defined in header, data format not described.
- NGL: no header
- ULR: data content and units defined in header, data format not described.
- SOPAC: data, content, data format and units defined in header

Fixed format or not?

A fixed format is easy to read but is not flexible.

Different possibilities:

- to have different versions of the field format according to the characteristics of the time series as NGL did (tenv and tenv3).
- to define field formats so that a maximum of cases is taken into account; ex: same number of digits for positions and deltas.
- the field format is free and given in the header

Metadata

In addition to the time series, a header section is included to give information about the station or site, the source, the content..., except for NGL formats which contain only columns of the time series.

		IDS	PBO/ UNAVCO	NGL tenv	ULR	SOPAC
	File information					
1	**format name**	-	X	-	-	X
2	**format version**	-	X	-	-	X
3	**creation date**	-	-	-	X	X
4	**release date**	-	X		-	X
5	**provider name**	X	X	-	X	X
6	**provider code**	-	-	-	-	X
7	**contact name**	X	-	-	-	X
8	**contact email**	X	-	-	-	X
9	**postal address**	-	-	-	-	X
10	**website**	-	-	-	-	X
11	**type of product**	X	X	-	-	?
12	**data fields content**	X	X	-	-	X
13	**data fields format**	X	-	-	-	X
14	**data fields units**	X	X	-	-	X
	Site information					
15	**4-character ID**	X	X	-	X	X
16	**DOMES**	X	-	-	X	X
17	**Other IDs**	-	-	-	-	X (SOPAC, NGS)
18	**station name**	X	X	-	-	X
19	**agency code**	-	-	-	-	X (owner of monument)
20	**location**					X (name of hosting agency) (f)
21	**type**	X	-	-	-	X (h)
22	**latitude**	X	-	-	-	X
23	**longitude**	X	-	-	-	X
24	**height**	X	-	-	-	X (g)
	Product information					
25	**solution code**	-	-	-	X	?
26	**solution url**	-	-	-	-	X
27	**input data**	X	-	-	-	-
28	**processing reference**	-	-	-	-	X (link)

29	**software**	X	-	-	-	X (e)
30	**hardware**	X	-	-	-	-
31	**start epoch**	-	X	-	-	X (c)
32	**end epoch**	-	X	-	-	X (c)
33	**sampling frequency**	-	-	-	-	-
34	**number of points**	-	-	-	-	X
35	**reference system**	X	X	-	X	X
36	**Earth ellipsoid**	X	X	-	X	X
37	**reference position X**	X	X	-	X +sigmas	X
38	**reference position Y**	X	X	-	X +sigmas	X
39	**reference position Z**	X	X	-	X +sigmas	X
40	**reference epoch**	X	-	-	X	X
41	**reference position N**	-	X	-	X	X
42	**reference position E**	-	X	-	X	X
43	**reference position U**	-	X	-	X	X
44	**VX**	-	-	-	X +sigmas	X +sigmas + correlations
45	**VY**	-	-	-	X +sigmas	X +sigmas + correlations
46	**VZ**	-	-	-	X +sigmas	X +sigmas + correlations
47	**VN**	-	-	-	X +sigmas	-
48	**VE**	-	-	-	X +sigmas	-
49	**VU**	-	-	-	X +sigmas	-
50	**Processing description**	-	-	-	-	X
51	**Models**	-	-	-	X (b)	X (d)

(a)Release date
(b) Given as notes
(c) Given in file info and time series info
(d) Largely detailed in a block motion model terms
(e) Given in the processing phase blocks of the processing description
(f) + Nearest city + county + state code + country + tectonic plate
(g) Height + ellipsoid height + geoid height
(h) + foundation type and depth + inscription + installation date + geological characteristics + status

Propositions for the exchange format

<u>FILE FORMAT</u>

A priori, text formats are the most readable for humans.

- XML language was defined to be both human readable and machine readable.
- YAML is a human-readable data serialization format. It could be a trade-off.

The format should be easily generated so to minimize resistance to using it (initially maybe there could be lots of optional blocks and descriptors) and there needs to be an ease of use of the format (e.g., ideally someone should be able easily plot files in Matlab/Octave/Excel). There should be documentation in the format of loading models that have used and the nature of the frame for the time-series (centre of mass versus centre of figure). The plate reference system should also be specified. Any scale changes applied should also be specified

METADATA

I identify three types of metadata:
1. file information
2. site information
3. product information

1. File information

This block gives information about its type, its date of creation, its provider, and a general description of its content.

Propositions for the content of this block

1	**format name**	*(file type)*	
2	**format version**	*(file type)*	
3	**creation date**	*(date of creation of the file)*	*(a) (b)*
4	**provider name**	*(file provider)*	
5	**provider code**	*(file provider)*	
6	**contact name**	*(file provider)*	
7	**contact email**	*(file provider)*	*(c) (d)*
8	**type of product**	*(content)*	*(e)*
9	*Citation information*	*(text containing how to cite use of data)*	

Comments:
(a) Date of creation and/or date of release? is it useful to distinguish between both cases?
(b) All calendar dates should be given with the same date and time system (see data)
(c) Is it useful to give a complete postal address too?
(d) A web site may be given too
(e) Human readable description. This point is not trivial to standardize. It could be optional if we consider there is only one type of product for this format. However, we may want to distinguish time series of station coordinates, time series of position residuals, etc.

One possibility could be to include the field description of the data tin this block. It would be necessary if some fields are optional. Field descriptors is a good approach with some recommendations for default values if they are not given in the file. Advantage is adding new descriptors would not break old code provided it is originally written so that unknown descriptors are ignored. Disadvantage is reading of software needs to decode each descriptor, straightforward but tedious.

2. Site information

This block gives information about the identification of the site and its location.

Propositions for the content of this block

9	**code**	*(identification)*	*(f)*
10	**DOMES**	*(identification)*	*(g)*
11	**station name**	*(identification)*	
12	**type**	*(identification)*	*(h)*
13	**latitude**	*(location)*	*(i) (j)*
14	**longitude**	*(location)*	*(i) (j)*
15	**height**	*(location)*	*(i) (j)*
16	*Reference date+time*	*(date/time at which the position is given)*	

Comments:

(f) the code is the 4-character ID; capital or small letters?

(g) if any

(h) it gives the type of instruments (GPS receiver, DORIS antenna, ...) Possible combined option as well i.e., when VLBI+SLR+GNSS are combined for an averaged position—this could also depend on time in the time series i.e., not all days would have all systems.

(i) in my opinion, only an approximate position should be given here. A precise reference geodetic position would require to define the reference frame and the reference epoch. I think the latter is worth considering.

(j) units need to be defined; decimal degrees and meters?

Additional descriptors to identify the monument location may be considered (cf SOPAC): Nearest city, County, State code, Country, Tectonic plate. To be discussed. Monumentation type is also important. Maybe a standard set of terms for monument types.

3. Product information

This block gives information about the time series.

It gives information about the product: its name (solution code given by the provider), what data are used to generate this product (input data), where to find more information (reference about the processing).

It gives the necessary elements to describe the time series itself: epoch range, sampling frequency, number of points, reference system, reference position.

SOPAC includes a block "Processing" including indications about motion models (slope, annual, semi-annual, co-seismic offset, co-seismic decay removed or not). To be discussed.

16	**solution code**	*(product)*	
17	**input data**	*(product)*	
18	**processing reference**	*(product)*	*(k)*
19	**start epoch**	*(time series; epoch range)*	*(l)*
20	**end epoch**	*(time series; epoch range)*	*(l)*

21	**sampling frequency**	*(time series)*	*(m)*
22	**number of points**	*(time series)*	
23	**reference system**	*(time series)*	
24	**reference position X**	*(time series)*	
25	**reference position Y**	*(time series)*	
26	**reference position Z**	*(time series)*	
27	**reference epoch**	*(time series)*	
28	**ellipsoid**	*(time series)*	*(n)*
29	Averaging duration	(length of time used to estimate position, 1-Hz, daily, weekly?)	

Comments:

(k) the reference could be a publication, a web link, a DOI, ...
(l) All calendar dates should be given with the same date and time system (see data)
(m) See how to represent the sampling For VLBI this is problematic.
(n) datum or flattening + equatorial radius ?

Users have requested offset values in time series so that they can just use these values (removed from the time series) when analyzing the series for say hydrological signals.

DATA

The time series must contain at least: time, dN, dE, dU, sN, sE, sU

- XYZ coordinates are necessary to express positions in a different reference frame or to obtain NEU and then deltas NEU on a different ellipsoid.
- XYZ sigmas and correlations are necessary to get NEU sigmas and correlations

An additional column could be useful to give a quality index.

General proposal is to keep:

Time, X, Y, Z, sX, sY, sZ, cXY, cXY, cXZ, dN, dE, dU, sN, sE, sU, index

References

(a) IDS
http://ids-doris.org/documents/report/CB_STCD_format_v1.0.pdf
(b) PBO/UNAVCO
http://www.unavco.org/projects/major-projects/pbo/lib/docs/gps_timeseries_format.pdf
http://pbo.unavco.org/doc/NOTICE%20TO%20UNAVCO%20DATA%20PRODUCT%20USERS%2020130315.pdf
(c) NGL
http://geodesy.unr.edu/gps_timeseries/README_txyz2.txt
http://geodesy.unr.edu/gps_timeseries/README_tenv.txt
http://geodesy.unr.edu/gps_timeseries/README_tenv3.txt

(d) ULR
None
(e) SOPAC
http://sopac.ucsd.edu/projects/xml/measures/geodeticMLTest_pos.xml
http://sopac.ucsd.edu/projects/xml/measures/geodeticMLTest.xml

Others formats:

- JPL http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf

Files

- One file per component of site: XXXX.lat , XXXX.lon ; XXXX.rad

Fields

- Time in years
- Value in cm
- Formal error in cm
- Site name
- Component
- Date

Example

1994.0014 -4.715238240429318e+00 7.453062599186759e-02 ALGO LAT 94JAN01
1994.0041 -4.890997156680867e+00 7.092009642598809e-02 ALGO LAT 94JAN02

IVOA time series

- http://dotastro.org/simpletimeseries/
- http://www.ivoa.net/documents/Notes/SimpleTimeSeries/
- http://www.ivoa.net/documents/Notes/SimpleTimeSeries/20140513/NOTE-Simple-TimeSeries-1.0-20140513.pdf
- http://www.ivoa.net/documents/latest/UCDlist.html

Another XML format

- http://magma.geonet.org.nz/services/gps/reception?markCode=taup

WG 1.1.2: Investigate methods for merging geodetic imaging systems (InSAR, LIDAR and optical methods) into a geodetic reference system.

With the development of new methods for studying surface deformations, such as InSAR, LIDAR and optical methods, this working group will explore the methods that should be used to ensure that these deformation measurements are made in a well-defined geodetic reference frame. Issues to be addressed include how to establish the reference frame for these classes of measurements, how to ensure the long-term stability of the reference frame, and to make recommendations for changes in future systems that would allow more robust reference frame realization.

WG 1.1.2: Investigate methods for merging geodetic imaging systems (InSAR, LIDAR and optical methods) into a geodetic reference system

- Chair Lead: Sebastien Leprince, California Institute of Technology
- Members:
  - Francois Ayoub, California Institute of Technology
  - Jean-Philippe Avouac, California Institute of Technology
  - Bruno Conejo, California Institute of Technology
  - Jiao Lin, California Institute of Technology
  - Sang-Ho Yun, NASA/JPL
  - Piyush Shanker Agram, NASA/JPL
  - Mark Simons, California Institute of Technology

The chair of this working group changed position to one that was not related to this working group and the working stopped activities with no new chair being appointed.

Possible new chairs if this working group is to be reconstituted are:
- Remi Michel, remi.michel@upmc.fr, Pierre et Marie Curie University, Paris
- Ian Joughin, ian@apl.washington.edu, University of Washington
- Sang-Ho Yun, Sang-Ho.Yun@jpl.nasa.gov, JPL
- Piyush Shanker Agram, piyush@gps.caltech.edu, JPL
- Mike Oskin, meoskin@ucdavis.edu, UC Davis
- Ramon Arrowsmith, ramon.arrowsmith@asu.edu, Arizona State University
- Craig Glennie, clglennie@uh.edu, University of Houston
- Peter Reinartz, Peter.Reinartz@dlr.de, DLR

The latest report of the working group is given below.

Activities of this geodesy group have focused around five main activities dedicated to producing dense and precise observations of ground deformation and changes using remote sensing systems. Group members have been meeting regularly and have been working in close collaboration on these topics:

3D estimation of ground motion using multi-temporal optical satellite acquisitions

Participants: Sebastien Leprince, Francois Ayoub, Jean-Philippe Avouac

This topic aims at taking advantage of the newly available high-resolution stereoscopic acquisitions from optical push broom satellites such as Worldview, Quickbird, or Pleiades. Using multi-temporal stereoscopic acquisitions, ground motion can be observed in three-dimension, with accuracy within tens of centimetres, and measurement density of one observation distributed every couple meters or so. This group aims at improving this technique to make it reliable and current study areas involve the 2010 El-Mayor Cucapah earthquake in Baja California, Mexico, and the observation of fast flowing alpine glaciers in New-Zealand, in particular the Franz Josef and the Fox Glaciers.

3D matching of 3D point clouds

Participants: Bruno Conejo, Sebastien Leprince, Francois Ayoub, Jean-Philippe Avouac

This topic aims at providing a new framework to extract three-dimensional measurement of deformation from point cloud data of surfaces. Point cloud data of surfaces can be generated from stereoscopic acquisition of optical imagery, or directly from LiDAR imaging technology. It has appeared to us that the computer vision community is indeed lacking such expertise providing precise measurements of surface deformation. The work currently involves formulating a regularized matching function of 3D point clouds, assuming a continuous deformation field, with potentially high deformation gradients. Test cases are currently being investigated using airborne LiDAR time series of the migrating White Sand Dunes in New Mexico.

Development of InSAR time-series analysis tools

Participants: Piyush Shanker Agram, Mark Simons

The project involves the development of a multi-scale wavelet-based InSAR time-series technique to extend the current MInTS processor, based on Short Baseline and Persistent Scatterer techniques.

A new simple covariance model has been developed for time-series techniques. Simple analytical models for decorrelation and atmospheric inhomogeneities in individual interferograms have been around for the last decade, but no work has been undertaken to model the covariance structure of interferometric phase - both in space and in time. Understanding the structure of the covariance matrix is key to designing optimal interferogram networks and to quantify the errors in the estimated time-series.

Damage detection of buildings combining multi-temporal stereo imagery and SAR decorrelation maps

Participants: Sebastien Leprince, Jiao Lin, Sang-Ho Yun, Mark Simons

This topic aims at merging information from optical satellite and SAR satellite sensors to provide rapid estimate of damages following large disasters around urban areas. Our approach relies on producing accurate maps of building heights using optical stereoscopic acquisitions. The challenge is to provide an automatic and reliable technique to produce 3D maps of buildings from space. Comparing building heights before and after an event provides good estimate of potential building collapse. In addition, the study of the phase decorrelation of SAR images acquired before and after an event has been found to be a reliable proxy to estimate zones affected by large disasters. This group is currently working on merging both techniques (stereo optical and SAR decorrelation) to produce more accurate damage maps estimation. On-going studies are currently focused on data that were collected during the 2010 earthquake near the city of Christchurch, New Zealand.

Datum inconsistencies in the processing of satellite imagery on Mars

Participants: Francois Ayoub, Sebastien Leprince, Jean-Philippe Avouac

Planetary bodies such as Mars have very few reference surfaces and projections available compared to Earth. This should be an advantage to limit the confusion surrounding the projections and datum conversions. On Mars, the traditional map projections used by the imagery community are the equirectangular and polar stereographic. However, the equirectangular projection is defined for a spheroid and not an ellipsoid reference surface. The spheroid radius is chosen arbitrarily by the user to best match the local radius of the area of interest. With the multiplication of imagery available and the increasing needs to put in a common projection system various source of imagery, this poses the immediate problem of potential different radius for the same area. For instance, the MOLA geoid reference is defined with respect to a spheroid of radius 3396 km, and the USGS is delivering DEMs and orthophotos of MRO imagery with respect to a spheroid whose radius is defined locally (unique radius per 5 degrees latitude increment). To avoid much of the confusion it would be convenient to define a cartographic projection that relies on an ellipsoidal reference surface, for instance the one defined by IAU 2000, in order to remove the arbitrarily-chosen spheroid radius issue and have a unique projection system, which would allow faster and easier merging and comparison of all the data now being collected on Mars.

The studies of this group have been supported by the Keck Institute of Space Studies, The Gordon and Betty Moore Foundation through Grant GBM 2808 to the Advanced Earth Observation Project at Caltech, by the NASA MDAP# 11-MDAP11-0013 grant, and by the NASA/JPL R&TD grant to the ARIA project.

Sub-Commission 1.2: Global Reference Frames

Chair: Claude Boucher (France)

The IAG Sub-Commission 1.2 was created in 2003 as a part of the new structure of the International Association of Geodesy (IAG). It is engaged in scientific research and practical aspects of the global reference frames. It investigates the requirements for the definition and realization of the terrestrial reference systems and frames, addresses fundamental issues, such as global geodetic observatories or methods for the combined processing of heterogeneous observation data.

Numerous activities are actually realized in other IAG-related structures, mainly:

- Sub-commission 1. On Regional reference frames, including EUREF, SIRGAS…
- International Earth Rotation and Reference Systems Service (IERS)
- other relevant IAG services (IGS, ILRS, IVS, IDS)
- IAG Global Geodetic Observing System (GGOS)
- Inter-Commission Committee on Theory.

We therefore encourage to refer to their individual reports.

Beyond IAG, cooperation with other relevant international organizations such as IAU, FIG or ISO are also developed.

Contributors to this report:

Zuheir Altamimi (France) IERS
Detlef Angermann (Germany)
Claude Boucher (France) President
Xavier Collilieux (France) C1
David Coulot (France)
Pacome Delva (France)
Sakis Dermanis (Greece) ICCT
Bruno Garayt (France)
Richard Gross (USA)
Gary Johnston (Australia) C1
Paul Rebishung (France) IGS
Pierguido Sarti (Italy) C1
Michael Soffel (Germany)
Tonie van Dam (Belgium) C1
Pascal Willis (France) IDS

Relativistic modeling

This topic is of great interest and was identified as one of the goals of the sub-commission. Two specific points were identified:

- extension of the IAU model to geodesy
- investigations on the use of emission coordinate systems

Detailed report on IAU model will be published in the final report.

Emission coordinates and relativistic reference frames

The development of the concept of emission coordinates (Coll and Morales 1991,Rovelli 2002, Blagojeviƒá, Garecki, Hehl, & Obukhov 2002, Lachieze-Rey 2006) led to new ideas about the realization of global reference frames. Clocks combined with time transfer techniques are powerful tools for positioning in the 4 dimensional space-time, and it has been suggested to use a constellation of clocks linked one to another with a time transfer technology, so called Inter-Satellite Links (ISLs), in order to build a satellite-based dynamical reference frame (Coll 2002). Such constellations are already a reality with GNSS (GPS, Galileo, GLONASS, Beidou), and the last generation of GPS implemented such links (NAVSTAR). It is planned to be implemented on the second generation of Galileo satellites (2020).

Inter-satellite links (ISLs) allow to directly synchronize the satellite clocks in space, and determine orbits using ISLs pseudo-ranges. This realizes an autonomous, four-dimensional, dynamical and relativistic reference frame, so-called the ABC (Autonomous Basis of Coordinate) frame (Delva et al 2011 bis, Gombac et al 2013). The benefit of such a reference system compare to the actual GNSS process is to separate the realization of the frame from the determination of Earth-specific parameters, such as the ground station coordinates, Earth rotation parameters and atmospheric parameters. Indeed the realization of the frame relies only on ISLs observables. Such a frame would be decoupled from an Earth fixed frame and even from a celestial frame. It would shine a new light on the space-time geometry around the Earth. Indeed, the space ensemble of clocks can be used to monitor Earth based clocks and determine their trajectories and the Earth gravity field (thanks to the red shift effect), and therefore link the ABC dynamical frame to an Earth fixed frame. Clock accuracies regarding the gravitational potential determination and height determinations begin to be competitive with classical techniques, e.g. in the sub-decimetre range for the determination of the geoid.

Several teams are developing concepts around relativistic positioning systems, and a workshop has been organized to exchange and foster new ideas: "Relativistic Positioning Systems and their Scientific Applications". It took place in Brdo near Kranj, Slovenia 19-21 September 2012. Proceedings have been published in Acta Futura in 2013 (http://dx.doi.org/10.2420/ACT-BOK-AF07).

ITRF

More details can be found in the report from the IERS ITRS Product Center. In general research activities related to ITRF are developed by three groups in the frame of IERS: DGFI, IGN and JPL.

ITRF2008 results

The ITRF2008 solution was released in May 2010. A dedicated website has been established (http://itrf.ign.fr/ITRF_solutions/2008/) providing full description of ITRF2008 solution, together with all associated products: station positions and velocities of the 920 stations (located at 580 sites) in SINEX as well as in simple table formats; Earth Orientation Parameters in different formats; plots of technique origin and scale time variations and station position residuals. The website also provides synthesized summary descriptions of the IERS Technique Centres (TC) solutions used in the ITRF2008 elaboration. All the submitted solutions were combined solutions by the Combination Center of each TC and based on reprocessed individual solution generated by the Analysis Centers of each one of the four techniques (VLBI, SLR, GNSS/GPS and DORIS). The submitted solutions cover the full history of observations, except for the GNSS/GPS series which start in 1997. These solutions are archived by the ITRS Center and the Central Bureau and were analysed by the two IERS Combination Centers (IGN and DGFI). Interaction and communication between the IERS Center and the TCs were operated as necessary and as a function of the ITRF2008 analysis conducted by the IERS CCs. The following table summarizes the final time series of station positions and EOPs submitted by the TCs.

TC	Span	Solution type	EOPs
IVS	1980.0–2009.0	Normal Equation	Full set
ILRS	1983.0–2009.0	Variance-Covariance	Polar Motion, LOD
IGS	1997.0–2099.5	Variance-Covariance	Polar motion, rate, LOD
IDS	1993.0–2009.0	Variance-Covariance	Polar motion, rate, LOD

A detailed article on ITRF2008 results was prepared and published in 2011 in Journal of Geodesy with the "open access" option so that the ITRF2008 users have full and free access to the details of the ITRF2008 analysis and results.(Altamimi Z., Collilieux X., and Métivier L. (2011),)

ITRF2008 Plate Motion Model

Detailed analyses of the ITRF2008 velocity field were undertaken in order to estimate a plate motion model consistent with ITRF2008. Indeed, for various geodetic and geophysical applications of ITRF2008, the aim of this study is to provide users with the most precise plate motion model derived from and consistent with the ITRF2008.The analysis consisted in simultaneously estimating angular velocities for 14 plates, together with an origin rate bias of the selected velocity field of 206 sites. The obtained results provide a model for 14 plates, with a global WRMS of 0.3 mm/yr. (Altamimi Z., Métivier L. and Collilieux X. (2012),)

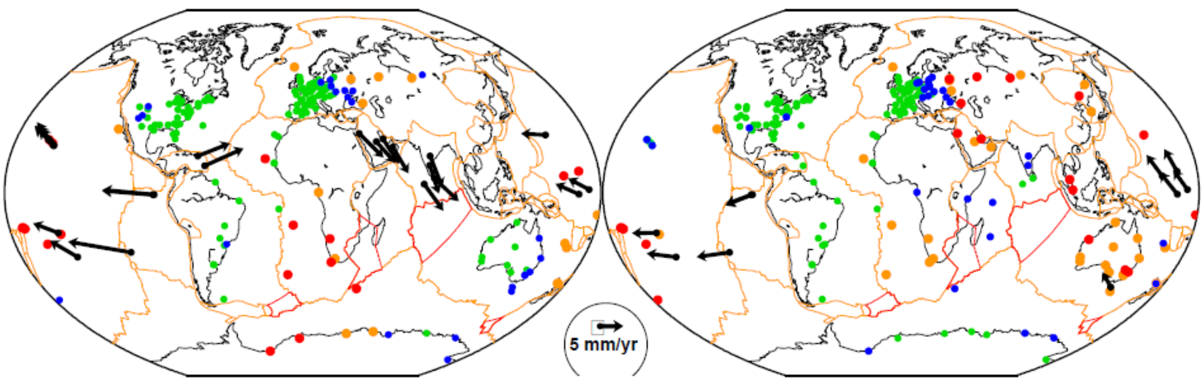

Figure 1. Velocity differences between ITRF2008 and (left) NNR-NUVEL-1A and (right) NNR-MORVEL56, after rotation rate transformation. In mm/yr, Green: less than 2 mm/a. Blue: between 2–3 mm/a. Orange: between 3–4 mm/a. Red: between 4–5 mm/a. Black: larger than 5 mm/a, and rates of velocity differences are shown only in this case.

The article details also the comparisons between ITRF2008 PMM and the geophysical models NN-NUVEL-1A and NNR-MORVEL56. Results show in particular a large angular velocity residual of about 4 mm/yr for the Australian plate between ITRF2008 PMM and NNR-MORVEL56, as illustrated by Figure 1. This bias is not observed in the comparison with NNR-NUVEL-1A and suggests that the Australian plate is probably mis-modelled in NNR-MORVEL56.

ITRF2014

At the time of writing, the ITRF2014 is under development and expected to be released by fall 2015. The full history of data of all four techniques, up to the end of the year 2014 will be used in the generation of the ITRF2014. Daily and session-wise solutions are provided by IGS and IVS, while weekly solutions are provided by IDS and ILRS. The main novelties of ITRF2014 compared with ITRF2008 are the estimation of periodic signals (e.g. annual and semi-annual) in the station position time series and the modelling of post-seismic deformation for sites which are impacted with large Earthquakes. The estimation of periodic signals is expected to improve the determination of station linear velocities and it actually helps identifying discontinuities in the time series. The modelling of post-seismic deformation will be operated by using logarithmic or/and exponential functions, as a function of the nature of the deformation per station. This modelling is expected to enhance the estimation of the linear part (velocity) of the station and therefore reinforce the connection between techniques at co-location Earthquake sites using the same parametric model.

Research and development activities

IGN

The IGN group, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Scientific results of specific data analysis and combination are published in peer-reviewed journals, as listed in the references' section, but also presented at international scientific meetings.

DGFI

In the report period, the DGFI group published the general paper about the computation of the DTRF2008 solution (Seitz et al. 2012). In a second publication DGFI compared the two reference frames DTRF2008 and ITRF2008 in order to assess the accuracy of the reference frames (Seitz et al. 2013). The agreement is between 7 and 10 mm and between 0.2 and 2.0 mm/a for the station positions and velocities, respectively, depending on the technique and if only core stations are considered.

In addition, DGFI performed various research and development act ivies in the field of global geodetic reference frames. This includes basic research related to the definition and realization of global terrestrial reference system and to the datum definition (Drewes 2012; Drewes et al. 2013). Other research topics were the common adjustment of the celestial and terrestrial reference frame together with the Earth Orientation Parameters (Seitz et al. in press) and the development of strategies for the computation of epoch reference frames (Bloßfeld et al. 2011; Bloßfeld et al. 2013).

JPL

CATREF, the software package used at IGN France to produce the well-known ITRFs, has been installed at JPL and has been used to reproduce ITRF2005. A Kalman filter and smoother algorithm has been developed and coupled to the CATREF software. This Kalman filter-based software package, KALREF, has been used to produce ITRF2005-like and ITRF2008-like reference frames that compare favourably with ITRF2005 and ITRF2008, respectively (Wu et al., 2015). It has also been used to solve for time-variable weekly coordinates, as well as a model of secular, periodical and stochastic motion components. In addition, KALREF has been used to define a nearly instantaneous reference frame by specifying constant frame parameters and combining different technique data weekly. It is currently being used to determine a solution for the IERS using the input SINEX files that were produced by the Services for ITRF2014.

A simulation tool to study the effect of network geometry on reference frame determination is being developed. The tool is based on synthetic station position and reference frame parameter (geocenter, scale) data. It has been used to study the effect of station distribution, number of stations, availability of site tie measurements, etc. on the reference frame. Preliminary conclusions indicate that reasonable TRFs can be determined from a network of about 30-40 well-distributed, co-located stations as long as accurate site ties are available at each site.

The Three Corner Hat (TCH) technique has been used to determine the uncertainties of estimates of positions of stations at co-located sites. For 16 co-located sites used in ITRF2008, the median (north, east, up) uncertainties are found to be (1.1, 1.2, 2.8) mm for the GPS stations, (2.2, 2.0, 6.2) mm for the VLBI stations, (8.5, 7.6, 9.0) mm for the SLR stations, and (9.2, 11.7, 10.6) mm for the DORIS stations (Abbondanza et al., 2015).

The GRASP mission

GRASP is a satellite mission which will carry very precise sensor systems for all the key geodetic techniques used to define and monitor the TRF: a Global Navigation Satellite Systems (GNSS) receiver, a Satellite Laser Ranging (SLR) retro-reflector, a Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) receiver, and a novel Very Large Baseline Interferometry (VLBI) beacon. It would allow to achieve the requirements established by the *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*: “Maintaining a terrestrial reference frame at the level that allows, for example, the determination of global sea level changes at the sub-millimetre per year level, pre-, co- and post-seismic displacement fields associated with large earthquakes at the sub-centimetre level, timely early warnings for earthquakes, tsunamis, landslides, and volcanic eruptions, as well as the monitoring of mass transport in the Earth system at the few Gig tons level requires an comprehensive Earth system approach.”

GRASP was proposed in response to the NASA's Earth Venture-Mission (EV-M) call of opportunity in 2011 and was graded 2nd after the CYGNSS mission. A new NASA's EV-M proposal opportunity is currently prepared for a release in Summer 2015. A new GRASP proposal is thus under study.

To reach mission goals, the first step is to determine the optimal orbit of this satellite. The GRGS studies an original approach, based on evolutionary algorithms, for determining such orbits. This method permits to optimize orbits according to specific criteria, such as the visibility of the satellite from ground stations and GNSS satellites, some orbital constraints, etc. Once the orbit chosen, GRGS will carry out, in collaboration with JPL, numerical simulations with the GINS software. These simulations aim to determine the boundary of the calibration of the on-board instruments required to reach the objectives of the mission.

TRF activities in IAG services

IGS

Since February 2010, IGN France has replaced Natural Resources Canada (NRCan) as coordinator of the IGS Reference Frame Working Group. On the operational side, this coordination consists in combining the SINEX solutions provided by the IGS final Analysis Centers (ACs) and updating a long-term cumulative solution each week. The switch from NRCan to IGN was the opportunity to bring some changes to the SINEX combination strategy (Rebischung and Garayt, 2013). But the formats and contents of all products were kept unchanged so as to ensure a smooth transition. Besides a continuous monitoring of the SINEX combination results, the main achievements of the Reference Frame Working Group since 2010 were:

* the publication of IGS08 (Rebischung et al., 2012), a new IGS reference frame based on ITRF2008;
* the generation of a homogeneous set of weekly solutions based on the IGN combination strategy back to 1994 and of a new, modernized IGS cumulative solution;
* the switch from weekly to daily terrestrial frame combinations in August 2012.

More details on the recent IGS Reference Frame Working Group activities can be found in the 2011 and 2012 IGS Technical reports available at ftp://igs.org/pub/resource/pubs/

IDS

Several TRF related activities can be found in references below, in particular Altamimi and Collilieux 2010, Angermann, Seitz and Drewes 2010, Govind et al 2010

External evaluation of TRF

This topic is mainly studied within the group

External Evaluation of Terrestrial Reference Frames

Chair: Xavier Collilieux (France).

An accurate Terrestrial Reference Frame (TRF) is fundamental for Earth science applications. To constrain the error budget of some geoscience products such as the determination of sea level variations from space, the uncertainty of tracking geodetic station coordinates should be known reliably. The scope of the this task force is to enumerate and assess all the methods that provide an evaluation of the Terrestrial Reference Frame accuracy, especially in terms of origin and scale.

This activity has started in 2011. First results have been discussed in Collilieux and Altamimi (2013). During the previous term of the IAG commission 1, the task force has written a report that has been finalized during this term (Collilieux et al., 2014). It establishes that the accuracy of the ITRF2008 in terms of origin rate is likely to be less than 0.5 mm/yr on the three components while the scale rate error is smaller than 0.3 mm/yr. In the meantime, Argus (2013) revisited the TRF origin and scale accuracy by relying on the assessment of space geodetic data. Post-glacial rebound models have been further investigated for evaluation purpose by several authors. King et al. (2011, 2012) have shown that models and observed station vertical velocities cannot be reconciled by shifting the origin of the TRF. However, their accuracy is sufficient to discriminate different modeling of the rotational feedback (Mactivier et al., 2012). Finally, we mention that Earthquake co-seismic models have been used globally to assess discontinuities and effect on station velocities on a global set of station. Such an approach in the future is likely to improve the accuracy of the TRF.

Too few activity of this working group has been reported during these first two years. For this reason, it is more reasonable not to continue this effort for the next two years.

Global Geodetic Observatories

Works on concepts and practical implementation are under progress. Detailed results with references will be provided in the final report.

We must mention the specific activities of the working group **Site Survey and Co-location** (jointly with IERS) chaired by Pierguido Sarti (Italy) (also Joint Study Group 1.2.2: Global Geodetic Observatories

The Joint Working Group has focussed on the provision of accurate tie vectors for ITRF computation and the assessment of their accuracy. It is a rather complex process as it must rely on the extent of (dis)agreement with the space geodetic solutions and the analysis of any possible cause, either on the local survey or the space geodetic observation side. The ITRF combination residuals do not often agree with the magnitude of the tie vector formal precisions, these latter usually being at the mm or sub-mm level. In addition, the WG has focussed on the definition and validation of new methodologies for the surveying and computation of the tie vectors and the definition of standards and guidelines. Finally, the creation of a central repository for local surveys data has been discussed and evaluated during a meeting held in Paris on May 21-22, 2013. This two days meeting was organized as an official IERS workshop and brought together more than 40 experts that had the opportunity to discuss different issues related to surveying methods and approach, tie vector estimation strategies, nomenclature, guidelines, documentation, data archiving and more. The workshop was a success in terms of participation and results. 25 oral contributions were presented during the meeting. All relevant information can be found at the workshop web page: http://iersworkshop2013.ign.fr/?page=scope

A recent review paper was also published on this subject in Advance Space Research (Boucher, Pearlman, Sarti, 2015)

Workshops, meetings, invited talks (2010-2013)

Convening activity:

Dec. 2013: Session convener - American Geophysical Union Fall meeting – G012: Reference Frames: Determination, Usage and Application – San Francisco – CA – USA: https://fallmeeting.agu.org/2013/scientific-program/session-search/sessions/g019-reference-frames-determination-usage-and-application-2/

May 2013: Chair of the Scientific Organizing Committee - International Earth rotation and Reference systems Service Workshop on Local Surveys and Co-locations – Paris – France: http://iersworkshop2013.ign.fr/?page=soc

Apr. 2010: Session convener – European Geosciences Union – G2: The Global Geodetic Observing System: tying and integrating geodetic techniques for research and applications – Vienna – Austria: http://meetingorganizer.copernicus.org/EGU2010/sessionprogramme/G

Invited/solicited talks:

2011: 37th course of the International School of Geophysics; Interdisciplinary Workshop on Earth expansion evidence: a challenge for geology, geophysics and astronomy, Erice, Italy

The consistency between local and space geodetic observations – Accuracy of the global terrestrial reference frame.

2010: IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010); Theory and realization of global terrestrial reference systems, Marne-La-Vallée, France

A review on local ties and co-location issues

Global Geodetic Reference Frame

The United Nation initiative on Global Geospatial Information Management aims at playing a leading role in developing the global use and data sharing of geospatial information to address key global scientific, societal and economic challenges, and consequently to emphasize the need for a sustainable Global Geodetic Reference Frame (GGRF).

The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) decided in July 2013 to formulate and facilitate a draft resolution for a Global Geodetic Reference Frame. In order to achieve this they created a Working Group on the Global Geodetic Reference Frame (WG on GGRF) co-chaired by Australia and Norway.

At its 4th session held in New York in August 2014, the UN-GGIM Committee of Experts approved a draft text of a resolution prepared by the WG on GGRF to be submitted to (ECOSOC: Economic and Social Council of the UN) for further referral to the UN General Assembly for adoption. The said resolution is entitled "A Global Geodetic Reference Frame for Sustainable Development".

In February 2015 the UN General Assembly adopted the resolution ***A Global Geodetic Reference Frame for Sustainable Development*** – the first UN resolution recognizing the importance of a globally-coordinated approach to geodesy was declared.

It is available, together with a descriptive Concept Note and other materials, at the UN-GGIM Website: http://ggim.un.org/UN_GGIM_wg1.html

The WG on GGRF was further tasked with developing a Road Map for the Maintenance and Enhancement of the GGRF. A draft of the Roadmap is due for delivery to the Committee of Experts at the 6th Session of the UN GGIM, August 2016.

ISO standardization

A project has been established within the International Standardization Organization (ISO) Technical Committee ISO TC 211 (geographical information) dealing with geodetic references. This project 19161 was chaired by Claude Boucher (France). Its objectives were to write a report showing the importance of geodetic references for geo-information and to propose some specific items relevant to an ISO standard. The ITRS has been proposed as one of them. IAG, which is a liaison organization with ISO TC211 was represented by Zuheir Altamimi. The final report was submitted to ISO TC211 on Feb 2015. For major recommendations were included, three on possible topics of standardization, and one on terminology issues.

It is planned to submit a so-called New Work Item Proposal (NWIP) on ITRS. In order to collect a comprehensive set of opinions within IAG and its services, GGOS has reactivated the WG chaired by Claude Boucher on this subject, linked to the GGOS Bureau of Products and Standards.

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Sub-Commission 1.3: Regional Reference Frames

Chair: João Torres (Portugal)

Introduction

Sub-Commission 1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organisations.

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

- Develop specifications for the definition and realization of regional reference frames, including the vertical component with special consideration of gravity data and other data.
- Coordinate activities of the regional sub-commissions focusing on exchange and share of competences and results.
- Develop and promote operation of GNSS permanent stations, in connection with IGS whenever appropriate, to be the basis for the long-term maintenance of regional reference frames.
- Promote the actions for the densification of regional velocity fields.
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations.
- Encourage and assist, within each regional sub-commission, countries to re-define and modernize their national geodetic systems, compatible with the ITRF.

Six regional Sub-Commissions compose the Sub-Commission 1.3:

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

Furthermore, two Working Groups (WG) are active within SC 1.3:

- WG 1.3.1: Integration of Dense Velocity Fields into the ITRF
  - The main task of this WG is to study and promote consistent specifications for the generation of GNSS-based velocity field solutions and their combination in order to derive a unified dense velocity field in a common global reference frame.
- WG 1.3.2: Deformation Models for Reference Frames
  - The primary aim of the WG is to develop tectonic deformation models that will enable transformation of locations within a defined reference frame between different epochs. Such deformation models are essential to support precise point positioning applications and CORS/NRTK operations within deforming zones

Overview

The activities of each of the regional Sub-Commissions and Working Groups "Integration of Dense Velocity Fields into the ITRF" and "Deformation Models for Reference Frames" are reported hereafter. A summary of those activities and the main results achieved is given below.

Sub-Commission 1.3 a: Europe

- The number of permanent GNSS tracking sites in Europe is still growing, with more than 260 EPN stations operating by mid-2015. The number of site, switch record GLONASS data simultaneously to GPS data is steadily increasing (70 %).
- Currently the EPN working group on Reprocessing conducts a second reprocessing campaign, EPN-Repro2 realized in the IGb08. The analysis is being carried out on the EPN data from 1996 till 2013 by five analysis centres.
- The preparation for the future Galileo system and the development of the EPN towards a multi-system GNSS network started.
- EUREF continued the validation of national GNSS campaigns. The following projects were accepted by the plenary as EUREF densification campaign between 2011 and 2015: "EUREF Serbia 2010" (Serbia), "EUREF-MAKPOS 2010" (Macedonia), "EUREF Faroe Islands 2007" (Faroe Islands), "EUREF BE 2011" (Belgium) , "EUREF Poland 2015" and "Central European Geodynamic Research Network (CERGN)".
- The EPN Project on "Real-time Analysis" is still developing. Based on orbit and clock corrections broadcasted in ETRS89 (realization ETRF2000), users can directly derive real-time coordinates referred to ETRS89 at few dm-level.
- The EUREF TWG set up three new Working Groups. One is on "Multi GNSS" to prepare recommendations on the use of the new signals within the EPN. The second one is on "Deformation Models", to improve the knowledge of surface deformations in Eurasia and adjacent areas. The third one is on EPN Densification to realize a continental-scale, homogeneous, high quality position and velocity product in an homogeneous reference frame, for a very dense network of GNSS stations.
- The UELN was enhanced by additional or updated leveling data. These data make possible to close the loop around the Baltic Sea. Some countries announced to provide their levelling data and join the UELN.
- The promotion of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) continued, following the adoption by INSPIRE of these systems as the basis for georeferencing in Europe.
- The latest EUREF symposia took place in Saint-Mandé, France (2012), in Budapest, Hungary (2013), Vilnius, Lithuania (2014), Leipzig, Germany (2015). Meetings of the EUREF Technical Working Group have been held three times a year. In addition a EUREF retreat was held in Nov. 2012 with the goal to review EUREF key themes and organizational structures and derive a plan to achieve the EUREF objectives for the next 4-8 years.

Sub-Commission 1.3 b: South and Central America

- The number of continuously operating GNSS stations that support the SIRGAS Reference Frame is still growing. It is composed by about 400 stations, 235 of which with GLONASS capability, 16 Galileo and 2 BEIDOU. The SIRGAS Reference Frame includes 58 formal IGS stations.
- The IGS Global Analysis Centres process 40 SIRGAS stations since January 2012 in order to improve the distribution of the ITRF sites in this region. These stations are included in the IGS Reprocessing 2.
- The SIRGAS-N national networks are computed by 9 SIRGAS Local Processing Centres. These processing centres deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. All Analysis Centres follow unified standards for the computation of the loosely constrained solutions.
- The computation (update) of the cumulative solution is performed every year, providing epoch positions and constant velocities for stations operating longer than two years. For the moment, the computation of multi-year solutions is stopped until it fills the criteria of getting weekly normal equations referenced to the IGS08/IGb08 and covering a time span of at least three years.
- The support of the countries interested on adopting SIRGAS as official reference frame continued. At this moment, 14 countries in the region have already adopted SIRGAS as the official reference frame for Geodesy and Cartography. More than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership.
- The installation of the service "Experimental SIRGAS Caster” with the goal to promote the availability of the SIRGAS Reference Frame in real time showed major advances, reported by several countries.
- The efforts needed towards the definition and realisation of a gravity field-related vertical reference system in Latin America and the Caribbean have been identified. The work has started in collecting and validating the existing databases, performing levelling field works to connect the fundamental points of the vertical networks with the SIRGAS reference station and with the main national tide gauges and levelling connections between neighbouring countries.
- The signature of the "2013-2015 Action Plan to Expedite the Development of Spatial Data Infrastructure of the Americas" constitutes a strategy for the adoption of SIRGAS as the official reference frame for Geodesy and Cartography, according to the recommendation issued in 2001 by the "United Nations Cartographic Conference for the Americas".
- The development of actions for capacity building and the promotion of SIRGAS in the member countries, in particular the 2 Workshops on Vertical Datum, 4 SIRGAS Schools, training courses on precise GNSS data processing, under the sponsorship of several international organizations and national institutions.
- The SIRGAS General Meetings took place in Costa Rica (2011), Chile (2012), Panama (2013) and Bolivia (2014).

Sub-Commission 1.3 c: North America

- Dr. Neil D. Weston replaced Dr. Jake Griffiths as the U.S. co-chair in 2013.
- The densification of the ITRF and IGS network from weekly combinations of 5 regional weekly solutions using different GPS processing software has been on hold since GPS week 1583.
- The enhanced version of the software to enable the weekly combinations of the large number of stations was released in 2014.
- The reprocessing of the regional networks is planned immediately following the release of IGS repro2 orbits, with the exception of INEGI, who has just completed their own reprocessing with repro1 orbits.
- The discussion of the implementation of a new geocentric, ITRF-based regional reference frame for North America in 2022 continued with the second Federal Geospatial Summit in April 2015.
- CGS and NGS have begun the process of updating the International Great Lakes Datum for the management of water levels in the Great Lakes Basin. Continued repeated GPS survey campaigns of the water level gauge network are planned for 2015 and 2020.
- A program of validating commercial RTK services and their base station coordinates, to ensure correct and consistent integration of RTK services in NAD83, has begun at CGS. NGS is also planning a similar validation program in the very near future.
- No activities related to the definition and maintenance of the relationships between international and North American reference frames/datums due to delays in the release of ITRF2013 (now ITRF2014). Transformations from/to subsequent versions of ITRF96 are obtained by updating the NAD83-ITRF transformation with the official incremental fourteen parameter transformations between ITRF versions as published by the IERS.
- The working groups dedicated to the different tasks met when appropriate.

Sub-Commission 1.3 d: Africa

- Prior to March 2013 the project fell within United Nations Committee for Development Information, Science and Technology (Geo-information) (CODIST-Geo). Since March 2013, the oversight and supervisory functions of CODIST-Geo (including AFREF) were transferred to the United Nations Global Geospatial Information Management: Africa (UN-GGIM: Africa).
- Approximately 90 stations have been installed and are registered on the AFREF Operational Data Centre which was installed to download and archive data from these stations. Of these 90 stations, however, only 60 have provided data to the ODC in 2015.
- The data of 50 AFREF stations together with 50 global stations was processed by 4 processing centres and combined to provide a set of static co-ordinates based on ITRF2008 to be used for everyday surveying and mapping operations.
- Workshops on the establishment and processing of permanent GNSS stations and networks are held annually at the Regional Centre for Mapping of Resources for Development in Nairobi, Kenya.

Sub-Commission 1.3 e: Asia-Pacific

- The increase of the number of stations of the CORS network (approximately 480 stations from 28 countries), whose data are processed by four Analysis Centres (ACs).
- The increase of the number of institutions contributing to APREF in several domains (analysis, archive and stations).
- The availability of a weekly combined regional solution, in SINEX format and a cumulative solution which includes velocity estimates.
- The publications of the weekly ITRF coordinate estimates in SINEX format, coordinates time series and velocity solutions for the APREF stations on the APREF website.
- The coordination of annual geodetic observation campaigns in order to densify the ITRF in the Asia-Pacific Region in countries without Continuously Operating Reference Stations (CORS). Four annual GNSS campaigns have been carried out since 2011.

Sub-Commission 1.3 f: Antarctica

- Dr. Mirko Scheinert replaced Dr. Reinhard Dietrich as chair of SC 1.3f in 2013.
- The realization of SCAR GPS Campaigns in every austral summer from 2011 until 2015. The data of 50 Antarctic sites are collected in the SCAR GPS database since 1995.
- The continuation of data analyses and presentation of the results at the XXXII SCAR Meetings (2012 and 2014).
- The establishment of the working plan of the SCAR Group of Experts on Geodetic Infrastructure in Antarctica (GIANT) for the years 2012-2014, where the goals of SC 1.3f are well reflected.

Working Group 1.3.1: Integration of Dense Velocity Fields into the ITRF

- The decision to start with the combination of weekly position solutions allowing the mitigation of biases, as a result of tests concluding that the level of agreement between the several multi-year solutions submitted before was not satisfactory.
- The submission of regional and global solutions containing more than 4000 stations.
- The realization of preliminary combinations of 2679 selected stations with more than 3 years observations, present in at least 104 weekly SINEX and present in at least 50% of the weekly SINEXs within the data span.
- The first solution obtained from the stacking of the weekly combined solutions is finalized. The multi-year positions and velocities are expressed in the IGS08 frame. The combination on a weekly level allows increasing the reliability of the velocity field.

Working Group 1.3.2: Deformation Models for Reference Frames

- The realization of considerable research on deformation modelling completed by WG members in Japan, South America, Australia, New Zealand and the USA, including the possibility to use remote sensing techniques such as InSar and LiDar to estimate local deformation models.
- The improvement of crustal deformation models (post-seismic deformation), the release of deformation patches which model the co-seismic and post-seismic deformation in Japan (Tōhuku earthquakes) and New Zealand (Canterbury earthquake sequence).
- The development of localised deformation models to support land surveying activities in zones where significant earthquakes occurred.

- The development of next-generation geodetic datums using deformation models.
- The activity of the WG members is being developed in the majority of the areas covered by the regional Sub-commissions. Also, the WG 1.3.2 has been working closely with FIG Commission 5 (Positioning and Measurement).

Conclusion

The activities developed by each of the regional Sub-Commissions and Working Groups (Integration of Dense Velocity Fields into the ITRF and Deformation Models for Reference Frames) make evident that all the components of the structure are working according to the main objectives of the SC 1.3.

Some general aspects deserve to be mentioned:
- The activities are contributing to the scientific and technical development in several topics such as GNSS analysis and processing, precise reference frame establishment, use of new GNSS signals, among others.
- The stronger involvement of the regional components in the global scientific goals of the IAG, especially their contribution to the ITRF solutions.
- The emphasis that all the regional Sub-commissions and both Working Groups are giving to the modelling of non-linear changes in the coordinates due mainly to geophysical phenomena.
- The recognition of the role of the WG on "Integration of Dense Velocity Fields into the ITRF" and the WG on "Deformation Models for Reference Frames" in the identification of problems and solutions when going from regional to global analysis, that is encouraged.
- The effort to bring together different types of institutions (R&D structures, National Mapping Agencies, political and economic agencies, etc.) to support and contribute to the activities related to the geospatial reference frames.
- The organizational and outreach aspects play a more and more important role and are crucial for the efficient achievement of results and their use by the geospatial community.
- The concern to develop education and training events, especially in less developed regions and countries. In this context, it's worth to mention the combined IAG, FIG and ICG workshop "Reference Frames in Practice" held in Rome prior to the FIG Working Week in May 2012. This effort must be continued and supported by the IAG.

The reports presented here reinforce the strategic decision to keep and develop this kind of regional organization within the IAG, since each region of the world has its own way to proceed, considering all the variables involved in this kind of work.

Sub-Commission 1.3a: Regional Reference Frame for Europe (EUREF)

Chair: Johannes Ihde (Germany)

Introduction

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

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

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

These activities are reported and discussed at the meetings of the EUREF Technical Working Group (TWG) and annual EUREF Symposia, an event that occurs every year since 1990, with an attendance of about 100-150 participants coming from more than 30 European countries and other continents, representing Universities, Research Centres and NMCA (National Mapping and Cadastre Agencies). The organization of the EUREF Symposia is supported by EuroGeographics, the consortium of the European National Mapping and Cadastral Agencies, reflecting the importance of EUREF for practical purposes.

The latest EUREF symposia took place in Saint-Mandé, France (2012) and in Budapest, Hungary (2013), Vilnius, Lithuania (2014), Leipzig, Germany (2015). Meetings of the EUREF Technical Working Group have been held three times a year. In addition a EUREF retreat was held in Nov. 2012 with the goal to review EUREF key themes and organizational structures and derive a plan to achieve the EUREF objectives for the next 4-8 years.

Members:

Z. Altamimi, E. Brockmann, C. Bruyninx (TWG chair), A. Caporali (EUREF secretary), R. Dach, J. Dousa, R. Fernandes, H. Habrich, J. Ihde (EUREF chair), A. Kenyeres, M. Lidberg, R. Pacione, M. Poutanen, K. Szafranek, W. Söhne, G. Stangl, J. Torres

In addition to the already existing partnerships with EUMETNET and EuroGeographics, EUREF and CERGOP (Central European GPS Geodynamic Network Consortium) signed a Memorandum of Understanding (MoU) at EUREF symposium at Chisinau, Moldova in 2011. The general goal of the MoU is to create the conditions to facilitate data exchange and promote the co-operation between EUREF and CERGOP in order to improve the densification of the European GNSS network for reference frame definition and geodynamical applications, and support the ECGN (European Combined Geodetic Network) project.

EUREF and EUPOS, a cooperation DGNSS service providers of RTK networks which densify the continental network EPN, agreed in 2014 a Memorandum of Understanding. Both parties, EUREF and EUPOS agreed that this general undertaking is related among other to:

- design of an interface between the European reference network EPN and the positioning services/networks of EUPOS members,
- realize a European Velocity Model for practical and scientific applications,
- working towards common standards and guidelines.

In 2014 a Knowledge Exchange Network (PosKEN) was installed. Partners are:

- EuroGeographics – representing national policy makers, namely NMCA's,
- CLGE – representing users of permanent GNSS networks for precise positioning, especially surveyors, a large group of users of GNSS precision applications,
- EUPOS and
- EUREF.

From the objectives and roles of all four organizations within the KEN, the following goals were identified for its initial operations:

- provide the European platform for networking and sharing best practice and expertise in the field of GNSS positioning
- aim at creating the uniform GNSS services for Europe, under the working name of European Positioning System
- develop common standards, policies and guidelines that require active contribution of experts in different fields
- show the commitment to working with other organizations where the members of each organization can benefit.

EUREF is an associated member of the International Committee on Global Navigation Satellite Systems (ICG) since 2009. The main ICG objective is to promote greater compatibility and interoperability among current and future providers of the Global Navigation Satellite Systems (GNSS). The annual ICG meetings review and discuss progress towards the realization of its main objective, as well as developments in GNSS where contributions from ICG members, associate members and GNSS user community are considered.

EUREF Permanent GNSS Network (EPN)

The EPN is the permanent GNSS network created by EUREF (Fig 1.3a.1). Its primary objective is to maintain and provide access to the ETRS89. The EUREF TWG is responsible for the general management of the EPN. The EPN Coordination Group and the EPN Central Bureau implement the operational policies of the EUREF TWG.

The EPN is based on a well-determined structure including GNSS tracking stations, operational centres, local and regional data centres, local analysis centres, combination centres and a Central Bureau (Bruyninx et al, 2011). These different EPN components (all based on voluntary contributions) follow specific guidelines set up by the EUREF TWG.

The EPN is the European densification of the International GNSS Service (IGS) network. Therefore, the EPN uses the same standards and exchange formats as the IGS.

More than 260 EPN stations are operated today by NMCA and other scientific and technical institutions. The number of sites that record GLONASS data simultaneously with GPS data is steadily increasing (70 %).

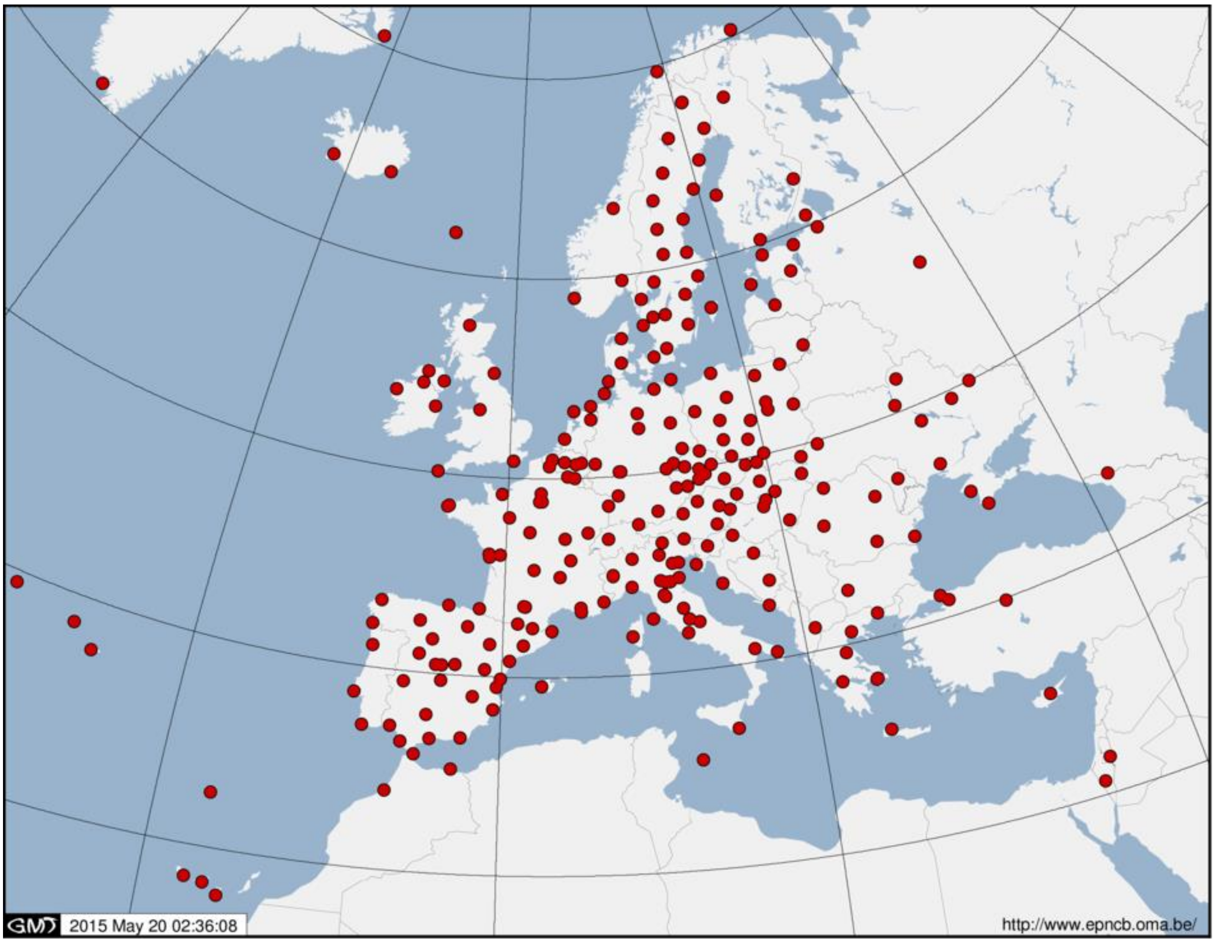

Figure 1.3a.1: EUREF Permanent GNSS Network (EPN), status May 2015

EPN reprocessing activities

Since the start of the EPN operations, its data are routinely analyzed by the EPN Local Analysis Centres in order to derive precise station coordinates and tropospheric zenith path delays. Throughout the years, the EPN has become more precise and reliable thanks to historical improvements of modeling parameters affecting the satellites (orbits, reference frame, and antenna calibration model), the propagation media (troposphere and ionosphere), the receiver units (e.g. elevation cut-off, antenna calibration model), geophysical phenomena (e.g. tidal forces, loading related to ocean, ground water and atmospheric pressure variations) and the reference frames. The EUREF TWG has therefore decided to reprocess all historical EPN data using present-day state-of-the-art models and to obtain improved and consistent coordinates, position time series and tropospheric parameters for each EPN site.

This first reprocessing (known as EPN-REPRO1) was done in 2011 for EPN observations gathered between Jan. 1996 and Jan. 2007. Different software packages, namely BERNESE, GIPSY/OASIS and GAMIT were used for the analysis (Habrich, 2011 and Völksen, 2011). The reprocessing was done using the epn_05.atx antenna calibration model, which is derived from the igs05.atx model. The reprocessed EPN results were used for weekly combined positions (in SINEX format) and tropospheric delays generated by the EPN Analysis Coordinator and EPN Troposphere Coordinator, respectively. At its fall meeting in Oct. 2011, the EUREF TWG endorsed the EPN-REPRO1 results and gave the green light to the EPN Reference Frame Coordinator for the generation of a new cumulative EPN position/velocity solution including the EPN-REPRO1 results.

Currently the EPN working group on Reprocessing conducts a second reprocessing campaign, EPN-Repro2 realized in the IGb08 and it is coordinated by the Bavarian Academy of Sciences and Humanities (BEK). The analysis is being carried out on the EPN data from 1996 till 2013 by five analysis centres. It will include three independent solutions obtained using Bernese 5.2, GAMIT 10.5 and GIPSY 6.2 for the entire EPN and the results of two EPN sub networks processed with Bernese 5.2. The analysis strategy is very much consistent with the recent LAC guidelines for the routine processing of the EPN. The processing of the data is performed as a regional network without orbit, EOP and clock parameter estimation and relies completely on available reprocessed products. Due to the lack of reprocessed combined IGS products (2nd IGS Reprocessing campaign), the reprocessed products provided by CODE and the preliminary reprocessed products by JPL are used.

In preparation of EPN-Repro2, a benchmark test with the different software packages, and based on the same data and network design, has shown good agreement between the different solutions (Völksen et al., 2014). The completion of the EPN-Repro2 daily solutions is expected for February 2014. First results of the combination of the different results will be presented at the next EUREF symposium in June 2015. The importance of the reprocessing activities has also been acknowledge by installing a Dedicated Analysis Centre (DAC) for Reprocessing at the Geodetic Observatory Pecny (GOP).

EUREF Densification of the ITRS

Using the EPN

Because the number of permanent GNSS tracking sites in Europe has grown considerably, only a selection of these sites (mostly those belonging to the IGS) are included in recent realizations of the ITRS. The latest realization of the ITRS, the ITRF2008, is based on observations from space geodetic techniques (GNSS, DORIS, VLBI, and SLR) up to December 2009.5 and does not take into account any of the IGS/EPN data gathered after that date. Consequently, it cannot reflect the most recent status of the EPN (due to e.g. antenna changes). The limited number of stations and the lack of frequent updates limit therefore the use of the ITRF for national densifications of the ETRS89.

The EUREF TWG decided at its meeting of Nov. 3-4, 2008 in Munich, to release regularly recomputed cumulative official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations. Using the 15-weekly updates of the EPN site coordinates, the EPN sites are classified in two classes:

- Class A stations with positions at 1 cm accuracy during the time span of the used observations (thanks to providing accurate station velocity estimates);
- Class B stations with positions at 1 cm accuracy at the epoch of minimal variance of each station.

Following the EUREF “Guidelines for EUREF Densifications” (Bruyninx et al., 2013), only Class A EPN stations can be used for EUREF densifications.

Table 1.3a.1 gives an overview of the weekly EPN SINEX files available for the computation of a new EPN cumulative position/velocity solution:

Table 1.3a.1: Overview of the weekly EPN SINEX files including the antenna calibration model used in the analysis.

Solution	GPS week Start / End	Antenna Calibration Model
EPN-REPRO1	835 / 1399	epn_05.atx
Routine	1400 / 1631	epn_05.atx
Routine	1632 / Now	epn_08.atx

In order to have a consistent set of weekly SINEX solutions, the EUREF TWG asked the ROB (Royal Observatory of Belgium, see Baire et al. 2011) to correct the solutions before week 1632 to make them consistent with the epn_08.atx antenna calibration model. Using these corrected SINEX files, complemented with the present-day EPN weekly SINEX files, a new cumulative EPN position/velocity solution has been created and tied to the IGS08/IGb08 reference frame (see Kenyeres, 2011; Kenyeres, 2012). The computations were done using the CATREF software (Altamimi et al., 2007) and are again updated each 15-weeks. The resulting station coordinates are available from http://www.epncb.oma.be/_productsservices/ coordinates/. Figure 1.3a.2 shows the map of Class A and Class B stations outcome of the latest cumulative EPN solution.

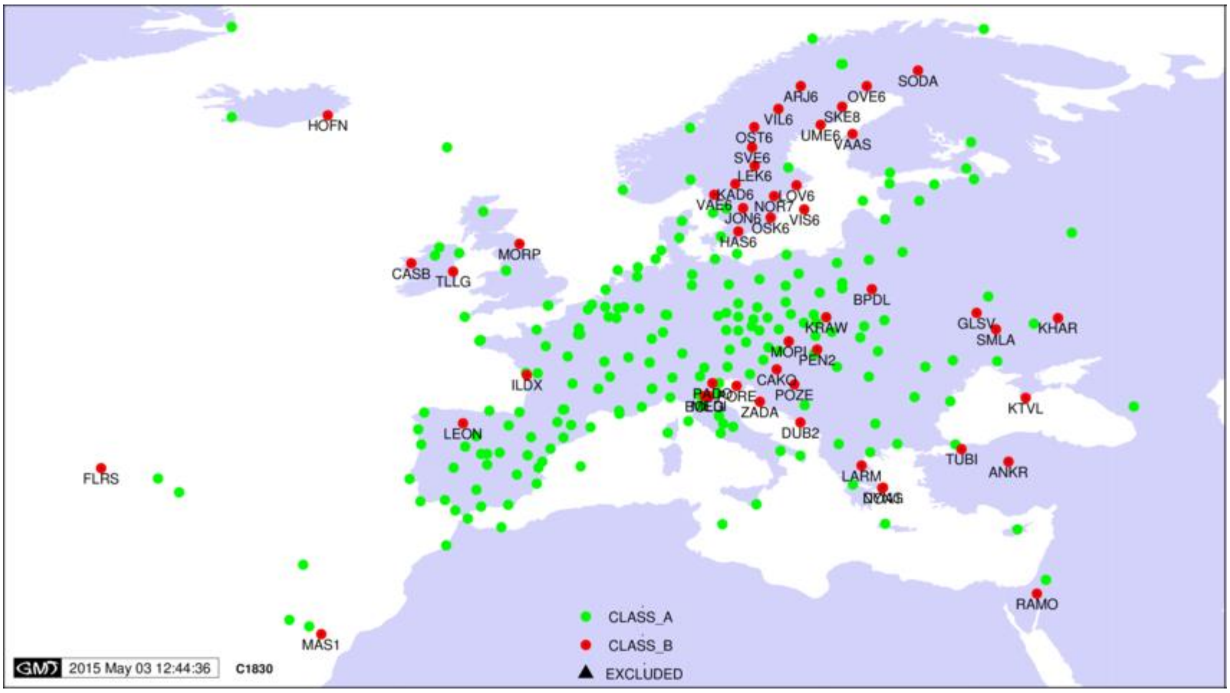

Figure 1.3a.2: EPN site categorization, status May 2015. In green: Class A stations; in red: class B stations.

Using the National GNSS Densification Networks

Many European countries operate national dense GNSS networks, whose stations are not all included in the EPN. In order to take advantage of these data for creating a dense European velocity field, EUREF invited these countries to routinely analyze these data following EUREF guidelines and to submit the weekly positions to EUREF. Several countries (Austria, Bulgaria, Czech Republic, Estonia, France, Germany, Hungary, Italy, Latvia, Poland, , Slovakia, Spain, , and UK) responded positively and provide now weekly SINEX solutions to the EPN Reference Frame Coordinator who combines these solutions with the weekly EPN solution and then stacks them to get consistent cumulative position/velocity solutions for the resulting densified EPN network (containing today already about a 2500 sites). Thanks to EUREF's Memorandum of Understanding with CERGN, also a CERGN solution (bi-annual campaigns) was submitted. This work is still in progress (see Kenyeres et al, 2012) and it will be an important input for the new EUREF Working Group on "Deformation Modelling" (see below).

Using Densification Campaigns

EUREF continued the validation of national GNSS campaigns. A report including the necessary information about the measurements, the processing and the validation of the results is delivered to the TWG. After successful evaluation by the TWG the following projects were accepted by the plenary as EUREF densification campaign between 2011, and 2015: "EUREF Serbia 2010" (Serbia), "EUREF-MAKPOS 2010" (Macedonia), "EUREF Faroe Islands 2007" (Faroe Islands), "EUREF BE 2011" (Belgium) , "EUREF Poland 2015" and "Central European Geodynamic Research Network (CERGN)".

EPN Real-time Analysis Project

The EPN Project on "Real-time Analysis" (http://epncb.oma.be/_organisation/projects /RT_ analysis) focuses on the processing of the EPN real-time data to derive and disseminate real-time GNSS products.

The EPN regional broadcaster at BKG (Federal Agency for Cartography and Geodesy, http:// www.euref-ip.net) is broadcasting satellite orbits in the ETRS89 (realization ETRF2000). Based on these orbit and clock corrections, users can directly derive real-time coordinates referred to ETRS89 at few dm-level (Fig. 1.3a.3; more details are given in Söhne, 2011). Additional solutions for other regional datums, e.g. for SIRGAS95 or SIRGAS 2000, are implemented and could be found at http://products.igs-ip.net.

One aim of the project is to increase the reliability of the EPN real-time data flow and to minimize the possibility of data and products outage. For this purpose, two additional regional broadcasters have been put in operation, one at ASI (Italian Space Agency, http://euref-ip.asi.it/) and one at ROB (http://www.euref-ip.be/). Based on the existence of three regional broadcasters, several stations and national broadcasters started uploading their data in parallel to all of the broadcasters.

To ensure the product generation without interruption and without jumps, it is necessary to have a back-up processing running in an identical environment. This scheme could be implemented on a second computer at the same facility or, to overcome problems at the facility itself, at another place. In case of an outage in the production scheme at the master facility the broadcaster will switch to the backup solution using the same source table entry (mount point). Therefore the user will notice neither any interruption nor any change in the origin of the streamed data.

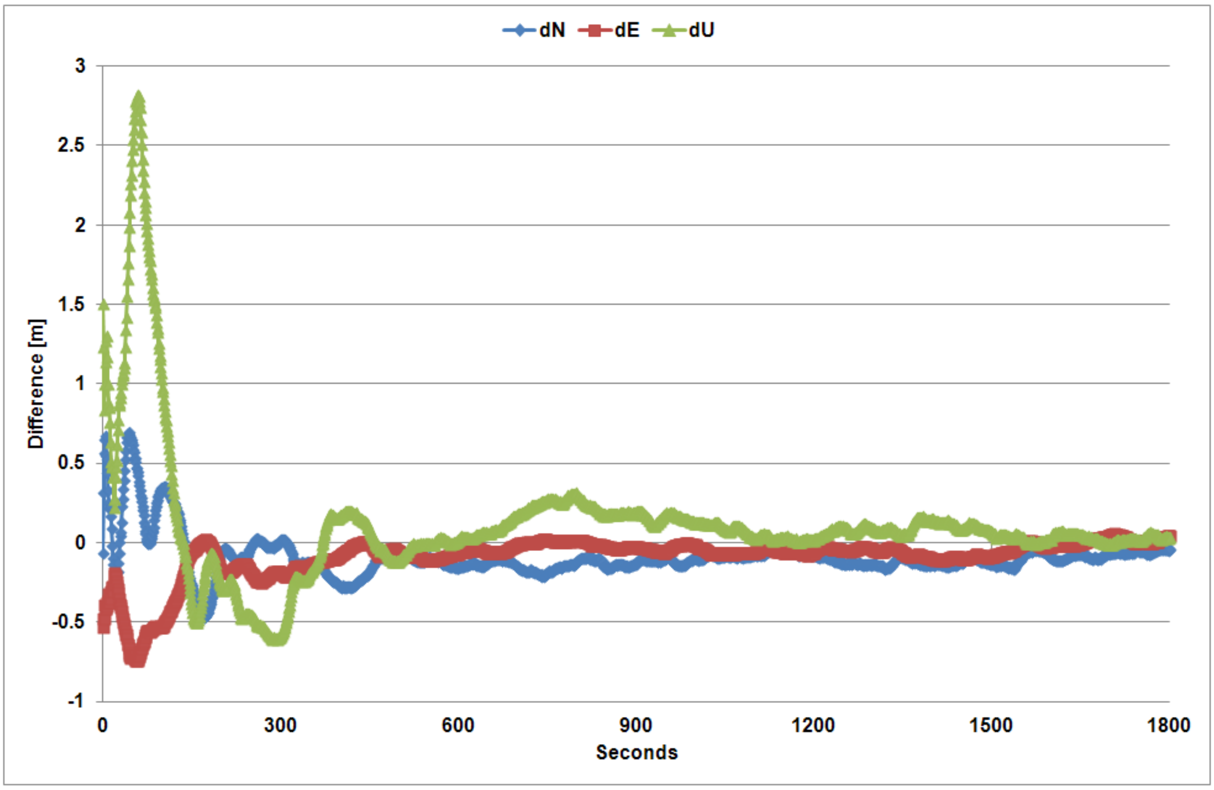

Figure 1.3a.3: Differences of real-time coordinates using the BKG Ntrip Client (BNC) with ETRS89-related satellite and orbit corrections for station ZIM2 w.r.t. the ETRS89 coordinates

While for the first step of the estimation of parameter corrections, i.e. satellite orbits and clocks, a globally distributed network (50-60 stations) is sufficient, any further steps, e.g. improved ambiguity fixing, ionosphere and troposphere corrections which go for an improved accuracy of the real-time Precise Point Positioning (PPP), require a denser network of real-time stations like the EPN or SIRGAS could provide.

New EUREF Working Groups

Multi-GNSS Working Group

In 2012 the EUREF TWG set up a new Working Group on "Multi GNSS". As written above, a number of station managers provide GNSS signals on top of the GPS and GLONASS L1 and L2 signals. Before introducing Galileo, BeiDou or new GPS signals into EPN routine operation they must be carefully checked. One goal of the WG is to test and evaluate the new formats (RINEX 3, RTCM Multi Signal Messages) on content and data quality. New processing techniques have to be used or even developed for analysis of the new signals. Finally, recommendations must be prepared which of the new signals should be declared as mandatory for further use within the EPN. EUREF members are actively contributing to the development of quality check software by developing and using two software packages: G-Nut/Anubis [1.2.1] (Vaclavovic and Dousa, 2015) and BNC [2.12] (Weber and Mervart, 2009). Both allow useful operations such as RINEX header manipulation and the generation of data quality statistics. The EPN Central Bureau today already routinely cross-checks the

RINEX v3 headers against the site log information (similarly to what is done for the RINEX v2 data) and also verifies the conformity of the RINEX v3 headers w.r.t. to the RINEX v3 format description. Station managers are notified in case errors occur.

Deformation Modeling Working Group

In 2012 the EUREF TWG set up a new Working Group on "Deformation Models". The objective of this WG is to create a crustal deformation model for Europe to 1) improve the knowledge of surface deformations in Eurasia and adjacent areas and 2) manage and use the national realizations of the ETRS89 by studying the behaviour of geodetic reference frames in the presence of crustal deformations. The Working Group aims at making more precise the concept of 'Stable part of Europe' underlying the definition of ETRS89. At the mm/yr level, areas of departure from the rigid rotation model of ITRS velocities about an Eurasian Eulerian pole are clearly visible in the Mediterranean area (Greece, Southern Italy, for example). Vertical motion due to Glacial Isostatic Adjustment (GIA) is clearly observed in the Fenno-scandia, causing the vertical datum to be accordingly adjusted periodically. The Working Group attempts a geophysical understanding of the non-rigid behaviour of the European crust, with the objective to monitor the evolution of the deformation of national coordinate grids caused by geophysical phenomena, and predict when the deformation exceeds a certain tolerance. When this occurs, the NMCA's are recommended to generate an update of the National realization of the ETRS89 and/or EVRS.

EPN Densification Working Group

The EPN Densification Working Group was created in the beginning of June 2015.

The primary goal of the EPN Densification is to realize a continental-scale (European), homogeneous, high quality position and velocity product in an homogeneous reference frame, for a very dense network of GNSS stations, and this with comparable quality from Greenland to Crete, from Svalbard to Gran Canarias.

Consequently, the EPN Densification is a joint venture of agencies and institutions from European countries which operate and/or analyse the data from dense national GNSS networks (in addition to their EPN stations) and are willing to submit the results of their data analysis (daily or weekly position SINEX files) routinely to EUREF.

To achieve its goal, the EPN Densification combines the national GNSS networks on the product level (daily or weekly position SINEX files) with the multi-year positions & velocities of the EPN stations and express them homogeneously in the ITRS/ETRS89 with the EPN as the backbone. Additionally, to support the station managers and guarantee the reliability of the combination, the station metadata (station naming, site logs) of the participating densification stations will maintained, cross-checked, harmonized and centrally managed by EUREF to avoid inconsistencies.

The EPN Densification products shall be used - in close cooperation with the EUREF Deformation Models Working Group - to support the ETRS89 realization not only over the stable part of Europe, but also over tectonically deforming areas like the Mediterranean region. The velocity product will be useful for general and specific tectonic studies, supporting the better understanding of the processes at deforming regions.

The EPN Densification will exploit the huge potential lying in these active GNSS networks both for geodesy and earth sciences. All the activities of the EPN densification require efficient cooperation between the data suppliers (e.g. NMCAs) and the geophysical community. Beside the well built structure and communication channels of the EPN, a close cooperation with other communities such as EPOS is foreseen.

European Vertical Reference System (EVRS)

In 1994 the IAG Sub-commission for Europe (EUREF) started the work on the Unified European Leveling Network (UELN) and resumed and enhanced previous projects, which existed in the Western and Eastern part of Europe separately. A European Vertical Reference System (EVRS) was defined in 2000 and the associated realization was named EVRF2000.

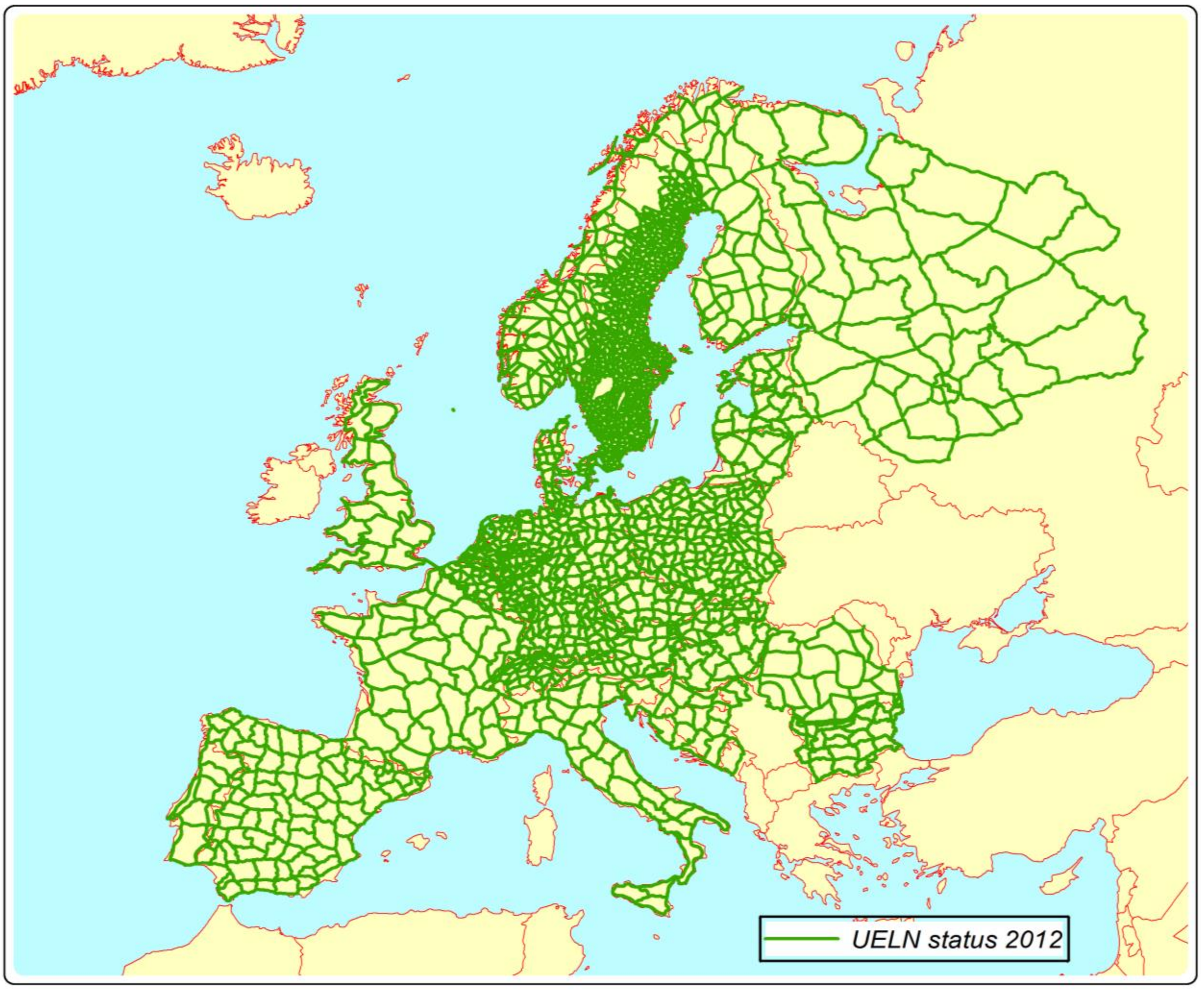

Figure 1.3a.4: EVRF2007 including extensions

During the following years about 50 % of the participating countries provided new national leveling data to the UELN data centre. Therefore a new realization of the EVRS was computed and published under the name EVRF2007. The datum of EVRF2007 is realized by 13 datum points distributed evenly over the stable part of Europe. The measurements have been reduced to the common epoch 2000 by applying corrections for the glacial isostatic adjustment (land uplift) in Fenno-Scandinavia, which are provided by the Nordic Geodetic Commission (NKG). The results of the adjustment are given in geopotential numbers and normal heights, which are reduced to the zero tidal system. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was approved proposing to the European Commission the adoption of the EVRF2007 (Figure 1.3a.4) as the mandatory vertical reference for pan-European geo-information.

The availability of EVRF2007 forced an update of the Geodetic Information and Service System. Transformation parameters between national height systems and EVRF2007 were estimated and are provided at http://www.crs-geo.eu/ since April 2010. Furthermore the transformation parameters to EVRF2000 are available. Additionally the online-transformation for heights of single points was implemented.

In the meantime, the UELN is continuously enhanced using additional or updated levelling data submitted by different countries. EUREF received in 2009 the European part of first order leveling network of Russia. Together with connection measurements between the national networks of Finland and Russia is was possible to close the loop around the Baltic Sea and strengthen the adjustment process. In addition, the new first order leveling data of Latvia (2011), and Spain (2012) were received by EUREF. For the next years Belarus and Ukraine announced to provide their levelling data and join the UELN. A new UELN adjustment will be computed after receiving the new data.

Promotion and Adoption of the ETRS89 and EVRS

Since 1989, many European countries have defined their national reference frames in ETRS89 by calculating national ETRS89 coordinates following the EUREF guidelines. The difference of the ETRS89 coordinates adopted in each country for a set of EPN stations with respect to the ETRS89 coordinates recently estimated by the EPN is now monitored on a regular basis by EUREF (Brockmann, 2010). These national ETRS89 coordinates can differ from the latest cumulative EPN coordinates due to e.g. differences in datum definition (different ETRFyy frames) and differences in used observation periods.

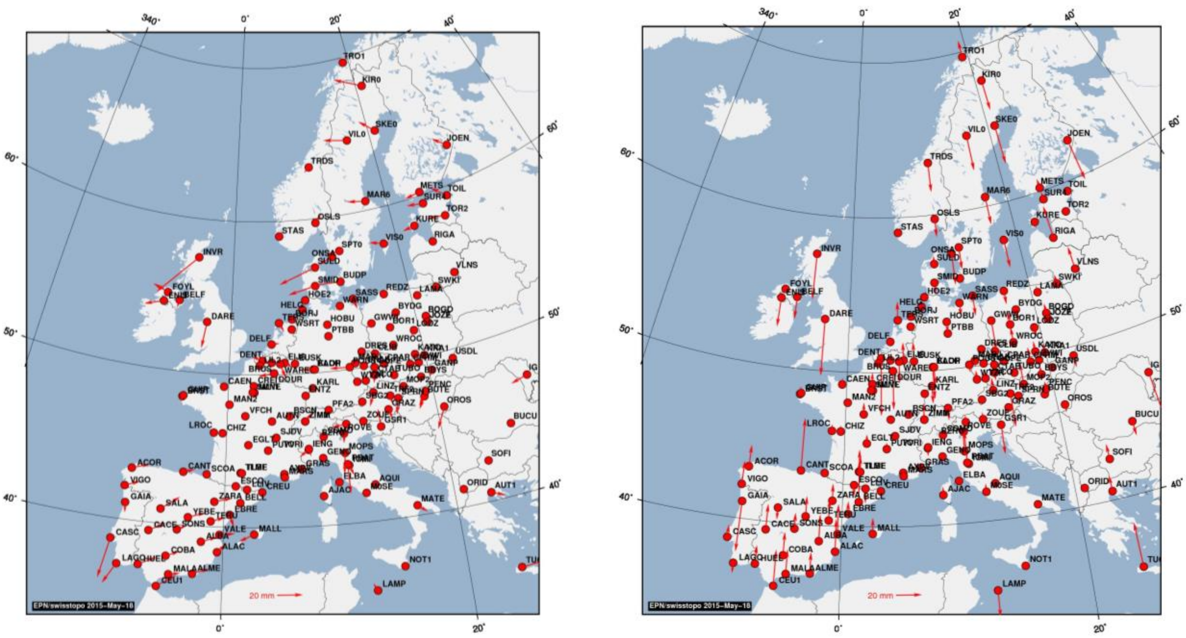

Figure 1.3a.5: Difference between official ETRS89 coordinates adopted in the different countries and the latest EPN cumulative coordinate solution

The results of the comparison show an agreement of a few cm (see Figure 1.3a.5). In addition, EUREF recently provid ed a new questionnaire to the NMCA on the utilization of the ETRS89 and EUREF products in their country and the first results were presented by Ihde et al. (2011). Up to now, 60% of the contacted countries replied to the questionnaire. About 85% stated that they adopted the ETRS89 in their country while other 10% were still working on this issue.

INSPIRE (Infrastructure for Spatial Information in Europe) was adopted in March 2007 by the Directive 2007/2/EC of the European Parliament and the Council. The goal of INSPIRE is to deliver an interoperable and integrated European spatial information service to users from different communities. The INSPIRE Directive addresses 34 spatial data themes needed for environmental applications, with key components specified through technical implementing rules. “Coordinate Reference Systems” (CRS) is one of the important themes. It establishes the geographical reference for many other themes. This makes INSPIRE a unique example of a legislative “regional” approach.

To ensure that the spatial data infrastructures of the member states are compatible and usable in a trans-boundary context, the Directive requires that common Implementing Rules (IR) are defined and applied in a number of specific areas (metadata, data specifications, network services, data and service sharing and monitoring and reporting).

These IRs are adopted as Commission decisions or regulations and are binding in their entirety. The Commission is assisted in this process by a regulatory committee composed of representatives of the member states and chaired by a representative of the Commission (known as the comitology procedure). Thanks to the efforts of the EUREF TWG, the ETRS89 and the EVRS, defined by EUREF, play now a fundamental role in the CRS IR.

The descriptions of national and pan-European geodetic reference systems are available by a Service System for European Coordinate Reference Systems (CRS). Transformation parameters between national geodetic reference systems and the European ETRS89 and EVRF2007 were calculated and provided. Additionally, an online-transformation capability for coordinates and heights of single points is implemented.

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

Chair: Claudio Brunini (Argentina)
Vice-chair: Laura Sánchez (Germany)

Structure

- SC1.3b-Working Group I: Reference system, *chair: Virginia Mackern (Argentina)*
- SC1.3b-Working Group II: SIRGAS at national level, *chair: William Martínez (Colombia)*
- SC1.3b-Working Group III: Vertical datum, *chair: Sílvio R. de Freitas (Brazil)*

Overview

The IAG Sub-commission 1.3b (South and Central America) encompasses the activities developed by the "Geocentric Reference System for the Americas" (SIRGAS). Its main objective is the definition, realization and maintenance of a state-of-the-art geodetic reference frame in Latin America and the Caribbean, including both, the geometrical and physical components. The present SIRGAS activities concentrate on:

- Maintenance and improvement of the ITRF densification in the SIRGAS Region;
- Contribution to the IGS through the operation of the IGS–RNAAC–SIR;
- Definition and realization of a gravity field-related vertical reference system in Latin America and the Caribbean;
- Promotion, coordination and support of national activities oriented to the use of SIRGAS as official reference frame in the individual countries;
- Measuring and modelling non-linear changes in the position of the reference stations;
- Monitoring vertical movements of tide gauges with GNSS;
- Expanding SIRGAS capabilities for real time GNSS positioning;
- Monitoring the ionosphere and neutral atmosphere with GNSS;
- Supporting the initiatives of the Regional Committee of the United Nations Global Geospatial Information Management for the Americas (UN-GGIM: Americas);
- Organizing and developing capacity building activities;
- Outreach through focused symposia, conferences, lectures, and articles.

In addition to be a Sub-commission of the IAG Commission 1, SIRGAS is at the same time a Working Group of the Cartographic Commission of the Pan American Institute for Geography and History (PAIGH). The linkage with the IAG ensures compliance with the policies of the Association and facilitates the access of the region to the IAG components. The interaction with PAIGH ensures agreement with the targets of the "2013-2015 Action Plan to Expedite the Development of Spatial Data Infrastructure of the Americas" that SIRGAS signed with PAIGH and other Pan American organizations in November 2012[1]. Thanks to the common work with the IAG and the PAIGH, 14 countries in the region have already adopted SIRGAS as the official reference frame for Geodesy and Cartography, according to the recommendation issued in 2001 by the "United Nations Cartographic Conference for the Americas" (New York, USA, January 22-26, 2001).

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[1] Borrero S., Brunini C., Fortes L. and Van Prag E. (2013): 2013-2015 PAIGH, SIRGAS, PC-IDEA, GeoSUR Joint Action Plan to Expedite the Development of Spatial Data Infrastructure of the Americas. PAIGH, Mexico City (www.ipgh.org/Iniciativas/JointActionPlan.pdf).

At present, more than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership. The main body of the organization is a Directing Council composed by one representative of each member country, one of IAG and one of PAIGH. This Council states the fundamental policies whose accomplishment is under the responsibility of an Executive Committee and the corresponding activities are conducted by the three working groups described in the following.

SC1.3b-WGI: Reference System

This WG is responsible for the analysis of the SIRGAS Reference Frame. This frame is composed by ca. 400 continuously operating GNSS stations, from this stations 235 track GLONASS, 16 GALILEO and 2 BEIDOU. The SIRGAS Reference Frame includes 58 formal IGS stations; however, in order to improve the distribution of the ITRF sites in this region, 40 additional SIRGAS stations are being processed by the IGS Global Analysis Centres since January 2012 and they are also included in the IGS Reprocessing 2. GNSS data are produced, archived, and processed according to the IERS and IGS standards and conventions to generate:

- Loosely constrained weekly solutions as input for the computation of cumulative (multi-year) solutions and to be integrated into the IGS polyhedron;
- Weekly station positions aligned to the ITRF to be used as reference for surveying applications in Latin America;
- Multi-year solutions with station positions for a given epoch and constant velocities to model the kinematics of the reference frame.

Since more and more Latin American countries are qualifying their national reference frames by installing GNSS continuously operating stations and these stations shall be consistently integrated into the continental reference frame, the SIRGAS-CON network comprises: (1) One core network (SIRGAS-C), primary densification of ITRF in Latin America, with a good continental coverage and stabile site locations to ensure high long-term stability of the reference frame; and (2) National reference networks (SIRGAS-N) improving the densification of the core network and providing accessibility to the reference frame at national and local levels. Both, the core network and the national networks satisfy the same characteristics and quality; and each station is processed by three analysis centres.

The SIRGAS-C network is processed by the IGS-RNAAC-SIR (i.e. DGFI-TUM, Germany). The SIRGAS-N national networks are computed by the SIRGAS Local Processing Centres: CEPGE (Ecuador), CNPDG-UNA (Costa Rica), CPAGS-LUZ (Venezuela), IBGE (Brazil), IGAC (Colombia), IGM-Cl (Chile), IGN-Ar (Argentina), INEGI (Mexico), and SGM-Uy (Uruguay). These processing centres deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. The processing strategy guarantees that each regional SIRGAS-CON station is included in three individual solutions. The SIRGAS Combination Centres are IBGE and the IGS-RNAAC-SIR (DGFI-TUM). INEGI and IGN use the GAMIT/GLOBK software[2], while the others use the Bernese GNSS Software V. 5.2[3]. The accuracy of the final SIRGAS coordinates is estimated to be ±2,0 mm in the North and the East, and ±4,0 mm in the height. All Analysis Centres follow unified standards for the computation of the loosely constrained solutions. These standards are based in general

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[2] Herring T.A., King R.W. and McClusky S.C. (2010): Introduction to GAMIT/GLOBK. Department of Earth, Atmospheric and Planetary Sciences, MIT (www-gpsg.mit.edu/~simon/gtgk/index.htm).

[3] Dach R., Hugentobler U., Fridez P. and Meindl M. (Eds.) (2007): Bernese GPS Software Version 5.0 Documentation. Astronomical Institute, University of Berne (www.bernese.unibe.ch/).

on the conventions outlined by the IERS and the GNSS-specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits, satellite clock offsets, and Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters).

To estimate the kinematics of the SIRGAS reference frame, a cumulative (multi-year) solution is computed (updated) every year, providing epoch positions and constant velocities for stations operating longer than two years; stations active during shorter time spans are omitted from the cumulative solutions. The coordinates of the multi-year solutions refer to the latest available IGS reference frame and to a common reference epoch, e.g., the most recent released SIRGAS multi-year solution SIR11P01 refers to IGS08 (ITRF2008), epoch 2005.0. It includes weekly normal equations from January 2, 2000 to April 16, 2011 for 230 stations with 269 occupations. Its averaged rms precision is estimated to be ±1,0 mm horizontally and ±2,4 mm vertically for the station positions at the reference epoch, and ±0,7 mm/yr horizontally and ±1,1 mm/yr vertically for the constant velocities.

Because the switch to the ITRF2008 (i.e. IGS08/IGb08) for the generation of the IGS products caused a discontinuity of some millimetres in the station position time series, the computation of multi-year solutions for the SIRGAS reference frame was discontinued until getting weekly normal equations referenced to the IGS08/IGb08 and covering a time span of at least three years. The two recently computed multi-year solutions SIR13P01 and SIR14P01 cover the period starting in April 2010, after the big earthquake in Chile. The main objective of these solutions is to identify and to model secular effects in the kinematics of the SIRGAS reference frame caused by that earthquake. At present, the entire SIRGAS network is being reprocessed from January 1997 using the latest IERS/IGS procedures and standards.

The loosely constrained weekly solutions as well as the weekly SIRGAS station positions and the multi-year solutions are available at ftp://ftp.sirgas.org/pub/gps/SIRGAS/ or at www.sirgas.org.

SC1.3b-WGII: SIRGAS at national level

After the determination of the first SIRGAS realisation in 1995, the South American countries concentrated on the modernization of their local geodetic datums through national densifications of the continental network and the determination of transformation parameters to migrate the existing geo-data from the old reference systems to SIRGAS. At the beginning, these densifications were realized by passive networks (i.e. pillars); today, most of the countries are installing continuously operating GNSS stations, which serve not only as local reference frame, but also as referential for daily applications based on satellite navigation and positioning. From 2000, the Central American countries started also to face these activities. The current undertakings of the SC1.3b-WGII concentrate on:

- Coordinating the SIRGAS activities to support the initiatives of the Regional Committee of the United Nations Global Geospatial Information Management for the Americas (UN-GGIM: Americas); especially the divulgation and practical adoption of the Resolution on the Global Geodetic Reference Frame for Sustainable Development released by the General Assembly of the United Nations at 26th of February, 2015.
- Supporting those countries interested on adopting SIRGAS as official reference frame. It includes advice on the establishment and processing of national GNSS reference networks, determination of transformation parameters between the classical geodetic datums and SIRGAS, alignment of the existing geo-data into SIRGAS, and generation of documents of

guidance to orientate local users approaching SIRGAS. During the last two years, significant advances were achieved in Bolivia, Costa Rica, Guatemala, and Honduras.
- Promoting the availability of the SIRGAS Reference Frame in real time by improving the transfer facilities at the reference stations and by installing a service called "Experimental SIRGAS Caster"[4]. Argentina, Brazil, Chile, Colombia, Uruguay, and Venezuela report major advances in this field.
- Coordinating local GNSS campaigns on passive points (where no continuously operating stations exist) to increase the availability of epoch station positions to detect deformations of the reference frame, especially in those areas affected by earthquakes (Argentina, Chile, Colombia, Costa Rica, Honduras, Guatemala, México, Peru, and Venezuela).

SC1.3b-WGIII: Vertical datum

Through this WG, SIRGAS is committed to the definition and realization (and further maintenance) of a gravity field-related vertical reference system in Latin America and the Caribbean, following the advice of the IAG Joint Working Group 0.1.1 on Vertical Datum Standardization. On-going tasks include
- Continental adjustment of the first order vertical networks in terms of geopotential numbers referred to a common W_0 value;
- Determination of a unified (quasi)geoid model for the region (under the responsibility of the IAG SC 2.4b, 'Gravity and Geoid in South America');
- Transformation (unifications) of the existing height systems into the new one.

Great efforts have been dedicated, and have still to be dedicated, to
- The collection and validation of the existing databases containing levelling and gravity data as well as tide gauge registrations;
- Transcription of old field notebooks to digital format;
- Levelling field works to connect the fundamental points of the vertical networks with the SIRGAS reference stations and with the main national tide gauges;
- More levelling connections between neighbouring countries.

Outreach and capacity building activities

- **SIRGAS 2011 General Meeting:** Heredia, Costa Rica, August 8 - 10, 2011. Hosted by the Universidad Nacional and attended by 116 participants from 17 countries.
- **SIRGAS 2012 General Meeting and technical visit to the Geodetic Observatory TIGO**: Concepción, Chile, October 29 - 31, 2012. Hosted by the Universidad de Concepción and the Instituto Geográfico Militar of Chile and attended by 135 participants from 15 countries.
- **SIRGAS 2013 General Meeting and celebration of the 20th anniversary of SIRGAS**: Panama City, October 24 - 26, 2013. Hosted by the Instituto Geográfico Nacional "Tommy Guardia" and attended by 184 participants from 28 countries.
- **Symposium SIRGAS 2014**: La Paz, Bolivia, November 24 - 26, 2014. Hosted by the Instituto Geográfico Militar and attended by 260 participants from 19 countries.

[4] This caster is hosted by the Universidad Nacional de Rosario, Argentina (www.fceia.unr.edu.ar/gps/caster).

- **Second workshop of the SIRGAS-WGIII (Vertical Datum).** Rio de Janeiro, Brazil. December 3 - 9, 2012. Hosted by the Instituto Brasileiro de Geografia e Estatística and attended by 11 participants from 9 countries.
- **Third workshop of the SIRGAS-WGIII (Vertical Datum).** Curitiba, Brazil. May 18 - 22, 2015. Hosted by the Universidade Federal do Paraná and attended by 30 participants from 9 countries.
- **Third SIRGAS/IAG/PAIGH School on Geodetic Reference Systems**: it took place together with the SIRGAS 2011 General Meeting in August 3-5, 2011 in Heredia, Costa Rica. It was attended by 116 participants from 17 countries.
- **Fourth SIRGAS/IAG/PAIGH School was devoted to the Real Time GNSS Positioning** and was carried out between October 24 and 26, 2012. It was hosted by the Universidad de Concepción and the Instituto Geográfico Militar of Chile and was attended by 50 colleagues from 16 countries. This School was possible thanks to the support of the Federal Agency for Cartography and Geodesy (BKG) of Germany.
- The **fifth SIRGAS School** was named **School on Reference Systems, Crustal Deformation and Ionosphere Monitoring**. It was a capacity building activity of the project **Monitoring crustal deformation and the ionosphere by GPS in the Caribbean**, which was supported by the IUGG, IAG (International Association of Geodesy), the IASPEI (International Association of Seismology and Physics of the Earth's Interior), and the IAGA (International Association of Geomagnetism and Aeronomy). The main objective of this project was to invite the Caribbean countries to participate actively in geodetic and geophysical initiatives going on in the Central and South American region, in order to enable the use the acquired data for practice and science in their countries, and to promote geosciences. The School was hosted by the Instituto Geográfico Nacional "Tommy Guardia" in Panama City, Panama, from October 21 to 23, 2013 and it was attended 145 participants from 28 countries.
- The **sixth SIRGAS** School was concentrated on **Vertical Reference Systems**. This school was hosted by the Bolivian Instituto Geográfico Militar and Escuela Militar de Ingenería in La Paz, Bolivia, from November 20 to 23, 2014 and it was attended 34 participants from 13 countries.
- **Capacity building on Geodetic Reference Systems** in Santiago de Chile, Chile, between September 26 and 30, 2011. It was organized by the Instuto Geográfico Militar of Chile with the support of the DGFI-TUM (Germany) and the IAG. It was attended by 120 Chileans.
- **Training courses on precise GNSS data processing**. This activity is possible thanks to the agreement between the University of Bern and the DGFI-TUM to provide with the Bernese Software Latin American institutions intending to establish a SIRGAS Analysis Centre. In this period, three courses were carried out:
  - Instituto Geográfico Militar of Chile, Santiago de Chile, Chile, between September 26 and 30, 2011. 5 attendants.
  - Escuela de Topografía, Catastro y Geodesia, Universidad Nacional, Heredia, Costa Rica from December 3 to December 7, 2012. 15 attendants.
  - Instituto Geográfico Militar of Bolivia, La Paz, Bolivia, between May 27 and 31, 2013. 15 attendants.
- Participation in the following meetings:
  - IUGG General Assembly. Melbourne, Australia. June 2011.
  - Latin American Geospatial Forum. Rio de Janeiro, Brazil. August 2011.

- VII Colóquio Brasileiro de Ciências Geodésicas, Sessão Especial sobre a Rede Vertical Brasileira. Curitiba. Brasil. September 2011.
- Curso avanzado de posicionamiento por satélites. Madrid, Spain. October 2011.
- International Symposium on Global Navigation Satellite Systems, Space-Based and Ground-Based Augmentation Systems and Applications. Berlin, Germany. October 2011.
- Jornada técnica acerca del Marco de Referencia Vertical de Argentina. Rosario, Argentina. November 2011.
- STSE-GOCE+Height System Unification Progress Meeting 2, Frankfurt am Main, Germany. December 2011.
- XI Congreso Nacional y VIII Latinoamericano de Agrimensura. Villa Carlos Paz, Argentina. May 2012.
- Congreso Internacional Geomática Andina 2012. Bogota, Colombia. June 2012.
- IGS Workshop 2012. Olsztyn, Poland. July 2012.
- AOGS-AGU (WPGM) Joint Assembly. Singapore. August 2012.
- XII Congreso Internacional de Topografía, Catastro, Geodesia y Geomática. San Jose, Costa Rica. September 2012.
- 8th FIG Regional Conference. Montevideo, Uruguay. November 2012.
- AGU Meeting of the Americas. Cancun, Mexico. May 2013.
- 10th United Nations Regional Cartographic Conference for the Americas. New York, USA. August 2013.
- Scientific Assembly of the International Association of Geodesy, IAG2013. Potsdam, Germany. September 2013.
- Semana Geomática Internacional 2013. Instituto Geográfico Aguatín Codazzi. Bogotá, Colombia. September 2013.
- Reunión de Consulta de la Comisión de Cartografía del IPGH, Montevideo, Uruguay. November 2013.
- Primer encuentro de investigadores de agrimensura, UMAZA-UNL. Mendoza, Argentina. June 2014.
- IGS Workshop 2014, Pasadena, California, USA. June 2014.
- 3rd International Gravity Field Service (IGFS) General Assembly. Shanghai, China. July 2014.
- International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH 2014). Matsushima, Miyagi, Japan. July 2014.
- Latin America Gesopatial Forum 2014. Mexico City, Mexico. September 2014.
- Jornadas nacionales de agrimensura, geomática y catastro. Santiago del Estero, Argentina. October 2014.
- EGU General Assembly. Vienna, Austria. April 2015

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The operational infrastructure and results described in this report are possible thanks to the active participation of many Latin American and Caribbean colleagues, who not only make the measurements of the stations available, but also operate SIRGAS Analysis Centres processing the observational data on a routine basis. This support and that provided by the International Association of Geodesy (IAG) and the Pan-American Institute for Geography and History (PAIGH) is highly appreciated.

More details about the activities and new challenges of SIRGAS, as well as institutions and colleagues working on can be found at www.sirgas.org.

Sub-Commission 1.3c: Regional Reference Frame for North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Neil Weston (USA)

Introduction

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

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

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

The following summarizes the activities of each working group. For more information and publications related to these working groups, see the regional Sub-Commission web site at <http://www.naref.org/>.

The regional sub-commission is co-chaired by representatives from the Canadian Geodetic Survey and the U.S. National Geodetic Survey, currently Dr. Michael Craymer and Dr. Neil Weston, respectively. Dr. Weston replaced Dr. Jake Griffiths as the U.S. co-chair in 2013.

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

The objective of this working group is to densify the ITRF and IGS global networks in the North American region. Meetings of the working group were held in 2011, 2012 and 2013 during the AGU Fall Meetings in San Francisco.

Originally, the regional densification of the ITRF and IGS network consisted of weekly combinations of different regional weekly solutions across the entire North American continent using different GPS processing software. Contributors and some details of their solutions are given in the Table 1.3c.1 (below). In addition to these contributions, NRCan plans to implement PPP solutions for the same set of stations in their Bernese contribution. This will provide redundant solutions for all NRCan stations.

Table 1.3c.1: Current NAREF weekly regional contributions

Contributor	Software	Region	No. Stations
NGS	PAGES	USA & territories (CORS network)	1853
Scripps	GAMIT	North America	1291
MIT	GIPSY+Bernese Combination	Western North America	1373
NRCan	Bernese	Canada, Greenland & northern USA	485
INEGI	GAMIT	Mexico	44

Not all stations in the Scripps and MIT solutions are being used because of the very high density of sites in southern California and some local areas of the Plate Boundary Observatory network. Presently, only those stations in the U.S. common with the NGS CORS solution will be included in the combinations.

Because of the increasing number of stations and the expected imminent generation of IGS repro2 orbits, no weekly combinations have been performed since GPS week 1583 due to the limitations of the SINEX combination software at that time. An enhanced version of the software has been development by NRCan to handle thousands of stations with greatly improved processing efficiency. The first version of the software has just been released. It I planned to attempt to restart the weekly NAREF combinations in the near future.

In the meantime, NGS has computed a multi-year solution of the CORS network covering the US, Mexico and Caribbean region, in addition to a set of global reference frame sites (see Fig. 1.3c1). This solution used data up to GPS week 1631, repro1 and IGS05 products. The solution was aligned to IGS08 and corrected for IGS08 antenna calibrations. A similar solution was also computed by CGS covering the northern have of North America, including Greenland (see Fig. 1.3c2). This solution was based on weekly solutions using data up to GPS week 1631 and the Bernese GPS Software 5.0. Because of the sparse permanent GNSS network in Canada, the solution was densified with campaign solutions of the high accuracy Canadian Base Network (CBN).

With the exception of INEGI, reprocessing of the regional networks are planned in conjunction with the IGS08 repro2 effort. Most contributors (NGS, NRCan, Scripps) plan to create their regional solutions as densifications of their global contributions to repro2 using their own orbits submitted to the IGS. INEGI has just completed their own reprocessing with repro1 orbits and has no immediately plans to reprocess again.

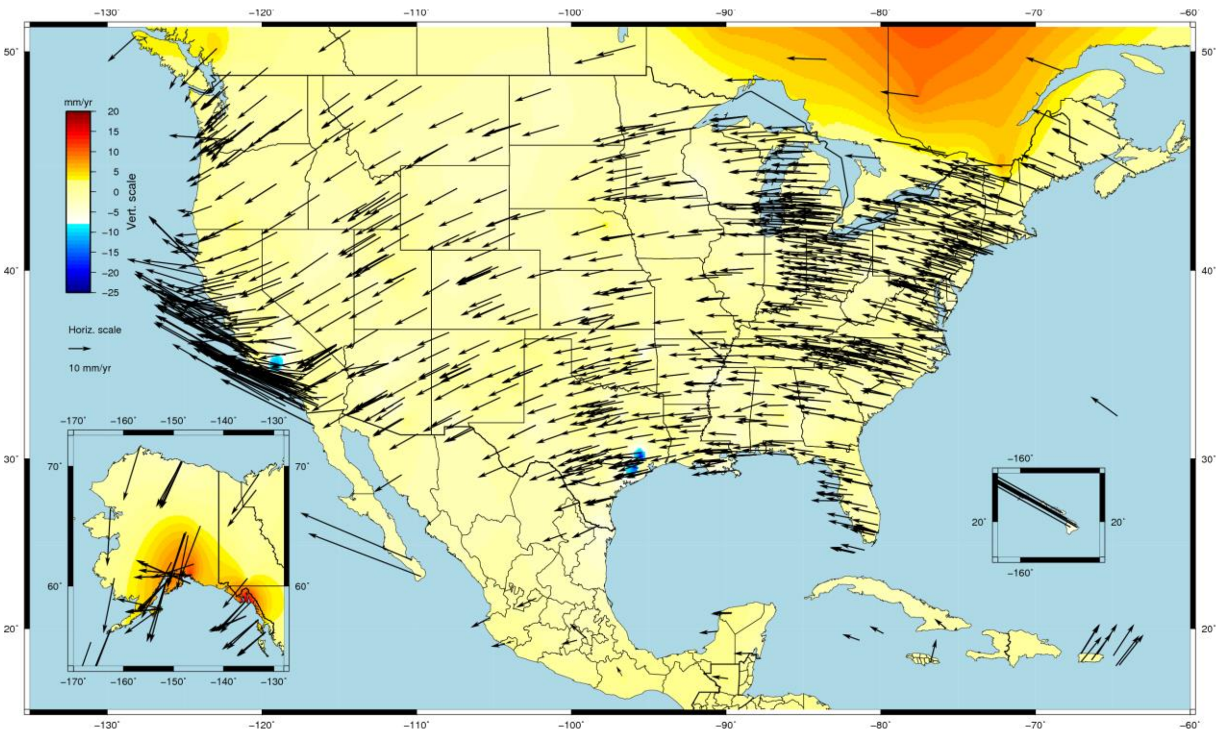

Figure 1.3c.1: NGS multiyear solution up to GPS week 1631.

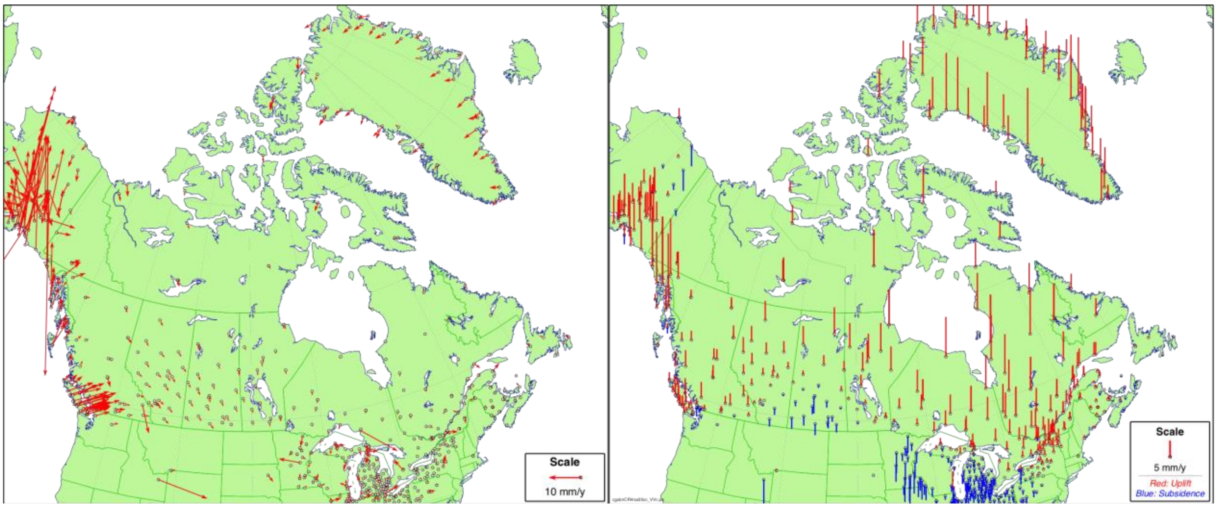

Figure 1.3c.2: CGS multiyear solutions up to GPS week 1631.

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

The objective of this working group is to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace the existing, non-geocentric North American Datum of 1983 (NAD83) reference system and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared.

Although the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that NAD83 is offset from the actual geocentre (and thus ITRF) by about 2 meters. It is also well known that the NNR-NUVEL-1A plate motion model, used to keep NAD83 aligned with the North American tectonic plate, is biased by about 2 mm/yr. These problems make NAD83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning system. Consequently, there is a need to replace NAD83 with a high accuracy geocentric reference frame that is compatible with ITRS/ITRF.

It is expected that NAD83 will not be replaced until 2022 when it is also planned to replace the vertical datum in the USA with one based on a geoid. There have been preliminary discussions at NGS and NRCan on the various options for defining a regional geocentric reference frame. It has generally been agreed that the new reference frame will be aligned exactly with the latest realization of ITRF at that time at some adopted reference epoch. In the meantime, discussions are underway on the best method of fixing such a frame to the North American plate, including the selection of a set of reference frame stations representing stable North America and the estimation of the motion of the North American tectonic plate.

In the meantime, NGS is installing a new high level network of 10-20 highly stable Foundation CORS sites across the U.S. that will be contributed to the IGS. Unlike most of the other CORS network in the U.S., these sites will be owned and operated by NGS and built and operated to IGS standards. Referred to as Foundation CORS, this network will provide a more stable foundation for the new reference frame in the U.S. Attempts will be made to co-locate these GNSS stations with other techniques in order to create true GGOS stations. The first of these sites was installed in Miami is late 2014.

There have also been informative discussions with the public in the US during two Federal Geospatial Summits organized by NGS in 2010 and 2015. Active promotion of the new reference frame and vertical datum are planned in the near future.

SC1.3c-WG3: Reference Frame Transformations in North America

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

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 frame is now defined in terms of a time-dependent 7-parameter Helmert transformation from ITRF96. Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental fourteen parameter transformations between ITRF versions as published by the IERS. The last update to the NAD83-ITRF transformation was for ITRF2008 in late 2010. A new update will be provided as soon as the new ITRF2014 is released.

Other Activities

Commercial real-time kinematic (RTK) services and their networks of base stations have grown over the years (see Fig. 1.3c.3). They are effectively providing access to the NAD83 reference frame for many users. Because these networks are not always integrated into the same realization of NAD83, CGS began a program of validating the NAD83(CSRS) coordinates of these services to ensure they are properly integrated into the NAD83CSRS) reference frame. CGS is now providing monthly coordinate and velocity solutions for 6 of the largest RTK services in Canada; a total of more than 800 stations (see Fig. 1.3c.4). Compliance agreements have signed with the three largest services where they have committed to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTK services are integrated into the latest realization of NAD83(CSRS). NGS is also working towards a similar program to validate their commercial RTK services.

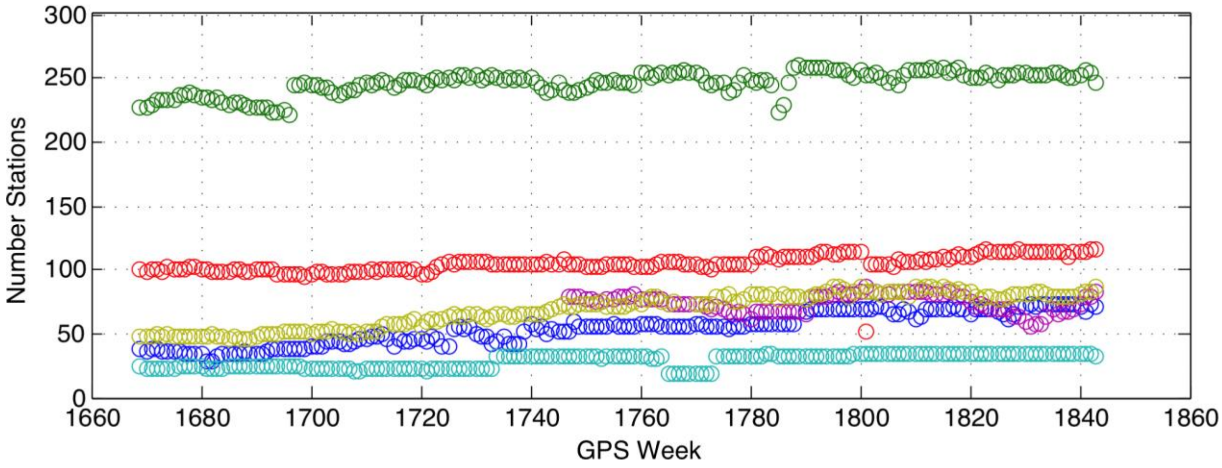

Figure 1.3c.3: Growth of the six largest commercial RTK networks in Canada.

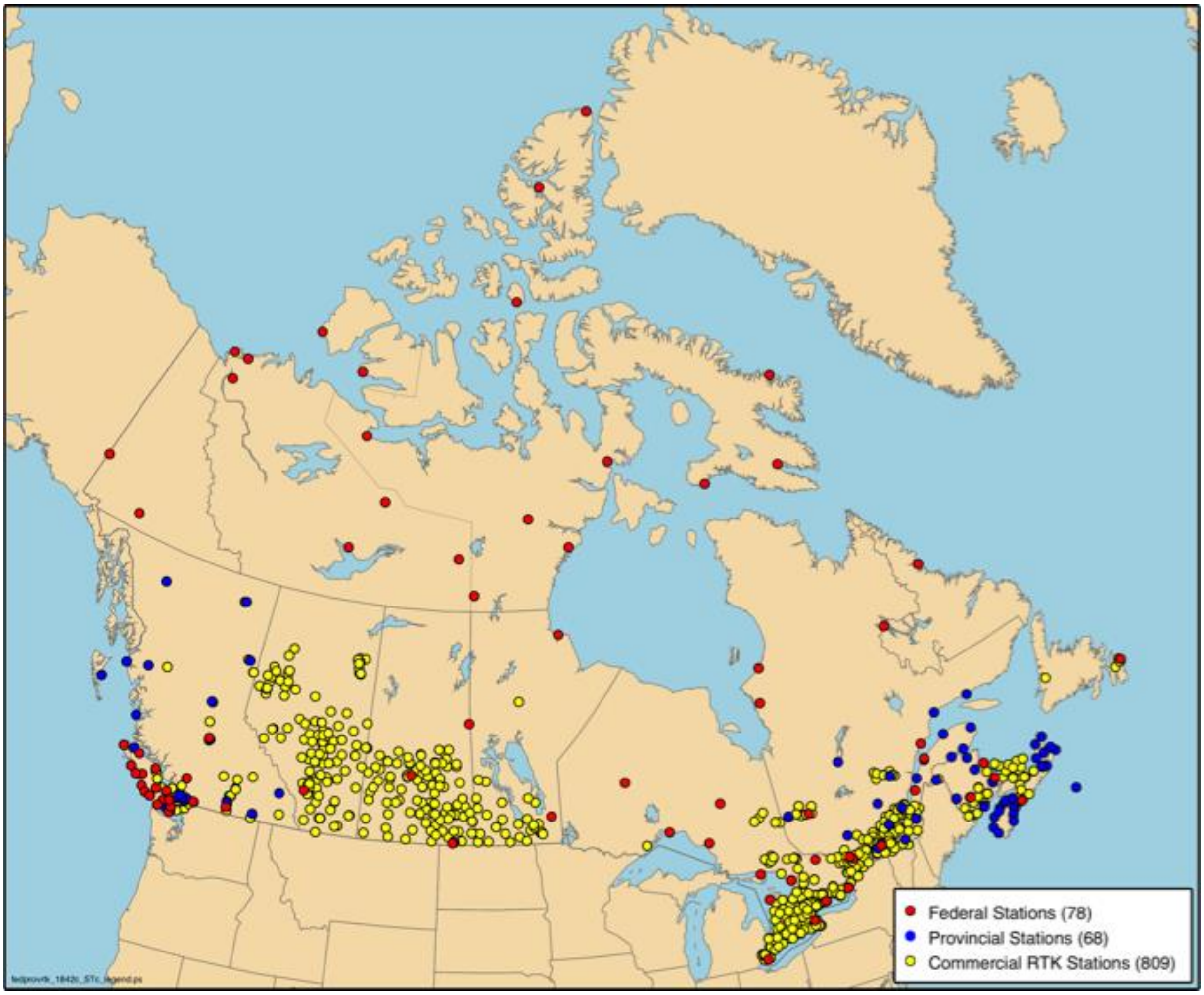

Figure 1.3c.4: Distribution of the six largest commercial RTK networks in Canada (yellow dots) in relation to public federal and provincial networks of permanent GNSS stations.

The International Great Lakes Datum (IGLD) is a vertical datum based on dynamic heights. It is used for monitoring water resources in the Great Lakes Basin. The datum needs periodic updating about every 30 years to account for the effects of glacial isostatic adjustment. The current velocity field, based on the CGS multiyear solution in SC1.3c-WG1, is given in Fig. 1.3c.5. The current realization, IGLD 1985, is based on NAVD88 transformed to dynamic heights. This datum is now in need of updating and planning has begun for the implementation of new geoid-based realization (IGLD 2020). IGLD 2020 is expected to use the latest North American geoid at the time of adoption. To support this update, improve the modelling of GIA and monitor the stability of reference benchmarks at IGLD water level gauges, repeated GPS surveys have been conducted in 1997, 2005 and 2010. New survey campaigns are also planned for 2015 and 2020.

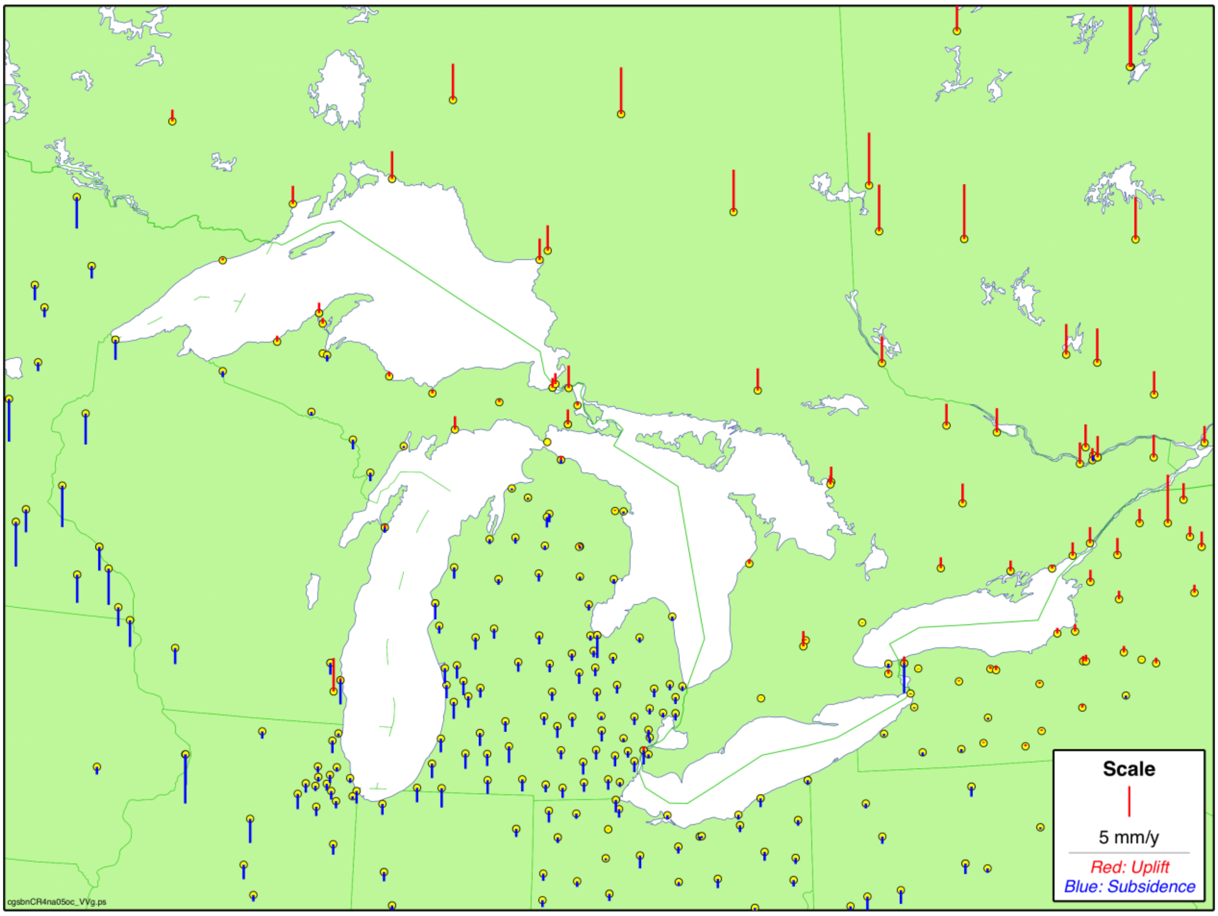

Figure 1.3c.5: Great Lakes velocity field based on CGS solution up to GPS week 1631.

Sub-Commission 1.3d: Regional Reference Frame for Africa (AFREF)

Chair: Richard Wonnacott (South Africa)

Introduction

This report summarizes the main activities related to the IAG Sub Commission 1.3d (Africa) for the period 2011-2015. This report focuses on the activities of the Africa Geodetic Reference Frame (AFREF). Many persons and institutions have contributed, either directly or indirectly, to the activities of the Sub-Commission and AFREF. The author wishes to thank all those who have contributed and at the same time apologize in advance for credits that may have been inadvertently omitted in this report.

Reference Frame

The major activity within Africa in relation to the activities of Commission 1 Reference Frames and in particular SC 1.3d Africa is the establishment of a network of permanent GNSS base stations in support of an effort to unify the reference frames in Africa. The project is known as the Africa Reference Frame project (AFREF). Prior to March 2013 the project fell within United Nations Committee for Development Information, Science and Technology (Geo-information) (CODIST-Geo). Since March 2013, the oversight and supervisory functions of CODIST-Geo (including AFREF) were transferred to the United Nations Global Geospatial Information Management: Africa (UN-GGIM: Africa).

Four of the seven major objectives of AFREF relative to this report are to:

– Define the continental reference system of Africa. Establish and maintain a unified geodetic reference network as the fundamental basis for the national 3-d reference networks fully consistent and homogeneous with the global reference frame of the ITRF;
– Establish continuous, permanent GPS stations such that each nation or each user has free access to, and is at most 500km from, such stations;
– Determine the relationship between the existing national reference frames and the ITRF to preserve legacy information based on existing frames; and
– Assist in establishing in-country expertise for implementation, operations, processing and analyses of modern geodetic techniques, primarily GPS.

In pursuance of these objectives, permanent GNSS base stations are being set-up throughout most of Africa. Approximately 90 stations have been installed and are registered on the AFREF Operational Data Centre which was installed to download and archive data from these stations. Of these 90 stations, however, only 60 have provided data to the ODC in 2015. For the period 1 January to 20 May 2015, an average of 48 stations provided data daily, albeit not always the same 48 stations.

The stations have been installed by a variety of agencies, organizations and projects such as the Africa Array (seismology), AMMA-GPS (meteorology) and SCINDA (ionosphere) projects. A number of the National Mapping Authorities have also established permanent GNSS networks within their own countries.

A two-week period was identified in Dec 2012 (Days 337 to 350) during which daily data from an average of 50 stations were downloaded. This data, together with a further 50 global stations, was processed by 4 processing centres and combined by the IGN, Paris to provide a set of static co-ordinates based on ITRF2008 at epoch 2012 Day 340 (GPS Week 1717) to be used for everyday surveying and mapping operations.

The four processing centres were:

– Ardhi Univesity, Tanzania / University of Purdue, USA
– Hartebeesthoek Radio Astronomy Observatory, South Africa
– Surveying and Mapping Division, Ministry of Lands, Tanzania
– University of Beira Interior, Portugal

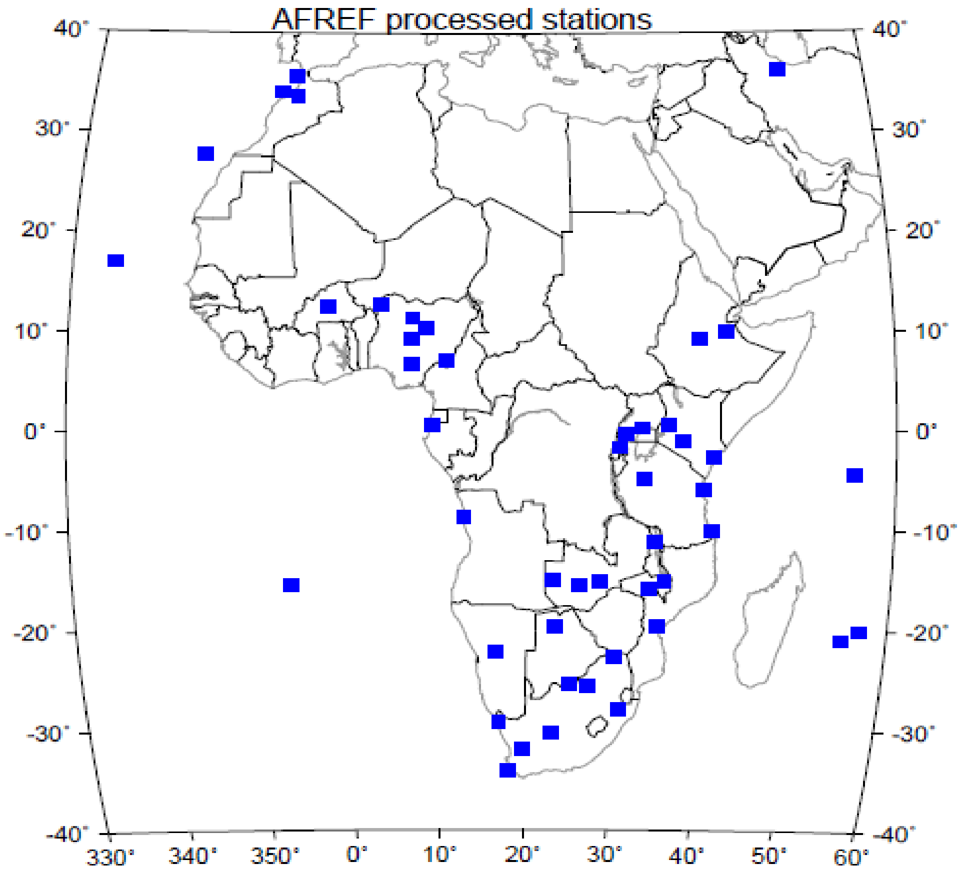

Figure 1: Stations for which a set of static co-ordinates was processed using data between Days 337 and 350 in 2012. The lack of freely available CORS data in the area from Angola through Central Africa, Sudan and Sahara and North African countries remains of concern.

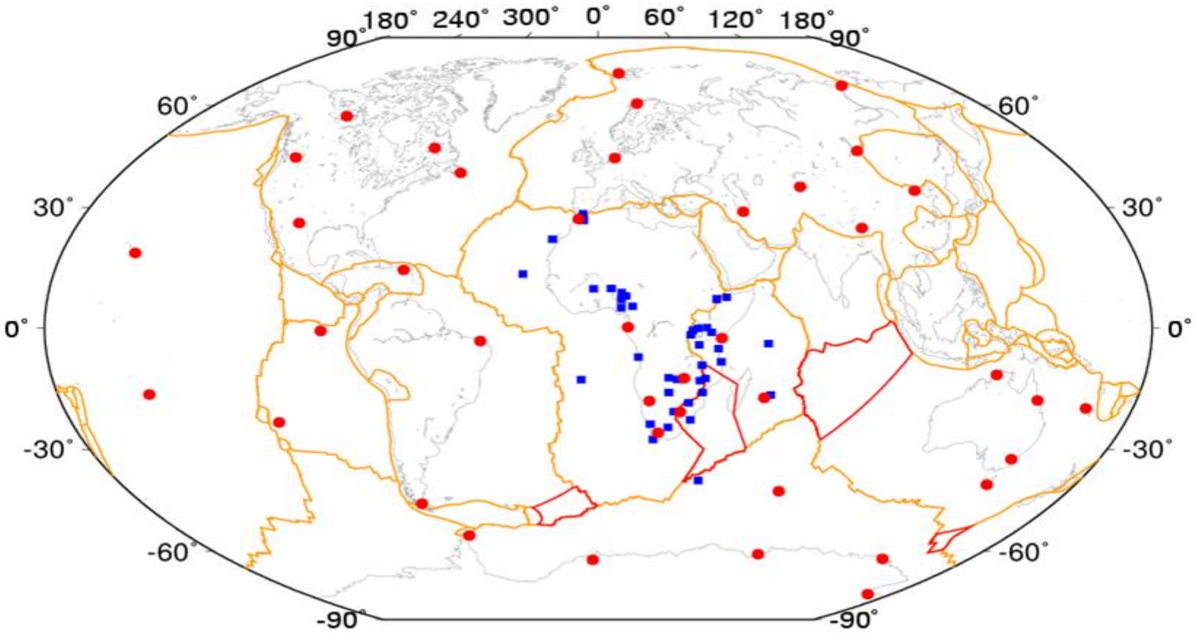

Figure2. Distribution of Global stations used in the computation of static AFREF co-ordinates.
Blue squares = AFREF stations, Red circles = Global stations

Table 1: WRMS in Easting, Northing and UP per Analysis Centre per week

Solution	Week 1717				Week 1718			
	# Sta	E	N	U mm	# Sta	E	N	U mm
HartRAO	80	1.4	1.0	4.9	79	1.2	1.1	5.0
DSM	84	1.2	0.9	3.9	86	1.2	1.0	3.8
Ardhi	75	1.0	0.9	3.4	77	0.9	0.8	3.4
SEGAL	87	1.3	1.7	6.7	85	1.3	1.8	6.0

Table 2: WRMS values of the alignment to ITRF2008 using 42 Global reference stations, in East, North and Up in mm for the two weeks that were processed.

	E mm	N mm	U mm
Week 1717:	2.9	3.2	7.4
Week 1718:	3.0	3.4	7.6

The computation of static co-ordinates for the remaining stations is in progress.

The second phase will be routine processing of the network to provide a velocity field. Data from the stations currently in place is being processed and used by IAG Working Group on Regional Dense Velocity Fields

Once the set of static co-ordinates has been published, the National Mapping Authorities will have to commence with determining the relationship between the new ITRF2008 based AFREF reference frame and the existing in-country reference frame in order to preserve all historical geospatial data and reference material.

Capacity Building

Workshops on the establishment and processing of permanent GNSS stations and networks are held annually at the Regional Centre for Mapping of Resources for Development in Nairobi, Kenya. Partially as a result of these workshops, a number of countries have either established or have commenced with the establishment of in-country CORS networks.

Sub-Commission 1.3e: Regional Reference Frame for South-East Asia and Pacific (APREF)

Chair: John Dawson (Australia)

Overview

To improve regional cooperation that supports the realisation and densification of the International Terrestrial Reference frame (ITRF). This activity is carried out in close collaboration with the United Nations Global Geospatial Information Management (UN-GGIM) Asia Pacific - Geodetic Reference Framework for Sustainable Development Working Group (formerly known as the Geodetic Technologies and Applications Working Group of the Permanent Committee for GIS Infrastructure in Asia and the Pacific - PCGIAP).

The objectives of the Sub-commission 1.3e are:

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

Activities

The activities of sub-commission 1.3e have focussed on the Asia Pacific Reference Frame (APREF) project. Table 1.3e.1 summarizes the current commitments to APREF. APREF products presently consist of a weekly combined regional solution, in SINEX format and a cumulative solution, which includes velocity estimates.

In addition to those stations contributed by participating agencies, the APREF analysis also incorporates data from the International GNSS Tracking Network including stations in the Russian Federation (16), China (10), India (3), French Polynesia (2), Kazakhstan (1), Thailand (1), South Korea (3), Uzbekistan (1), New Caledonia (1), Marshall Islands (1), Philippines (1), Fiji (1), and Mongolia (1).

GNSS data from a CORS network of approximately 480 stations, contributed by 28 countries is now available and processed by four Analysis Centres (ACs): Geoscience Australia, the Curtin University, the Department of Sustainability and Environment in Victoria, Australia, and the Institute of Geodesy and Geophysics, Chinese Academy of Sciences.

The APREF project websites was established as http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame. The weekly ITRF coordinate estimates in SINEX format, coordinates time series and velocity solutions for the APREF stations are published on the APREF website.

Table 1.3e.1: Responses to the APREF Call For Participation. Responding agencies have indicated whether they would undertake analysis, provide data archive and product distribution or supply data from GNSS stations

Country/Locality	Responding Agency	Proposed Contribution		
		Analysis	Archive	Stations
Afghanistan	National Geospatial-Intelligence Agency, USA			2
Alaska, USA	National Geodetic Survey (USA)			90
American Samoa	National Geodetic Survey (USA)			1
Australia	Geoscience Australia	x	x	132
Australia	Curtin University of Technology	x		1
Australia	University of New South Wales	x		1
Australia	Department of Environment and Resource Management, Queensland			10
Australia	Department of Sustainability and Environment, Victoria	x		96
Australia	Department of Lands and Planning, Northern Territory			5
Australia	Department of Primary Industries, Parks, Water & Environment, Tasmania			2
Australia	Radio and Space Weather Services, Bureau of Meteorology			3
Australia	Land and Property Management Authority, New South Wales			128
Brunei	Survey Department, Negara Brunei Darussalam			1
Cook Islands	Geoscience Australia			1
Cook Islands	Geospatial Information Authority of Japan			1
Ethiopia	Ethiopian Mapping Agency			3
Federated States of Micronesia	Geoscience Australia			1
Fiji	Geoscience Australia			1
French Polynesia	Geospatial Information Authority of Japan			1
Guam, USA	National Geodetic Survey (USA)			1
Hawaii, USA	National Geodetic Survey (USA)			19
Hong Kong, China	Survey and Mapping Office			7
Indonesia	Bakosurtanal			4
Iran	National Cartographic Center, Iran			6
Iraq	Iraqi Ministry of Water Resource General Directorate for Survey			6
Japan	Geospatial Information Authority of Japan	x	x	10
Kazakhstan	Kazakhstan Gharysh Sapary			2
Kiribati	Geoscience Australia			1
Kiribati	Geospatial Information Authority of Japan			2
Macau, China	Macao Cartography and Cadastre Bureau			3
Malaysia	Department of Survey and Mapping Malaysia (JUPEM)			7
Manus Island	Geoscience Australia			1
Marshall Islands	Geoscience Australia			1
Micronesia	Geoscience Australia			1

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

In addition to APREF, the sub-commission has and will continue to coordinate an annual GNSS campaigns along with APREF so that countries without Continuously Operating Reference Stations (CORS) can connect their national geodetic infrastructure to the regional/ global network. Four annual GNSS campaigns have been carried out since 2011; the analysis reports for these campaigns have been distributed to participant member countries.

Sub-Commission 1.3f: Regional Reference Frame for Antarctica (SCAR)

Chair: Mirko Scheinert (Germany)

Observation Campaigns

Observation campaigns in the framework of the Scientific Committee on Antarctic Research (SCAR) Expert Group on Geodetic Infrastructure (GIANT) took place every austral summer from 2011 until 2015 (SCAR Epoch Crustal Movement Campaigns). The respective data and data of further Antarctic GNSS stations are archived in the SCAR GNSS Database maintained at TU Dresden. For the time period since 1995, data of about 50 stations have now been stored in the database.

Data analysis

The analysis of the data acquired during the SCAR Epoch Crustal Movement Campaigns are regularly analysed in order to come up with an up-to-date realization and densification of the terrestrial reference frame in Antarctica. Results were presented at the SCAR meetings in Portland (USA), 2012, and Auckland (NZ), 2014. A detailed report on the latest analysis incorporating data from 1995 until 2013 is given by Rülke et al. (2015). Using a modified version of the Bernese GNSS Software v5.0 station coordinates and velocities were inferred with respect to the TRF solution IGS08.

Meetings

Regular meetings took place in the framework of the SCAR Meetings, namely the XXXII SCAR Meeting in Portland (USA), July 2012, and the XXXIII SCAR Meeting in Auckland (NZ), August 2014. The goals of SC 1.3f are well reflected in the working plan of the SCAR Expert Group on Geodetic Infrastructure in Antarctica (GIANT), especially in GIANT subproject "GNSS observations for geodetic and geodynamic applications".

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Working Group 1.3.1: Integration of Dense Velocity Fields into the ITRF

Chair: Carine Bruyninx (Belgium), co-chair: J. Legrand (Belgium)

1. Introduction

The objective of the Working Group (WG) "Integration of Dense Velocity Fields into the ITRF" is to provide a global GNSS-based dense, unified and reliable velocity field referenced in the ITRF (International Terrestrial Reference Frame) and useful for geodynamical and geophysical interpretations.

2. Working Group Members

- Zuheir Altamimi
- Carine Bruyninx (Chair)
- Mike Craymer
- John Dawson
- Jake Griffiths
- Ambrus Kenyeres
- Juliette Legrand (Co-chair)
- Laura Sanchez
- Álvaro Santamaría Gómez
- Elifuraha Saria

3. Activities

The WG originally started by combining multi-year position/velocity solutions submitted by the IAG regional reference frame sub-commissions (APREF, EUREF, SIRGAS, NAREF) and global (ULR, (Santamaría-Gómez et al. 2011) and IGS) analysis centres. However, the level of agreement between the solutions was not satisfactory and the combination was affected by geographically correlated biases (Legrand et. al. 2012).

In 2012, the WG therefore decided to start combining weekly position solutions instead, allowing to mitigate the biases. All initial contributors agreed with this approach and in addition, AFREF also started to submit its first solutions.

3.1 Data Set

The list of submitted solutions is shown in Table 1. The solutions contain in total more than 4000 stations and consist (for each contributor) of the weekly SINEXs (cleaned or with a list of outliers to be removed), a cumulative solution and associated residual position time series, the position and velocity discontinuities that should be used for the cumulative solution, and the station site logs (if available). Only 2679 stations (# selected stations) with enough data to estimate reliable velocities (data span > 3 year, present in at least 104 weekly SINEXs and present in at least 50% of the weekly SINEXs within the data span) have been retained for further analysis (stations in blue and red in Figure 1).

Table 1: Weekly solutions submitted to the WG.

	AC	Solution	Data span (year)	Antenna calibrations		# initial stations	# selected stations	# new stations wrt ITRF2008
				Before GPS week 1631	After GPS week 1631			
IGS	IGS	Global	1996.0-2012.9	igs05	igs08	1157	705	186
AFREF	AFR	Global	1996.0-2012.9	igs08	igs08	197	132	72
APREF	APR	Global	2004.0-2012.9	igs08	igs08	606	396	102
EUREF	EUR	Regional	1996.0-2012.9	igs05 + indiv	igs08 + indiv	296	261	145
NAREF	GSB	Global	2000.0-2012.9	igs05	igs08	600	553	444
	NGS	Global	2000.0-2012.9	igs05	igs08	2832	1914	1519
SIRGAS	SIR	Regional	2000.0-2012.9	igs05	igs08	333	255	189
Total			**1996.0**-2012.9			**4173**	**2679**	**2251**

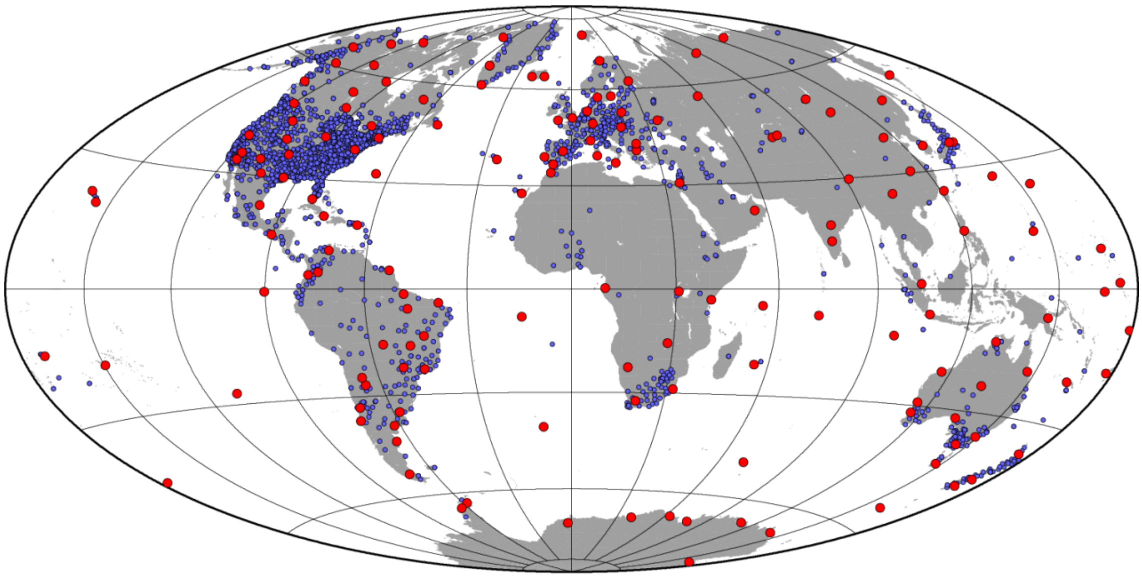

Figure 2: Map of the network; in red: sub-network used to mitigate the aliasing effect.

3.2 Methodology

The multi-year station positions & velocities have been computed in a two-step approach: first the individual weekly solutions were combined on the weekly level and then in a second step, the weekly combined positions were accumulated in order to estimate the dense global velocity field. All the combinations have been performed using the CATREF Software (Altamimi et al., 2007).

3.2.1 Combination of the individual weekly solutions:

The IGS weekly solution is used as reference and the "regional" individual weekly solutions are aligned to it using seven Helmert parameters. In order to solve the datum defect that affected some of the solutions, minimum constraints were added to the individual input solutions prior to the combination. The constraints used (translation, rotation and/or scale) were identified for each solution and missing constraints were added when necessary.

In order to mitigate the impact of the disagreements between the individual solutions and to stabilize the alignment of the individual solutions during the weekly combinations, the weekly combinations are done in 4 iterative runs:

1. Rough cleaning of the weekly solutions: allows identifying, for example, geographically different stations with identical 4-chararacter ids and domes numbers, errors in the antenna type or antenna height used during the processing or also differences in the data modelling which are too large to be neglected. In this run, the network was restricted to stations present in at least 2 solutions and covariance matrices were neglected and set to the identity matrix.
2. Combination of the weekly solutions for a subset of stations. The a priori weighting (σ1) of the covariance matrices is based on the formal errors in the individual weekly SINEXs. This run allows to estimate, each week, the Helmert transformation parameters between the individual weekly solutions and the IGS weekly solution and the variance factor (σ2) for each solution.
3. Combination of the weekly solutions for a subset of stations using the variance factors (σ2) estimated in the previous run. This runs allows to estimate, each week, the Helmert transformation parameters between the individual weekly solutions and the IGS weekly solution.
4. Combination of the weekly solutions for the full network using the variance factor (σ2) and the Helmert transformation parameters estimated in the previous run.

The RMS of the weekly combinations is between 2 to 5 mm (see Figure 2).

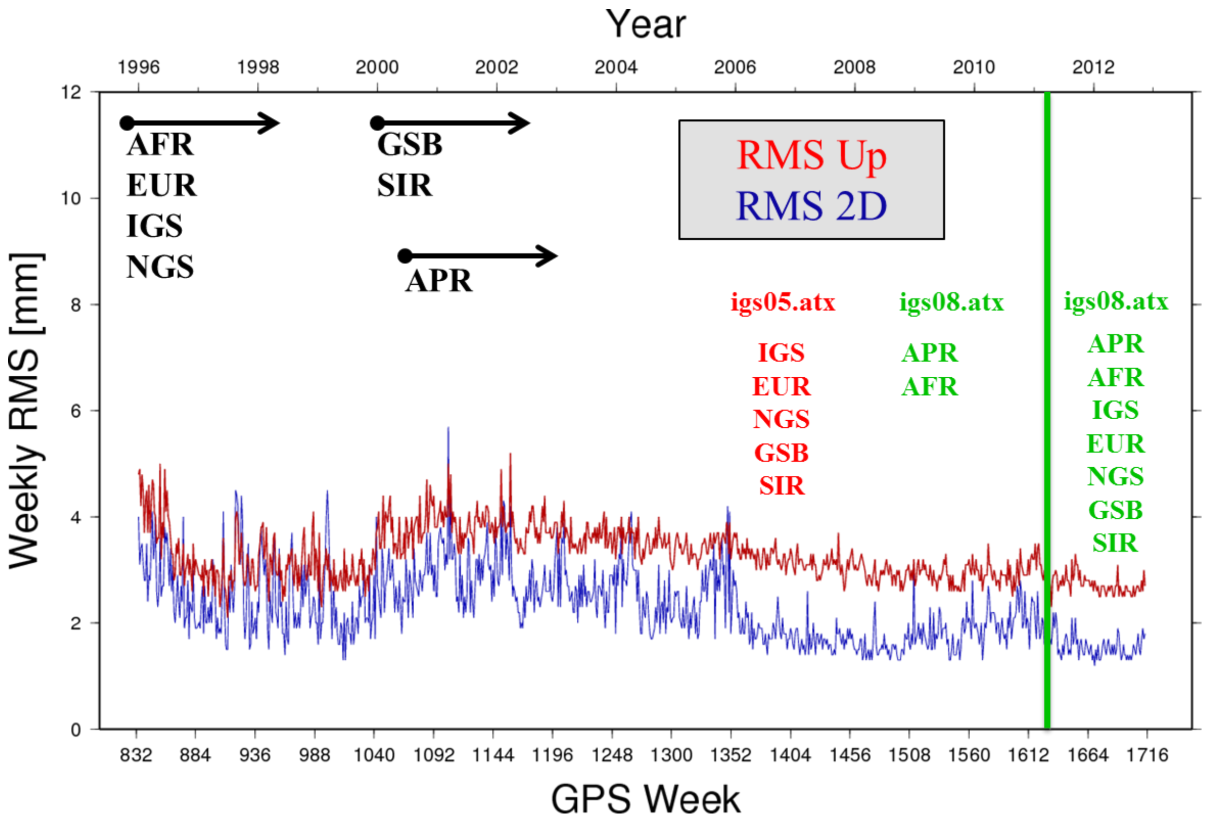

Figure 3: RMS of the weekly combinations as a function of time in mm (Up in red and 2D horizontal in blue)

3.2.2 Computation of the multi-year solution:

The multi-year positions and velocities are expressed in the IGS08 frame. In order to mitigate the aliasing effect [Collilieux et al. 2011], a global and well distributed sub-network, containing the igs08 core stations plus a few good quality stations with more than 10 years of data, was used to estimate the transformation parameters between the weekly combined solution and the cumulative solution. Then, these transformation parameters were re-used with the full network, preserving the non-linear signals embedded in the time series.

During the stacking of the combined weekly positions, discontinuities are introduced in order to take into account jumps in the position coordinate time series and changes in the velocities, see *section 3.2 - Discontinuities* for more information on how the discontinuities have been handled.

3.3 Issues and Lessons learned

3.3.1 Metadata

From the beginning, this WG faced issues linked to station naming or metadata.

When a station belongs to several networks, each network has a version of the site log. In order to populate our site log database, we downloaded site logs from each network to discover that they were not identical. In few cases, the differences were problematic (e.g. antenna type, different dates or hours of antenna/receiver installation or removal, elevation cut off). Unfortunately, these few important cases were drowned in a bunch of, difficult to handle, sit log format or version differences.

The information coming from the submitted weekly SINEX files and site logs was cross-checked wrt the IERS domes numbers list (ftp://itrf.ign.fr/incoming/codomes_coord.snx). More than 6000 triplets of 4-character ids/DOMES/PT were present in the original raw SINEXs. After the check, this number dropped to about 4000 unique stations. From them, 2000 stations were unknown to the IERS and we attributed them virtual domes numbers.

Coordinates and some station mistakes were corrected in the IERS list thanks to feedback sent to its responsible.

A lot of the position inconsistencies can be explained by the use of an incorrect antenna height or antenna type during the data analysis. Unfortunately, we identified incorrect reporting of station metadata used during the analysis in some SINEX headers. This incorrect information, together, with the inconsistent site logs, made an automated process, able to handle the metadata problems, unreliable. As a consequence, in case of a disagreement between solutions, all the information was manually checked.

3.3.2 Antenna modelling

As shown in Table 1, some solutions used the igs05.atx antenna calibration model before GPS week 1631 and igs08.atx after GPS week 1632 (IGS, EUR, GSB, NGS, SIR), while others used igs08.atx (APR, AFR) for the whole period. In addition, the EUR solution also used individual antenna calibrations when available. This situation entailed systematic biases affecting some stations.

A possible way to mitigate these biases is to apply the Rebischung (et al. 2012) model. However, due to erroneous or missing antenna metadata in the submitted weekly SINEXs and to the imperfection of the model for some stations, we decided not to apply the model and to handle the disagreement between solutions on a station per station basis by excluding solutions for the affected station. In order to handle the position changes at GPS week 1632 due to the antenna calibration model switch, position discontinuities have been added when necessary. Therefore, the impact on the velocity field has been properly mitigated. Nevertheless, the mix of the antenna calibration models (igs05.atx, igs08.atx and individual antenna calibrations) is the main drawback of this combination.

3.3.3 Discontinuities

All discontinuities provided by the contributors have harmonized and merged. During this process, the all residual position time series were manually screened together with the information on station hardware changes, earthquakes (larger the magnitude 5 occurring in the area of each station from http://earthquake.usgs.gov), and suspected changes in the antenna calibration model. All the discontinuity dates were checked and set to the exact date of hardware installation or earthquake.

3.4 Results

The velocity field derived from the combination is shown in
Figure 4 (horizontal) and
Figure 5 (vertical).

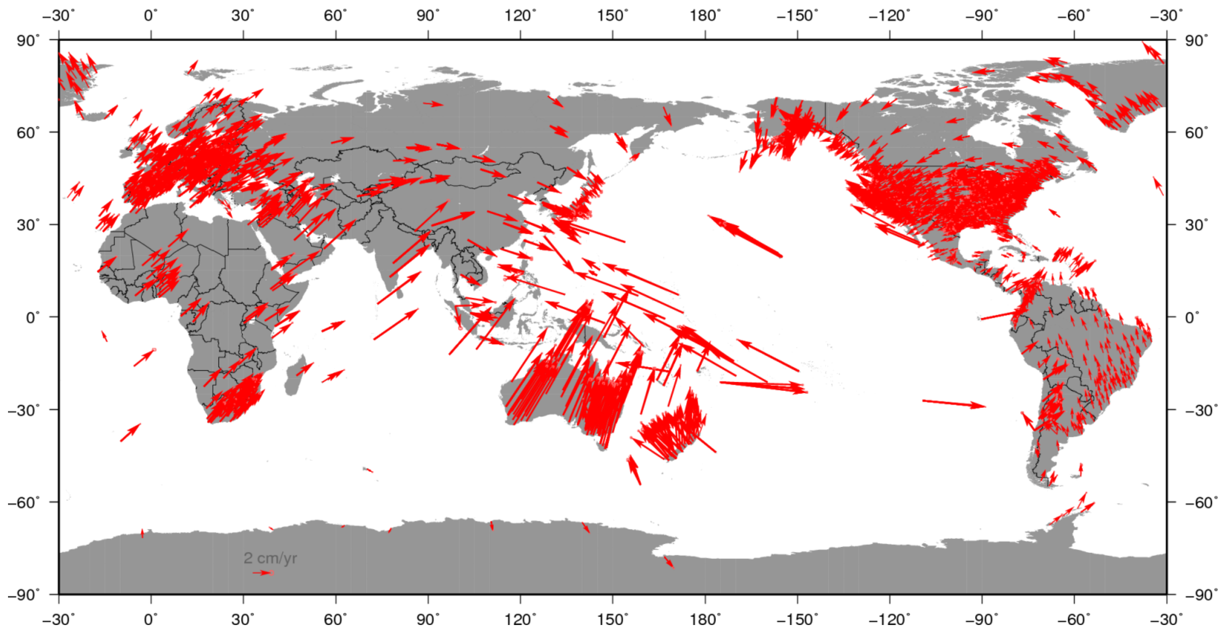

Figure 4: Horizontal velocity field expressed in the IGS08.

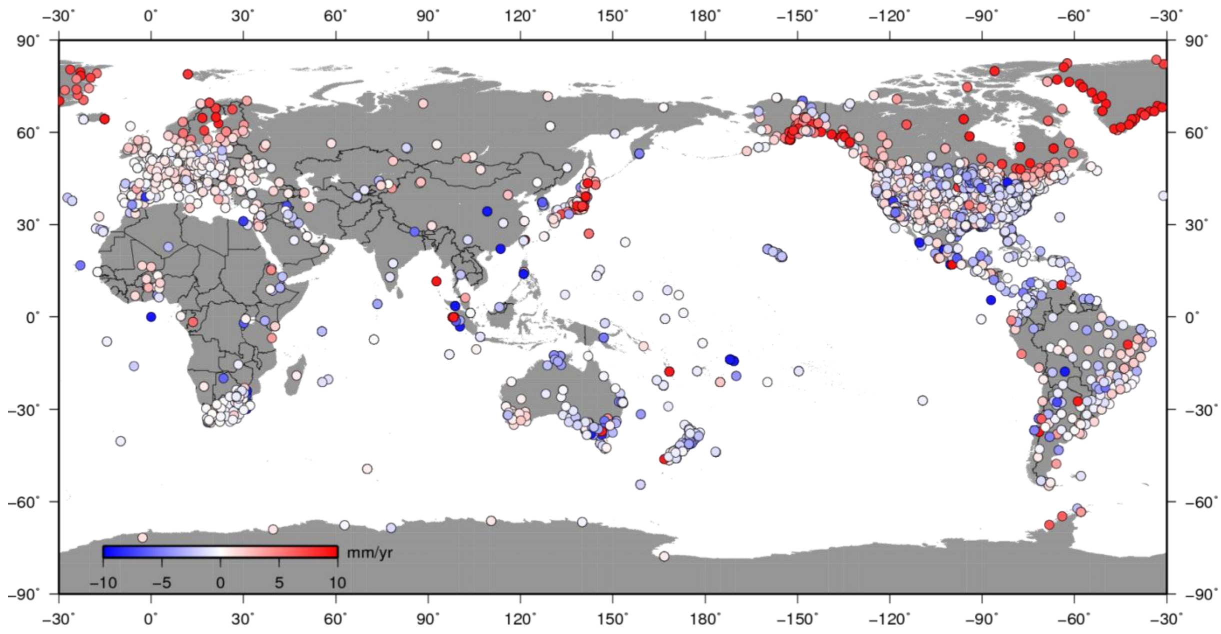

Figure 5: Vertical velocity field expressed in the IGS08.

In addition to the velocities, for each station, several types of time series are produced:

- Residual position time series of the individual solutions (e.g.
- Figure 6 left for DAEJ in Korea) ;
- Residuals of the weekly combination plotted as a time series ;
- Residual position time series of the combined solution (e.g.
- Figure 6 right for DAEJ in Korea) ;
- Position time series of the combined solution ;
- De-trended position time series of the combined solution with the mean position and velocity removed. They allow visualising the size of the discontinuities and the change in the velocities ;
- Residual position time series of the combined solution after removing the 6 and 12-month seasonal signals.

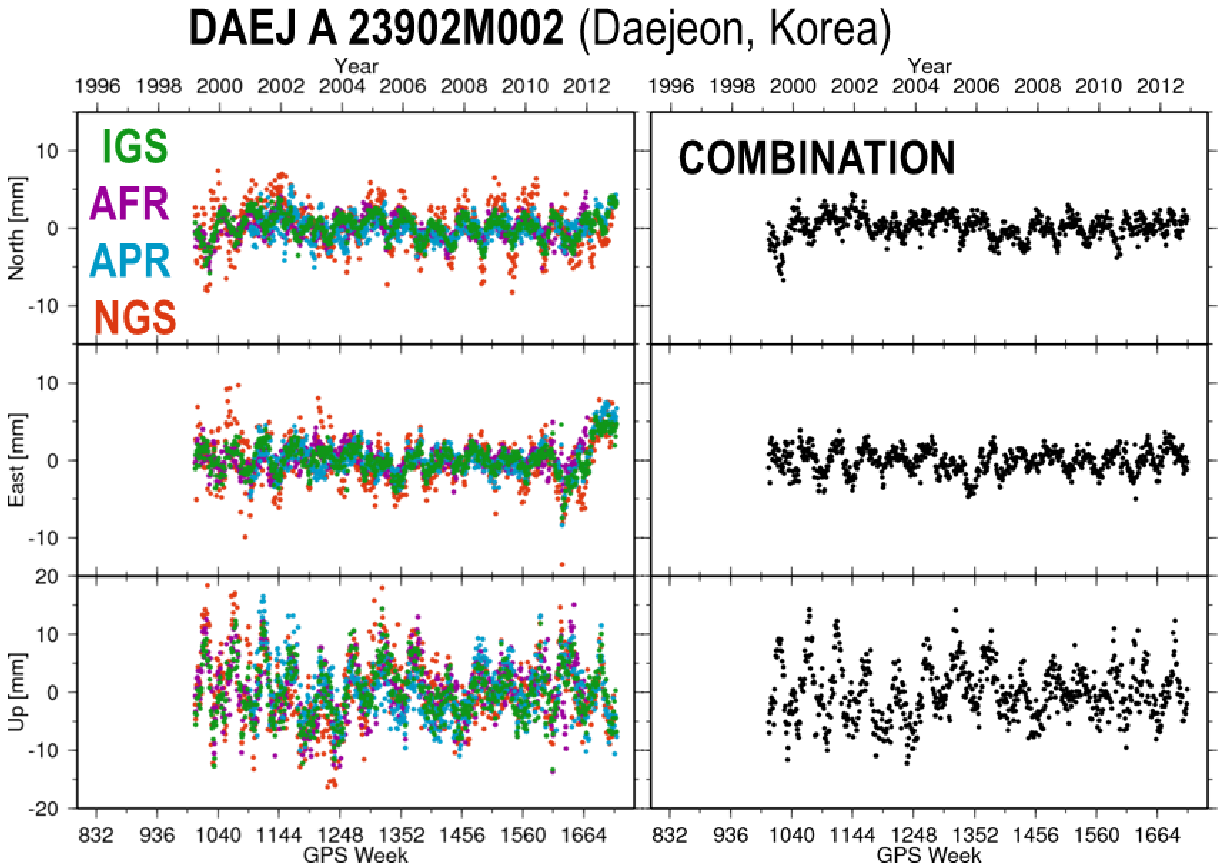

Figure 6: Residual position time series with respect to cumulative solution of individual weekly regional solutions (left) and weekly combined solution (right).

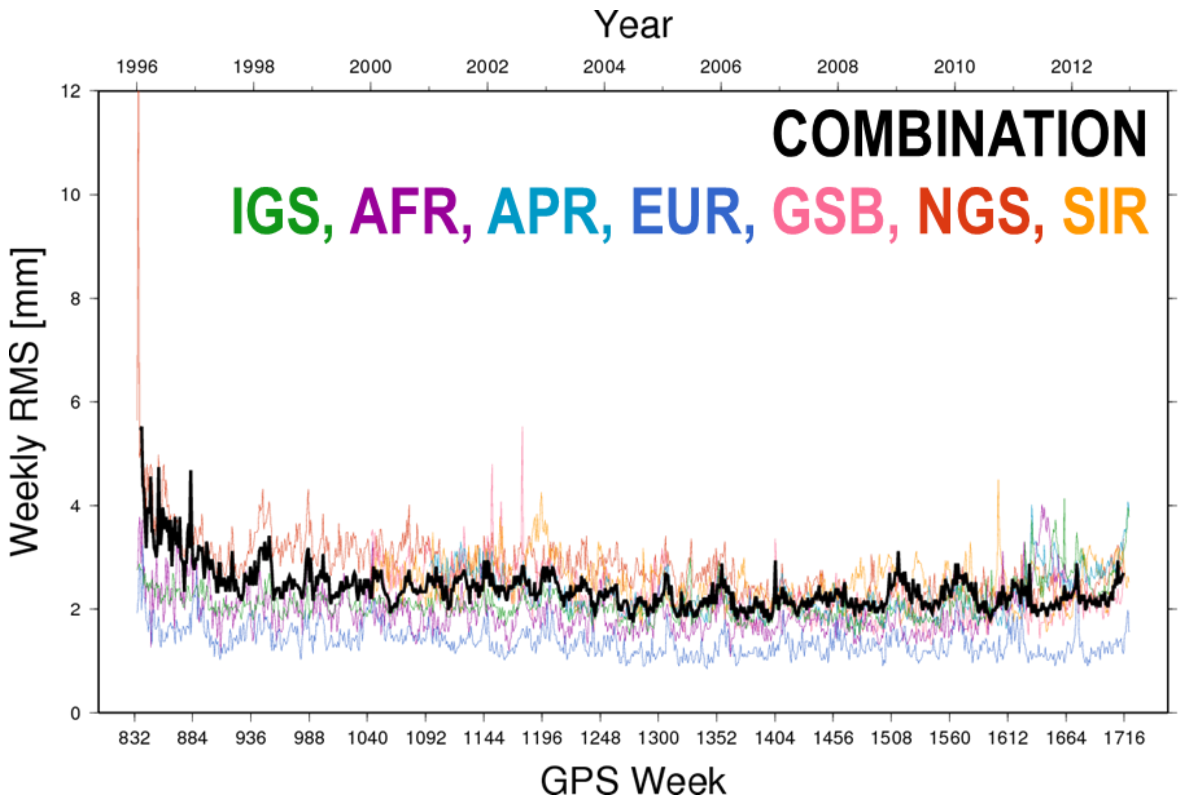

Figure 7: Weekly RMS of the cumulative solution in mm.

All these plots are available online as interactive plots. The web site will soon be open publicly.

The weekly RMS (
Figure 7) of the combination is at the same level as the RMS of the individual solutions. The time series of the combination are however longer (+4% of data span) and more populated (+11% of weeks).

3.5 Conclusion

Based on the weekly SINEX position solutions from the different reference frame sub-commissions, the Working Group computed a combined velocity field including more than 2600 stations.

From the beginning, the WGs biggest challenge, and the most time consuming issue, was metadata management (due to incomplete knowledge or conflicting information). Examples are station naming (DOMES number or 4-character id) conflicts, incorrect reporting of station metadata used during the analysis in the SINEX headers, or the use of incorrect antenna heights during the data analysis. However, a rigorous check of all the metadata resulted in a unique list of discontinuities for each of the 2600 stations contributing to the final velocity.

The combination was successful showing longer and more populated time series compared to the individual solutions. In addition, the combination on a weekly level allows increasing the reliability of the velocity field thanks to the redundancy. All the results will be available online at http://iagvf.oma.be.

4. Working Group Communications

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Bruyninx C., Legrand J., Altamimi Z., Becker M., Craymer M., Combrinck L., Combrink A., Dawson J., Dietrich R., Fernandes R., Govind R., Griffiths J., Herring T., Kenyeres A., King R., Kreemer C., Lavallée D., Sánchez L., Santamaria-Gomez A., Sella G., Shen Z., Wöppelmann G. (2013) IAG WG SC1.3 on Regional Dense Velocity Fields: First Results and Steps Ahead, In: Altamimi Z. and Collilieux X. (Eds.): Reference Frames for Applications in Geosciences, IAG Symposia 138:137-145, doi:10.1007/978-3-642-32998-2_22, 2013

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Working Group 1.3.2: Deformation Models for Reference Frames

Chair: Richard Stanaway (Australia)

Introduction

WG 1.3.2 "Deformation Models for Reference Frames" was formed at the IUGG in Melbourne, Australia in July 2011. The main aim of the WG has been to focus research in deformation modelling into the rapidly emerging field of regional reference frames used in applied geodesy, particularly positioning and GIS. Deformation models and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for land surveying and mapping. In 2011 there was no consistent approach and methodology to perform high precision transformations between these reference frames.

WG 1.3.2 has been working closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames) as there has been a great deal in common with the aims of both working groups. The members of WG 1.3.2 comprise a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

Working Group members

The WG currently consists of 19 members:

Richard Stanaway, University of New South Wales, Sydney, Australia
Christopher Pearson, University of Otago, Dunedin, New Zealand
Paul Denys, University of Otago, Dunedin, New Zealand
Kevin Kelly, ESRI, Redlands, California, USA
Rui Fernandes, University of Beira Interior, Covilhã, Portugal
Craig Roberts, University of New South Wales, Sydney, Australia
Graeme Blick, Land Information New Zealand, Wellington, New Zealand
Chris Crook, Land Information New Zealand, Wellington, New Zealand
Nic Donnelly, Land Information New Zealand, Wellington, New Zealand
John Dawson, Geoscience Australia, Canberra, Australia
Mikael Lilje, Lantmäteriet, Gävle, Sweden
Laura Sánchez, Deutsches Geodätisches Forschungsinstitut, München, Germany
Rob McCaffrey, Portland State University, Portland, Oregon, USA
Yoshiyuki Tanaka, Earthquake Research Institute, University of Tokyo, Japan
Sonia Alves, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil
Norman Teferle, University of Luxembourg, Luxembourg
Laura Wallace, University of Texas, Austin, Texas, USA
Yasushi Harada, Tokai University, Shizuoka, Japan
Daphné Lercier, Trimble, Nantes, France

Summary of WG activities from 2011 to 2015

Considerable research on deformation modelling has been completed by WG members in Japan, South America, Australia, New Zealand, Europe and the USA. Significant earthquakes since 2011 including those in Chile, Japan and New Zealand have resulted in localised deformation models being developed to support land surveying activities necessary for recovery and reconstruction in those countries. Geodetic analysis of co-seismic displacement and post-seismic decay from significant earthquakes has resulted in improved models that can be incorporated in the next realisations of ITRF and the development of more complex epoch reference frames that incorporate non-linear modes of deformation.

Background

The existing hierarchy of geodetic reference frames is necessary to support a wide range of different research activities within the Earth sciences and real-world applications. The ITRF is considered to be the fundamental geodetic terrestrial reference frame from which other frames are derived or linked by transformation and deformation models. Coordinates within ITRF are necessarily kinematic in nature to account for deformation arising from geophysical phenomena such as plate tectonics, earthquakes, volcanism, loadings and post-glacial rebound. Anthropogenic affects such as subsidence arising from water abstraction and mining also contribute to coordinate kinematics. Space geodetic positioning techniques such as GNSS intrinsically provide positions within ITRF or closely aligned frames such as WGS-84.

The Earth's surface is broadly composed of stable tectonic plates where plate-fixed reference frames can be defined by plate motion models (PMM), which quantify the rotation of the stable portion of a tectonic plate with respect to adjoining plates or the ITRS. In plate boundary regions, deformation is more complex, warranting the application of active fault locking and deformation models. Deformation models can also be used within stable plates to model localised and intraplate deformation. Episodic deformation (e.g. from earthquakes) can also be modelled to enable propagation of coordinates across deformation events. These deformation models (referred to as patches in some literature e.g. Blick *et al.*, 2006) can include both co-seismic displacement and post-seismic relaxation coefficients.

Deformation classically refers to change of shape described by strain tensor diagrams that define the magnitude and orientation of the deformation. In the context of rotating rigid tectonic plates deformation would be zero within the plate and non-zero with respect to adjoining plates and deforming zones. Absolute deformation can refer to displacement of features on the Earth's surface with respect to the axes of a no-net-rotation (NNR) geocentric frame. Relative deformation can refer to the displacement rate (shortening or extension) between adjacent points. Relative deformation within stable tectonic plates is close to zero, even if the absolute deformation will be non-zero to account for plate rotation.

Poles of rotation of stable plates can be estimated by inversion of observed site velocities and other geophysical observations such as slip vectors estimated from earthquake data. Inter seismic strain accumulation should be accounted for in any inversion using realistic fault locking models. Geologically derived poles of rotation for plates will differ slightly from those derived by inversion of inter seismic site velocities due to the fact that geologically derived velocities include far-field co-seismic deformation over considerably longer periods than any space geodetic time series can provide.

Plate-fixed (or ground-fixed) reference frames have formed the basis for many regional reference frames and national geodetic datums to support land surveying and mapping activities at a more prosaic level. The increased usage and precision of GNSS positioning since the 1990s, however, has highlighted the disparity between ITRF and ground-fixed frames. This disparity requires a significant paradigm shift in how emerging positioning technologies will interact with spatial data infrastructure defined by coordinates in ground-fixed reference frames that have been the mainstay of surveying, mapping and civil engineering.

Summary of WG 1.3.2 research activities (2011-2015)

WG members from Japan (Yoshiyuki Tanaka and Yasushi Harada) have been analysing data from the dense GEONET CORS network in Japan in order to improve Japanese crustal deformation models, particularly post-seismic deformation in the aftermath of the great Tōhuku earthquakes of March 2011. Related work in Japan has been conducted by Atsushi Yamagiwa and Yohei Hiyama of the Geospatial Information Authority of Japan to develop deformation models for use with the Japanese Geodetic Datum JGD2000 (Figure 1), (Kato *et al.*, 2011; Tanaka *et al.*, 2011; Yamagiwa and Hiyama, 2013).

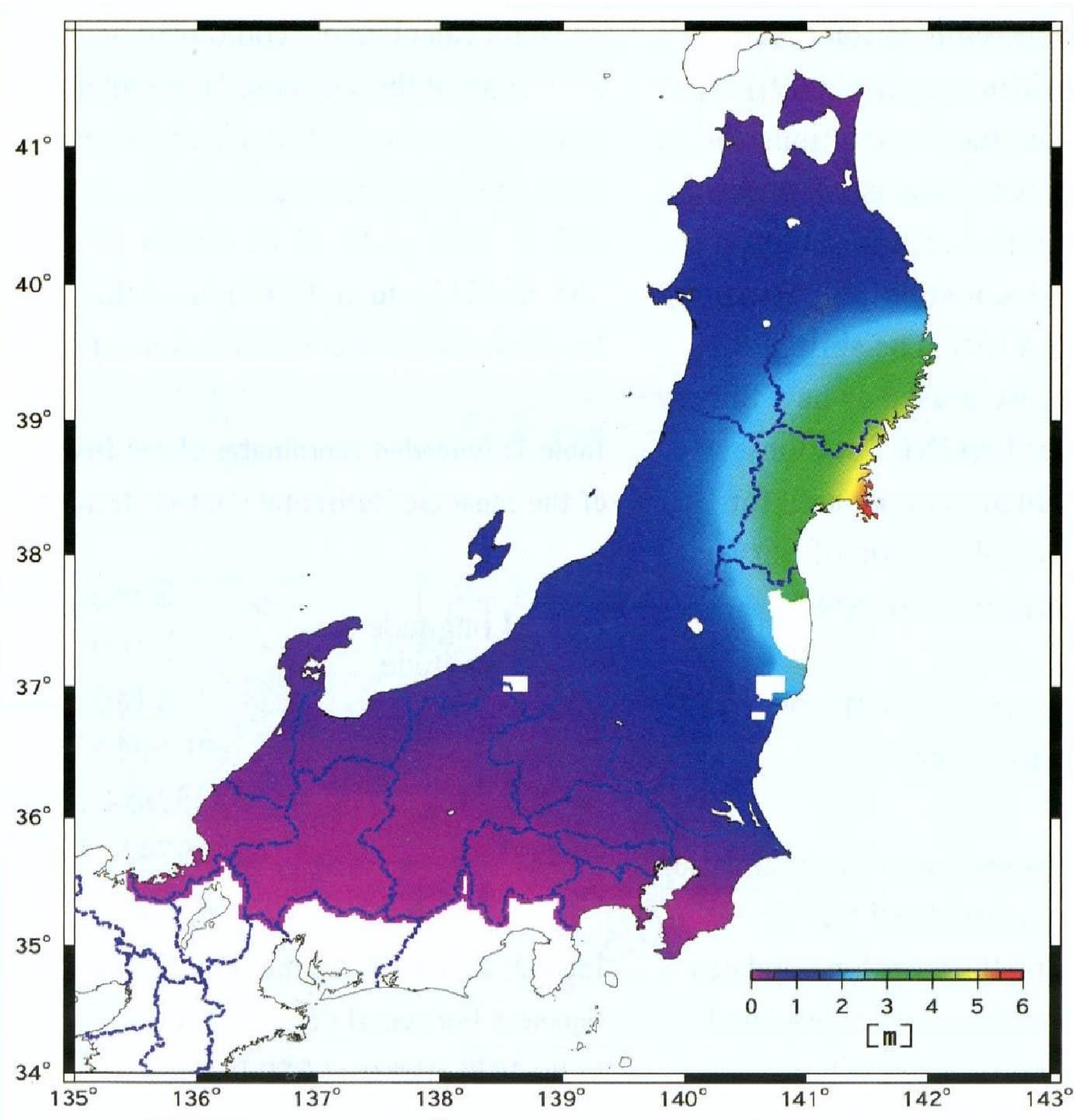

Figure 1. Correction parameters developed for coordinates in Japan - Horizontal component

Development of geodetic deformation models is well advanced in New Zealand, particularly after the Canterbury earthquake sequence between 2010 to 2012. Chris Crook and Nic Donnelly from Land Information New Zealand (LINZ) have revised the New Zealand Deformation Model which models inter-seismic deformation in New Zealand. They have recently released deformation patches which model the co-seismic and post-seismic deformation from the Canterbury earthquakes (Crook, 2013). Other WG researchers (Paul Denys, Chris Pearson and Laura Wallace) have provided insights into localised deformation in New Zealand and geophysical modelling and definition of rigid crustal blocks. Nic Donnelly is currently researching how local deformation models can be estimated from remote sensing techniques such as InSar and LiDar. This research is being conducted at the University of New South Wales.

In Australia, a next-generation geodetic datum, which will be fundamentally kinematic in nature is being developed by the geodesy team at Geoscience Australia, led by WG member John Dawson. A deformation model for Australia has been developed by Richard Stanaway and Craig Roberts (Stanaway *et al.*, 2013; Stanaway and Roberts, 2015). This work is being done in close co-operation with the LINZ members of the WG under the aegis of the Co-operative Research Centre for Spatial Information (CRC-SI). A Stable Australian Plate Reference Frame (SAPRF) has also been developed and was presented at the IAG Commission 1 REFAG Symposium at Luxembourg in October 2014.

In May 2012, a combined IAG, FIG and ICG workshop "Reference Frames in Practice" was held in Rome prior to the FIG Working week (Figure 2). WG 1.3.2 members Mikael Lilje, John Dawson, Richard Stanaway and Graeme Blick provided substantial input into the workshop with presentations on deformation models being developed in Australia and New Zealand. This workshop was a great success, and similar workshops were also run in June 2013 as part of the South-East Asian Surveyors Congress in Manila, The Philippines, and in Suva, Fiji in September 2013 at the FIG Pacific Small Island Developing States Symposium.

Figure 2. Participants of the IAG, FIG and ICG Reference Frame in Practice (RFIP) Workshop held in Rome, May 2012.

Kevin Kelly and colleagues at Esri are continuing to develop a grid format (e.g. Esri Geodetic data Grid eXchange Format - GGXF) that can support deformation models and other time dependent transformations (e.g. 14 parameter) in GIS. This is a very important contribution to the WG, as the dynamic (kinematic) nature of international and regional reference frames currently mitigates against their use for most surveying and mapping purposes where precision and repeatability is important over time. A 4D GIS will enable spatial data within a GIS to seamlessly maintain alignment with kinematic reference frames and positioning technology.

Chris Pearson and colleagues Richard Snay, Jeff Freymueller and Rob McCaffrey have been continuing development of the US Horizontal Time-Dependent Positioning software (currently version 3.2) used to transform coordinates in North America, particularly within the deforming zone of the Western United States (Figure 3), (Snay and Pearson, 2010; Pearson and Snay, 2011; Snay et al., 2013; Pearson *et al.* 2013 and 2014). Rob McCaffrey has been developing geophysical modelling tools (e.g. DEFNODE) which currently underpin the HTDP (Pearson, Snay and McCaffrey, 2012). Rob McCaffrey and colleagues have also been continuing research into the deformation field of the NW USA (Payne *et al.*, 2012; McCaffrey *et al.*, 2013) and California (Parsons et al., 2013; Petersen et al., 2014).

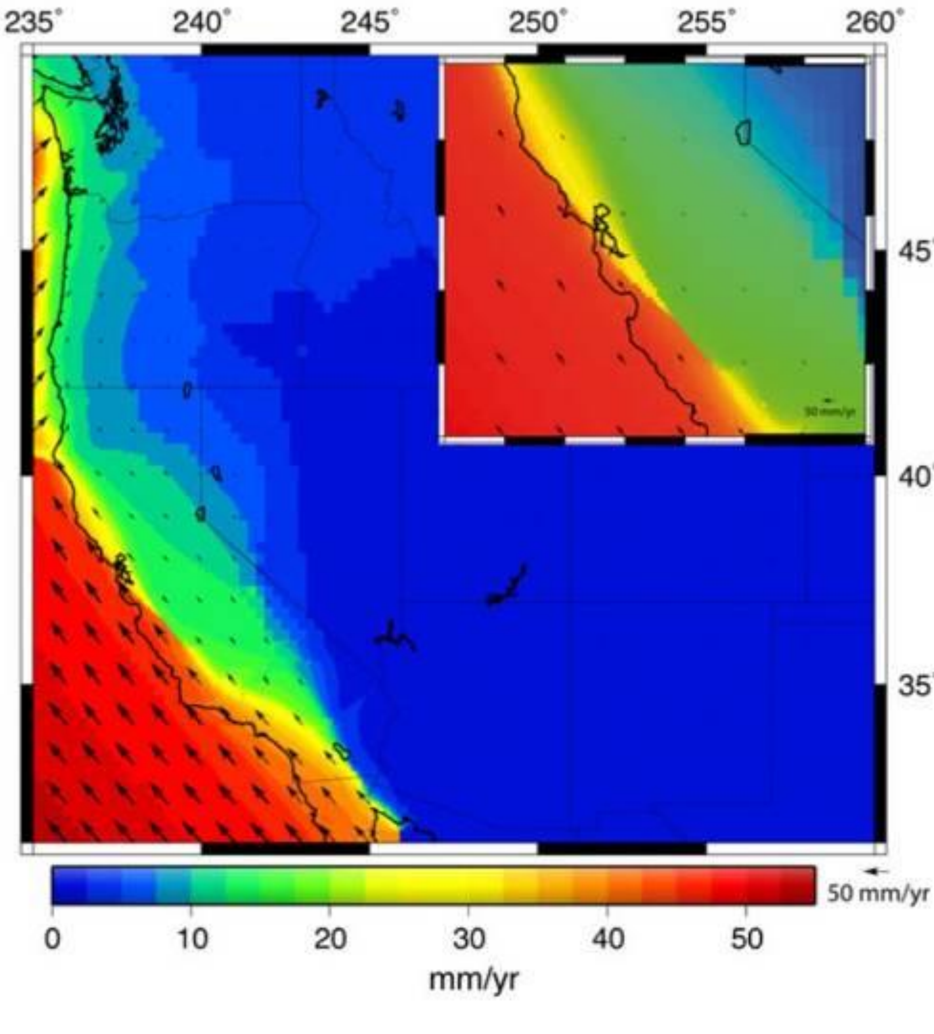

Figure 3. Visualization of the HTDP3.1 velocity field relative to NAD 83(2011). Predicted velocities on 1 degree grid are shown in black. The pixel size in this figure represents the cell spacing in the HTDP velocity grid, coarse in the east where the velocities change very slowly and becoming finer in the tectonically active regions along the west coast.

Rui Fernandes is continuing valuable research in Africa, with the development of a velocity field within the Nubian, Somalian, Arabian and Eurasian plates (Fernandes *et al*., 2013; Neves *et al.*, 2014). Findings were presented at FIG and IAG conferences in 2013. Laura Sánchez, Hermann Drewes and Sonia Alves have been involved with development of a high precision deformation model for the South American and Caribbean regions (Figure 4) as part of ongoing development of SIRGAS (Sánchez *et al.*, 2013, 2015).

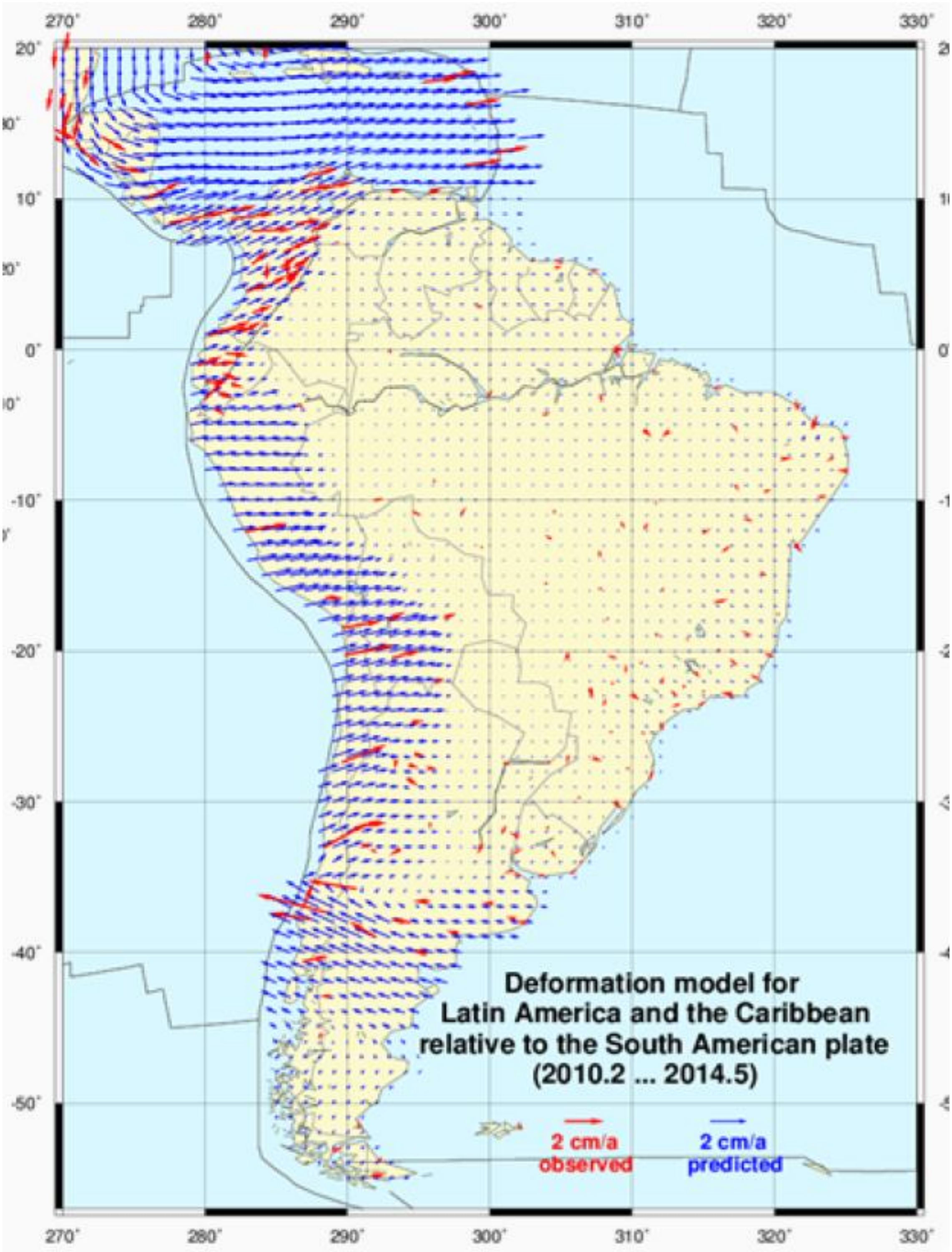

Fig. 4. Horizontal deformation model for South America and the Caribbean (VEMOS2014, Sánchez, Drewes and Schmidt, 2014)

Important research has also been completed by members outside the WG. In particular Kreemer et al. (2014) have updated the Global Strain Rate Model version 2.1 (GSRM) which is a very significant improvement on GSRM version 1 with the inclusion of 22511 site velocities to define the Euler poles of 50 tectonic plates and a dense strain rate grid in 14% of the Earth surface located in deforming zones (Figure 5).

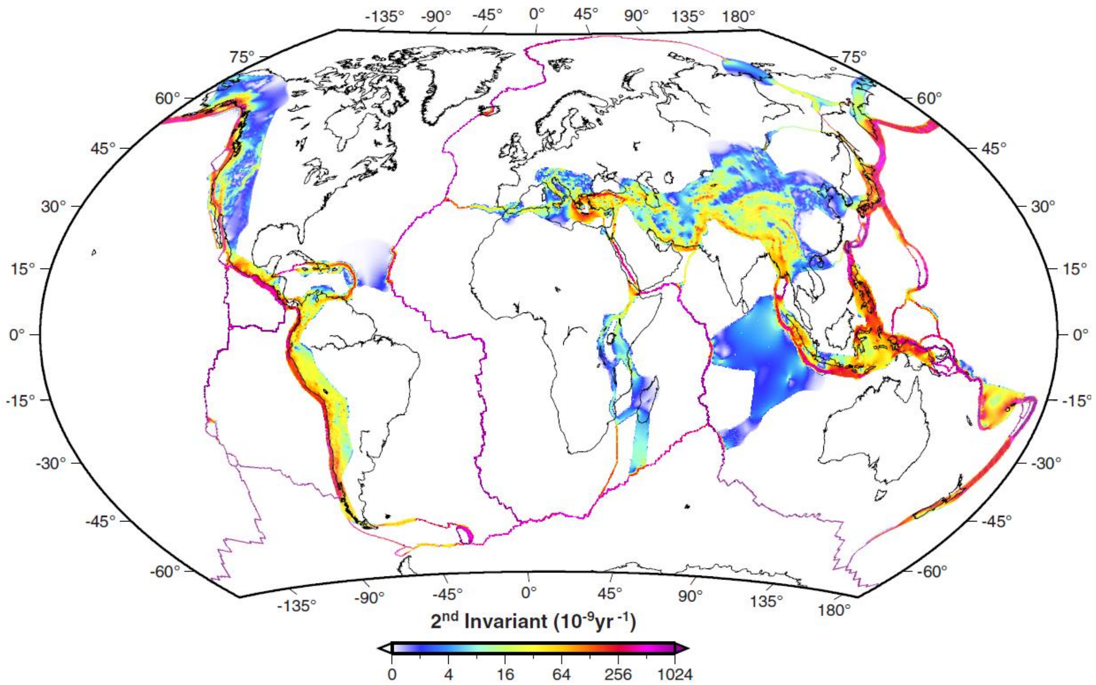

Figure 5. Contours of the second invariant of the model strain rate field. White areas were assumed to be rigid plates (from Kreemer et al., 2014)

Chatzinikos et al., (2015) describe the application of a velocity model in Greece to support the Hellenic semi-kinematic geodetic datum. A similar approach has been developed for the Indonesian geodetic datum (Hasanuddin Abidin and colleagues) and Papua New Guinea (Paul Tregoning, Laura Wallace, Richard Stanaway and Robert Rosa).

Daphné Lercier from the Paris Observatory and colleagues from the IGN LAREG have developed a parametric post-seismic decay model that is planned to be implemented in future realisations of ITRF (Lercier *et al.*, 2014; Métivier *et al.*, 2014). ITRF is currently realised as a secular frame with allowance for co-seismic offsets and velocity changes at specific epochs. This approach does not support non-linear deformation and the logarithmic or exponential character of post-seismic deformation. Consequently, ITRF is compromised in portions of the Earth surface that have been subjected to observable seismic deformation that has occurred after the release of the latest realisation of ITRF. Major earthquakes result on significant deformation over a range of thousands of kilometres from the epicentre (Figure 6). Tregoning *et al.*, (2013) have also studied the effects of recent large earthquakes on the global reference frame. Co-seismic and post-seismic deformation must be modelled in global geodetic analysis, particularly to support precise orbit determination and real-time positioning in seismically affected areas. The use of epoch reference frames currently overcomes this current limitation of ITRF.

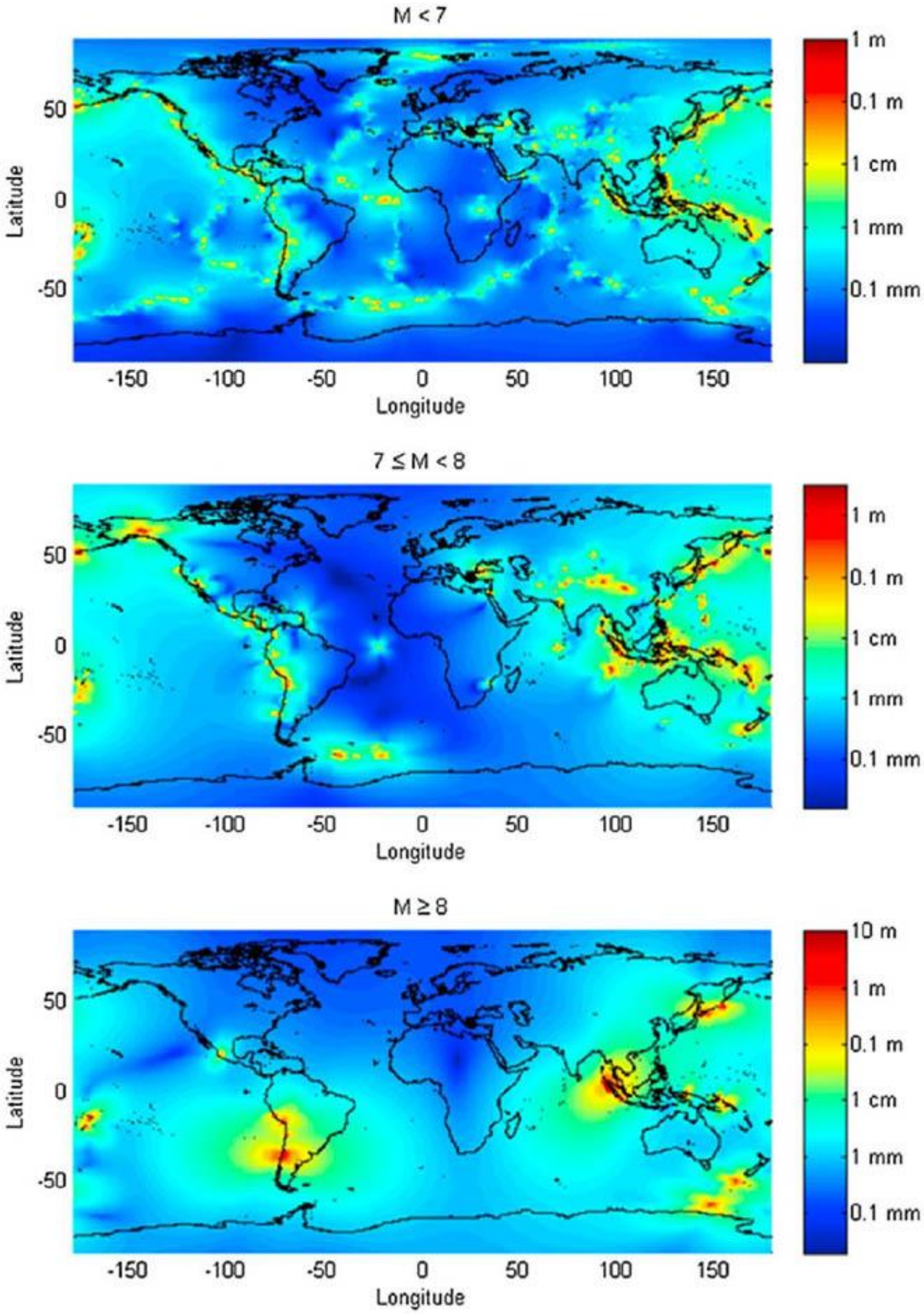

Fig. 6. Theoretical cumulative co-seismic ground displacement between 1 January 1991 and 31 December 2010 depending on the magnitude (M) range of EQ., Métivier *et al.*, 2014)

Proposal for reformulation of the WG for 2015 - 2019

Considerable progress has been made with research into modelling of the global deformation field since the formation of the WG in 2011 in parallel with WG 1.3.1 (Integration of Dense Velocity Fields into the ITRF). For the period 2015 - 2019 it is proposed to integrate the findings of WG 1.3.1, the EUREF WG on Deformation Models and the work of Kreemer *et al*., (2014) into developing a global deformation and transformation model schema that can be used to support realisation of regional and local reference frames from ITRF to support GIS and positioning technologies such as Network RTK (NRTK). This will require development of a standardised deformation model format that can be accessed from international registries of geodetic parameters such as ISO/TC211 and EPSG.

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

Chair: Johannes Böhm (Austria)
http://iag.geo.tuwien.ac.at/sc14

Structure

- Working Group 1: Geophysical and Astronomical Effects and the Consistent Determination of Celestial and Terrestrial Reference Frames (Chair: Z. Malkin)
- Working Group 2: Co-location on Earth and in Space for the Determination of the Celestial Reference Frame (Chair: S. Lambert)
- Working Group 3: Maintenance of the Celestial Reference Frames and the link to the new GAIA frame (Chair: C. Ma)

The interaction between the terrestrial and celestial frames has become an important issue in the last years, in particular due to the different estimation strategies of the International Terrestrial Reference Frame (ITRF: combination of different space geodetic techniques) and the International Celestial Reference Frame (ICRF: VLBI-only solution from a single analysis centre). Considering that

> *"...the IUGG ... urges that highest consistency between the ICRF, the International Terrestrial Reference Frame (ITRF), and the Earth Orientation Parameters (EOP) as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS" (IUGG Resolutions 2011),*

one of the primary goals of this Sub-Commission was to evaluate whether the CRF benefits from (or at least is not degraded by) a combination of VLBI observations with those from other space geodetic techniques. If the latter is proven, the next ICRF should be determined within a combined solution from different techniques. Seitz et al. (2011, 2012) have derived very interesting results, indicating that the combination with other space geodetic techniques has only a very small effect on the source coordinates. Exceptions with larger differences are found for VLBI Calibrator Survey (VCS) sources in right ascension with differences up to 1 mas (see Figure m.1). These particular sources are only observed with the regional VLBA network and are thus likely to benefit from Earth rotation parameters from Global Navigation Satellite Systems (GNSS). The impact of using polar motion estimates from GNSS for the analysis of VCS sessions was also shown in presentations by Krásná et al. (2014) and Mayer et al. (2015).

The next ICRF (ICRF-3) is expected for 2018, and it will probably be the last ICRF in the radio for some time, because then GAIA will provide a frame in the optical with significantly more quasars and stars and of similar precision. An important task is the link between the ICRF and sources in the optical domain - a task which is covered by Working Group 3 of this IAG Sub-Commission as well as by the ICRF-3 Working Group of the International Astronomical Union (IAU) chaired by Chris Jacobs. Consequently, a very close co-operation was held between those two groups, and a very fruitful joint meeting between the communities was organized at the European Working Meeting on VLBI for Geodesy and Astrometry (EVGA) in early March 2013 in Espoo, Finland.

In addition to work related to ICRF-3, many investigations have been carried out with respect to improved geophysical and astronomical models and their impact on terrestrial and celestial references frames and EOP, as well as with respect to new observations scenarios like VLBI observations to satellites which are potentially useful for a better linking between the frames. More details are provided below in the sub-sections on the three Working Groups.

Working Meetings of Sub-Commission 1.4

Annual meetings were held to discuss topics related to the interaction of celestial and terrestrial references frames. Three of them were held as splinter meetings during the General Assemblies of the European Geosciences Union (EGU) and one was held as a joint meeting with the ICRF-3 Working Group of the IAU. All agendas and presentations of the Sub-Commission meetings are accessible at: http://iag.geo.tuwien.ac.at/sc14/meetings/

IAG SC 1.4 Meeting on 25 April 2012 in Vienna during the EGU 2012

A meeting of IAG Sub-Commission 1.4 was held on 25 April 2012 at TU Wien. Four presentations were given to stimulate the discussion on future improvements of terrestrial and celestial reference frames, and in particular the consistency between them. For example, Robert Heinkelmann reported about the efforts at DGFI aiming at the consistent determination of the ITRF and ICRF in one combination solution, and Lucia Plank presented simulation results of the observation to satellites with VLBI radio telescopes, i.e., on linking the kinematic and dynamical reference frames.

Joint Meeting of the IAU WG on ICRF-3 and the IAG Sub-Commission 1.4 in Espoo, Finland on 7 March 2013

An important joint meeting with large participation was held between the IAU Working Group on the ICRF-3 (chaired by Chris Jacobs) and the IAG Sub-Commission 1.4 and its Working Groups on 7 March 2013. It took place immediately after the Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA) in Espoo, Finland. Both groups are having similar goals, e.g., the best possible ICRF-3. Additionally, an IUGG resolution is requiring, that the ICRF-3 will be fully consistent with all space geodetic techniques, i.e., not only with VLBI but also with GNSS, SLR, and DORIS. This joint meeting served well the purpose to introduce the two communities to each other.

IAG SC 1.4 Meeting on 1 May 2014 in Vienna during the EGU 2014

This meeting was based on six presentations, e.g., by Hana Krásná on the impact of seasonal station variations on Earth orientation parameters and the celestial reference frame. She showed that neglected station motions in the reduction of observations can have a significant impact on sources which are only observed a few times as well as on Earth orientation parameters if the neglected station motions are dominated by common modes over the sites. Chopo Ma reported about the IVS source monitoring program for ICRF-3 and Gaia transfer sources, and Lucia Plank showed simulation results for the connection of dynamical and kinematical reference frames by the use of observations to satellites.

IAG SC 1.4 Meeting on 16 April 2015 in Vienna during the EGU 2015

The final Sub-Commission 1.4 meeting was mainly devoted to issues related to source coordinates and source structure corrections. For example, Oleg Titov reported about observational ICRF activities in Australia and Chopo Ma provided information on CRF-related work at Goddard Space Flight Center. Lucia Plank presented her work on simulated source position offsets due to source structure and considered adapted scheduling strategies to account for it.

Working Groups of Sub-Commission 1.4

Working Group 1.4.1: Geophysical and Astronomical Effects and the Consistent Determination of Celestial and Terrestrial Reference Frames

Chair: Zinovy Malkin (Russia)

Working Group 1 was dealing with geophysical and astronomical effects on the consistent determination of celestial and terrestrial reference frames. There have been many papers and presentations on related topics in the past four years, some of which are summarized below. Ongoing topics of research are the galactic rotation and seasonal station motions.

Malkin (2013) outlines several problems related to the realization of the international celestial and terrestrial reference frames at the millimetre level of accuracy, with emphasis on ICRF issues. He considers the current status of the ICRF, the connection between the ICRF and ITRF, and considerations for future ICRF realizations. Several urgent tasks to improve the existing CRF and TRF realizations are proposed and discussed.

Böhm et al. (2011) compare the influence of two different a priori gradient models on the terrestrial reference frame as determined from VLBI observations. One model has been determined by vertical integration over horizontal gradients of refractivity as derived from data of the Goddard Data Assimilation Office (DAO), whereas the second model (APG) has been determined by ray-tracing through monthly mean pressure level re-analysis data of the European Centre for Medium-Range Weather Forecasts. The authors compare VLBI solutions from 1990.0 to 2011.0 with fixed DAO and APG gradients to a solution with gradients being estimated, and find better agreement of station coordinates when fixing DAO gradients compared to fixing APG gradients. As a consequence, the authors recommend that gradients are constrained to DAO gradients, in particular in the early years of VLBI observations (up to about 1990), when the number of stations per session is small and the sky distribution is far from uniform. Later than 1990, the gradients can be constrained loosely and the a priori model is of minor importance.

Heinkelmann and Tesmer (2013) assess systematic effects between VLBI terrestrial and celestial reference frame solutions caused by different analysis options. Comparisons are achieved by sequential variation of options relative to a reference solution, which fulfils the requirements of the IVS analysis coordination. Neglecting the total NASA/GSFC Data Assimilation Office (DAO) a priori gradients causes the largest effects: Mean source declinations differ by up to 0.2 mas, station positions are shifted southwards, and heights are systematically larger by up to 3 mm, if no a priori gradients are applied. The effect is explained with the application of gradient constraints. Antenna thermal deformations, atmospheric pressure loading, and the atmosphere pressure used for hydrostatic delay modeling still exhibit significant effects on the TRF, but corresponding CRF differences (about 10 μas) are insignificant. The application of the Niell Mapping Functions (NMF) can systematically affect source declinations by up to 30 μas, which is in between the estimated axes stability (10 μas) and the mean positional accuracy (40 μas) specified for the ICRF-2. Further significant systematic effects are seasonal variations of the terrestrial network scale (±1 mm) neglecting antenna thermal deformations, and seasonal variations of station positions, primarily of the vertical component up to 5 mm, neglecting atmospheric loading. The application of NMF instead of the Vienna Mapping Functions 1 results in differences of station heights of up to 6 mm.

Krásná et al. (2013) reaffirm results firstly shown by MacMillan and Ma (1997) with a larger span of data (27 years) including recent, very precise data obtained by the VLBI technique. If tropospheric gradients are neglected, the TRF will experience a scale change of 0.65 ppb compared to a TRF with estimated gradients. Furthermore, clear trends in the north and height components are visible. In the CRF, there is a mean systematic change in the estimated declinations of 0.36 mas with a maximum of about 0.5 mas. On the other hand - concerning the choice of mapping functions (VMF1 or Global Mapping Functions) - only small systematic changes between the reference frames can be observed, e.g. a mean height difference of –0.5 mm over the stations in the terrestrial reference frames.

Liu et al. (2012) show that the effect of the Galactic aberration strongly depends on the distribution of the sources that are used to realize the ICRS. According to different distributions of sources (of the ICRF-1 and ICRF-2 catalogues) the amplitude of the apparent rotation of the ICRS is between 0.2 and 1 μas per year. It was shown that this rotation has no component around the axis pointing to the Galactic centre and has zero amplitude in the case of uniform distribution of sources. The effect on the coordinates of the Celestial Intermediate Pole (CIP) is between about 1 to 100 μas after one century from J2000.0, while the effects on the Earth rotation angle (ERA) are between 4 and several tens of μas after one century. Thus, the Galactic aberration is responsible for a variation with time of the orientation of the ICRS axes and consequently for systematic errors in the determination of the EOP, which refer to the ICRS. The effect on the ICRS and EOP increases with time and is not negligible after several decades. With high-accuracy astrometry and the increasing length of the available VLBI observation time series, this effect should be considered, particularly in constructing the next realization of the ICRS. Observations of more radio sources, especially in the southern hemisphere, should be developed to more homogeneously distribute defining sources in the ICRF to minimize that effect. Rigorous algorithms to account for the Galactic aberration during VLBI data processing are provided by Malkin (2014).

Malkin (2011) as well as Krásná and Böhm (2014) investigate the impact of seasonal station motions on EOP and reference frames. They find that a significant annual term is present in the position time series for most stations; however, the annual signals found at co-located VLBI and GPS stations at some sites differ substantially in amplitude and phase. The semi-annual harmonics are relatively small and unstable, and for most stations no prevailing signal is found in the corresponding frequency band. Test computations show that systematic errors in UT1 estimates caused by seasonal station motion can exceed 1 μs for Intensive sessions and can reach 10 μs for multi-baseline sessions. On the other hand, no systematic propagation of the seasonal signal into the orientation of celestial reference frame is found, but position changes occur for radio sources observed non-evenly over the year.

Several studies were devoted to developments in troposphere modelling for improving the accuracy of the terrestrial reference frames. Halsig et al. (2014) investigate the effect of modelling atmosphere turbulence and find improvement of baseline length respectabilities for VLBI observations, especially for C_n values estimated from GNSS. Based the CONT11 VLBI experiment, Eriksson et al. (2014) show that the application of ray-traced atmospheric delays decreases baseline respectabilities and improves station position precision.

Working Group 1.4.2: Co-location on Earth and in Space for the Determination of the Celestial Reference Frame

Chair: Sebastien Lambert (France)

Working Group 2 covered the co-location on Earth and in space for the determination of the CRF. This WG also included the combination of different space geodetic techniques. Over the last years, a lot of simulation work has been carried out towards co-location in space, e.g. at ETH Zürich, Bonn University, or Technische Universität Wien. Upcoming satellite missions like GRASP or MicroGEM will provide the possibility to use ties on the satellite in addition or instead of ties on ground, but also GNSS satellites can be used for observations with VLBI telescopes, as e.g. demonstrated by Wettzell and Onsala.

Seitz et al. (2011) show the first results of a consistent computation of CRF, TRF, and the EOP series linking both frames. The CRF is slightly influenced by the combination in two different ways: by the combination of the EOP and by the combination of the station networks. It is shown that both effects are small. The effect of combining the station networks – mainly driven by the misfits between local ties and results of space geodetic techniques – reaches up to 2 mas, but is much smaller for most of the sources. The mean difference is about 10 µas. However, small but clearly systematic effect can be seen. The combination of the EOP also leads to small changes in the source positions. Sources close to the celestial South Pole are affected by a maximum of ±1 mas. A further systematic effect (−0.5 mas maximum) is detected for some of the sources with declinations between + and -40°. The reasons are not known. The integral impact of the combination on the CRF is small and not significant w.r.t. the axis stability (10 µas) and the noise floor (40 µas) of ICRF-2.

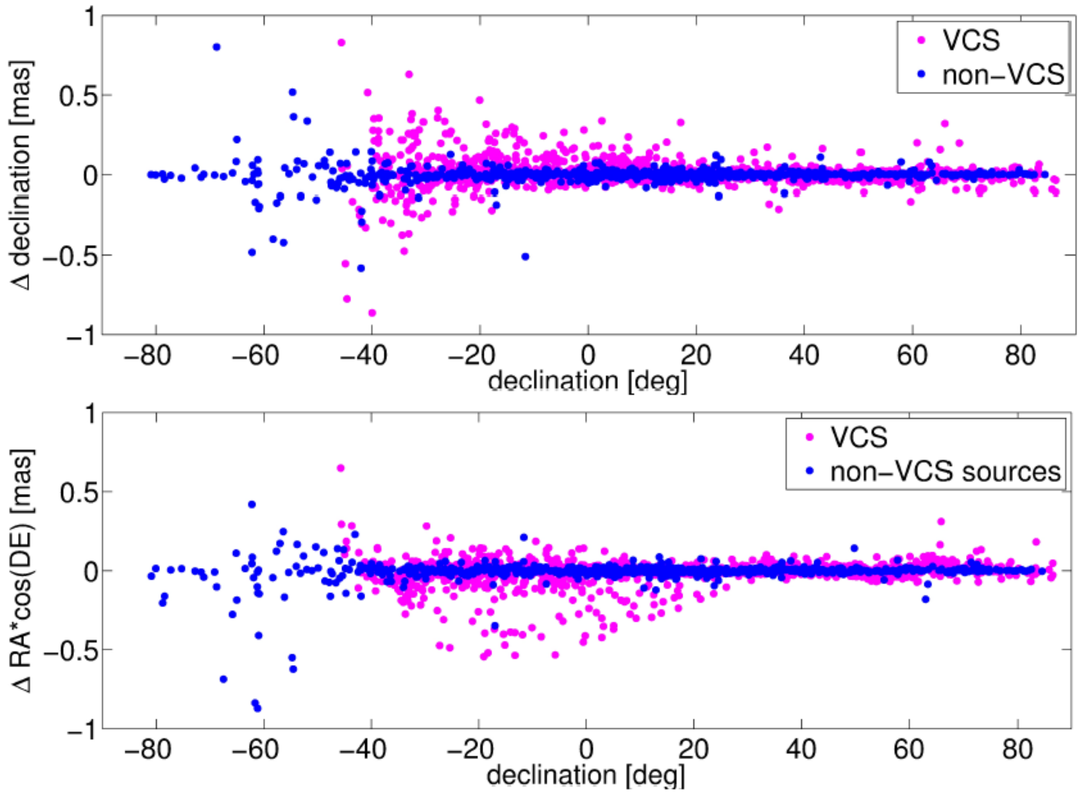

Figure m.1: Differences in source positions between the combined TRF-CRF solution and a VLBI-only solution: declination (upper plot), right ascension (lower plot) (from Seitz et al., 2012).

In continuation of their work, Seitz et al. (2012) deal with the consistent realization of ITRF and ICRF by combining normal equations from VLBI, SLR, and GNSS. The results for the CRF are compared to a classical VLBI-only CRF solution and it turns out that the combination of EOP from the different space geodetic techniques impacts the CRF, in particular the VCS (VLBA Calibrator Survey) sources (see Figure m.1).

Plank et al. (2013), in their proceedings paper for the EVGA meeting in Espoo, Finland, discuss and simulate VLBI observations to satellites at different altitudes, like the proposed GRASP mission at 2000 km and a GPS satellite at 20200 km height. Figure m.2 illustrates the benefit of VLBI observations to satellites allowing for space ties in addition to the local ties. These additional constraints are expected to have a positive impact on the consistency between terrestrial and celestial reference frames.

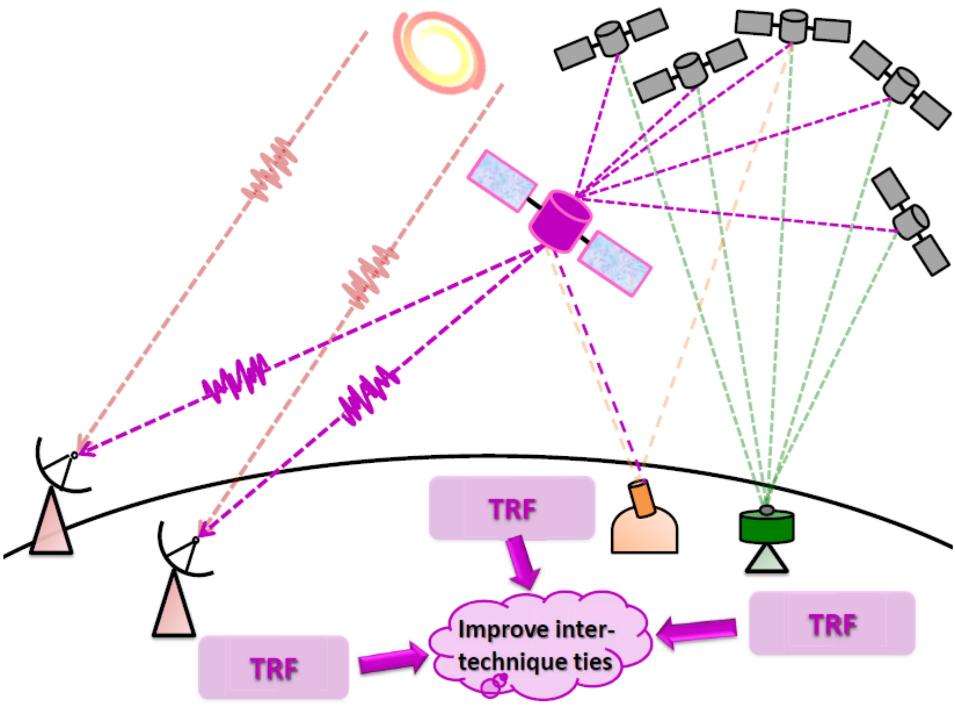

Figure m.2: Concept of co-location in space. A satellite that can be tracked by several space geodetic techniques (e.g. VLBI, SLR, GNSS) realizes a space-tie, directly connecting the frames determined by the different techniques (from Plank et al., 2013).

Working Group 1.4.3: Maintenance of Celestial Reference Frames and the link to the new GAIA Frame

Chair: Chopo Ma (U.S.A.)

Working Group 3 dealt with the maintenance of the ICRF and the link to the new GAIA frame. This WG was the main link to the ICRF-3 WG by the IAU, and it guaranteed that the requirements for both communities were fulfilled: the best possible ICRF-3 as well as the consistency of the ICRF-3 with other space geodetic techniques.

A lot of activities were stimulated towards observing new observation campaigns, in particular for sources in the southern hemisphere. For example, the AUSTRAL network was applied since the second half of 2013 to observe sessions dedicated to southern sources. Furthermore, a VLBA proposal by David Gordon et al. entitled "Second Epoch VLBA Calibrator Survey Observations for ICRF3" was approved and eight days of VLBA observations were used to re-observe many single epoch sources. The VLBA broadband RDBE system was used, which gave much greater sensitivity than the original VLBA Calibrator Survey sessions. For 2063 VCS sources that were re-observed the position errors were improved on average by a factor of ~4. Furthermore, Bourda et al. have provided a list of GAIA transfer sources that will be observed regularly by the IVS to improve their radio positions.

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Joint Working Groups of Commission 1

Joint Working Group 1.1: Tie Vectors and Local Ties to Support Integration of Techniques

Chair: Peirguido Sarti (Italy)

The Joint Working Group focuses on the provision of accurate tie vectors for ITRF computation. The estimation of tie vectors at co-location sites relies on several different and inter-connected phases that contribute and impact the final accuracy.

The JWG has been acting to focus the attention on tie vectors estimation and their importance in the ITRF computation, to bring together and discuss different approaches adopted locally at ITRF co-location sites and to compare the different methods with the purpose of assessing the accuracy of tie vector estimation procedures.

The JG has been meeting in a timely manner since 2004, usually at the most important international scientific meeting venues. A detailed list of the meetings can be found at the following web address: http://www.iers.org/nn_10900/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html?__nnn=true.

The activities of the JWG are closely linked to the realization of the ITRS and aims at spreading know-how and at defining standards to be adopted as reference in the tie vector estimation process.

So far, different surveying approaches and computation methods are adopted worldwide, mainly on a site-dependent base, which is determined by the surveying crew capabilities. There is a stringent necessity to validate the tie vectors that have been recently estimated as well as re-survey a number of co-location sites whose tie vectors are old (up to 25 years) and whose formal precision are dubious.

The JWG has boosted the discussion and brought together a very large number of scientists and surveyors whose interest are related to the ITRF, GGOS, space geodetic data analysis and local geodetic surveys. Indeed, the number of members of the JWG should reflect the large (33) number of members of the IERS WG and should therefore be updated.

The JWG has the merit to have finally brought together expertise covering the aspects of tie vector surveying and estimation, ITRF combination and space geodetic data analysis and provision of techniques specific solutions used in the combination.

Workshop on Site surveys and Co-locations – Paris – May 2013

The second workshop on site surveys and co-location sites took place in May 2013 in Paris. The web page of the meeting (http://iersworkshop2013.ign.fr/?page=scope) nicely and efficiently resumes relevant information such as the scopes of the workshop, its location, the list of participants, the list of presentations and the .pdf files containing the oral contributions. A very important product of the workshop was a list of recommendations that were identified with the contributions of all participants. The document sets actions, deadlines and the person in charge of the specific actions.

Main items and topics were identified and relate to the definition of a clear nomenclature and terminology to be adopted for local tie aspects, to the models to be adopted in the local tie survey data reduction, to the survey priority list for the next ITRF2013 computation, to the surveying frequency, to the creation of a local survey data archive and the preparation of a draft document containing the site survey guidelines and specifications.

This last aspect has been a long-term objective of the working group whose solution is needed but is far from trivial. A coordinated effort of the whole surveying community is needed and the JWG is the best context to approach the topic and try to solve it with an international coordinated effort.

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

Chair: Xavier Collilieux (France)
http://iag.uni.lu/index.php?id=53.

Overview

The accuracy and precision of current space geodetic techniques are such that displacements due to non-tidal surface mass loading are measurable. Although some models are available, there are still open questions regarding the application of loading corrections for the generation of operational geodetic products. The goal of this working group is to ensure that the optimal usage of loading model is made for Terrestrial Reference Frame (TRF) computation.

Working group meetings

- April 2013: EGU general assembly
- May 2014: EGU general assembly
- October 2014: REFAG 2014. Notes of the meeting can be found on the IAG commission 1 website.

Main activity

The working group activity has been dominated by the IERS campaign "for space geodetic solutions corrected for non-tidal atmospheric loading", an action following the Unified Analysis Workshop 2011. A call for participation has been sent to the analysis technique coordinators of every service in the beginning of 2012. A 6-year loading data set has been generated at The Global Geophysical Fluid Center (GFC) to be used a priori in the data processing of the space geodetic technique observations. Analysis Centers from the four technique services have submitted 12 individual solutions from GNSS, Satellite Laser Ranging (SLR, Very Long Baseline Interferometry (VLBI) and Doppler Orbitography Integrated by satellite (DORIS). These solutions have been analyzed to determine:

- The effect of non-tidal atmospheric loading on the TRF datum and the Earth Orientation Parameters (EOPs)
- The effect of non-tidal atmospheric loading on individual averaged coordinates and velocities
- The level of agreement between a priori corrections and a posteriori corrections

Preliminary results have been presented at the EGU in 2013. They were of primary importance for the generation of the next ITRF. This campaign has been successful since it has allowed dialogues between modeling experts and technique ACs. The results of the analyses have been summarized in a paper in preparation (Collilieux et al., to be submitted). The main conclusions are:

- A posteriori and a priori corrections are similar at less than 0.2 mm WRMS
- for GPS/DORIS/VLBI after 6-parameter transformation.
- WRMS >=0.3 mm for SLR core stations
- but small effect on estimated long-term coordinates (> 3 years)
- Effect of atmospheric gravity in SLR analysis, even on EOPs.

Although they inform about the impact of the corrections on the daily/weekly and long-term geodetic products, only one model from one contribution (atmosphere) has been tested in this campaign. Future works are needed to investigate the level of agreement of all available loading models, which will be the main task for the next couple of years. It is crucial that users be aware of the strengths and limitations of the available models. In addition, the modeling of loading deformation related to ice melting should be a priority for the next term of the commission 1 in addition to missing lakes or other water basin contribution. Finally, a consistent model of geocenter motion and low degree gravity potential coefficients would be worth recommending in the future to be used by the 4 technique services.

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Publications

Collilieux X.; Altamimi, Z.; Métivier, L.; van Dam, T.; Appleby, G.; Boehm, Y.; Dach, R.; Fritsche, M.; Govind, R.; Koenig, R.; Krásná, H.; Kuzmicz-Cieslak, M.; Lambert, S.; Lemoine, F. G.; Luceri, C.; MacMillan, D.; Mareyen, M.; Pavlis, E.; Thaller, D., Using non-tidal atmospheric loading model in space geodetic data processing: Preliminary results of the IERS analysis campaign, EGU General Assembly 2013, 7-12 April, Vienna, Austria, EGU2013-4178, http://recherche.ign.fr/labos/lareg/IAG-JW1.2/nt-atml_campaign.html

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Joint Working Group 1.3: Understanding the Relationship of Terrestrial Reference Frames for GIA and Sea-Level Studies

Chair: Tilo Schöne (Germany)

Overview

Studies about long-term and/or regional sea level changes are depending in many ways on a global terrestrial reference frame. Radar altimeters (RA) measure sea level heights from space in a TRF, while tide gauges measure sea level at local spots with a local vertical reference. Both sea level information sources are connected and combined within a common reference frame for example by, adding GNSS or other space geodetic techniques to tide gauges. On the other hand, only a few tide gauges worldwide have such a connection to the TRF but are useful for many studies. To correct those gauges for at least the long-term 'geological' vertical displacement, GIA corrections are commonly applied.

The use of GNSS information in sea level science, the combination and assimilation of GNSS information into Glacial Isostatic Adjustment (GIA) models, the correction of GIA effects on altimetry or tide gauges, or combined studies using information from the different sources requires a common understanding of the individual reference frame realizations.

Today the ITRF realization and their respective updates form the basis for the individual space geodetic techniques. But, in researcher's daily work, individual realizations may more often be used. For example, the IGS time series are in a respective IGS frame close to ITRF, or satellite orbits for radar altimetry are using Laser- and DORIS-augmented frames. GIA models employ their own ITRF-independent reference.

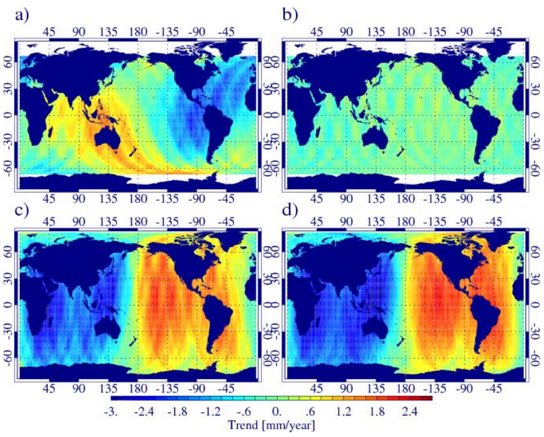
A major topic is about effects on RA satellite orbits from various external forces. Today, none of the RA satellites have complete kinematic orbit determination allowing directly constraining altitudes to the ITRF. Thus the derived orbit is dependent also on modeling of external forces and the effect of static and time variable gravity field models. Effects of the reference frame uncertainties on orbit determination may be predictable, while effects of the gravity field can heavily mask the impact.

Activities

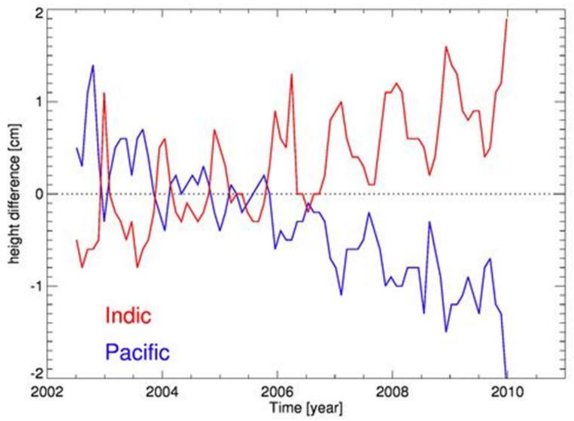
Due to the non-availability of new GNSS@TG reprocessing and new ITRF, studies concentrated on the evaluation of static- and time variable effects in orbit determination (e.g., Rudenko et al., 2014a) and in effects of reference frame (ex-)changes (e.g., Couhert et al., 2014). Both effects are of interest, since the effects of time-variable coefficients in the gravity field map in apparent hemispheric changes in sea level. Also recently studies were published demonstrating the effects of vertical land motion models (VLM) on RA-derived sea level time series (e.g., Watson et al., 2015).

Earlier studies focusing on effects on ERS-1, ERS-2, and ENVISAT have been extended to Topex/Poseidon and JASON-1. The reference frames underlying the orbit determination included ITRF2005, ITRF2008, but orbit determination also uses SLRF2008 (for laser tracking stations) and DPOD2008 (for DORIS tracking stations). The effects of the inclusion of the later both reference frames have not yet studied in detail, but should be once the new ITRF is available. Still a pitfall for the reference frame is the missing inclusion of the PRARE system requiring inhomogeneous inclusion into each ITRF realization (Rudenko et al. 2102).

However, it needs to be recognized that currently reference frame effects in RA satellites still have smaller effects on the radial component than other orbit modeling effects, like gravity (e.g., Esselborn et al., in press).



Trend of radial orbit differences for different processing centres (ESOC/GFZ/GSFC) and different orbit standards (C/D): Jason-1 **a**: GDR (C) minus ESOC (D) *and* **b**: GDR (C) minus GSFC; Envisat **c**: GDR (C) minus ESOC (D) *and* **d**: GDR (C) minus GFZ (D)



Time series of Envisat radial orbit differences for two sites located at areas of high RMS: 32°S / 42°E and 15°N / 155°E. Both orbits originate from GFZ and differ only by the geopotential field used (EIGEN-GL04S_ annual and EIGEN-6S). These time series are equivalent to sea level changes when updating the orbit model. (Esselborn et al., in press)

Important contributions for the understanding of reference frame issues in sea level research are summarized in Collilieux and Altamimi (2013) and in the External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2 (Collilieux et al., 2014).

Outlook

Until the release of the IGS TIGA Working Group and IGS repro2 results, the studies necessary for this task cannot fully continued and performed. After the release and the availability of the new ITRF studies for reference frame issues for the combination of GNSS time series and GIA corrections with tide gauge and altimetry time series will be performed outside the JWG 1.3 but within this scope. Also under study will be loading effects in the near- and at-shore GNSS stations at tide gauges and their relation to tide gauge time series.
Also the reference frame studies for radar altimetry will be extended to more recent other missions, like Topex/Poseidon, Jason-1, Jason-2. The studies will be extended to better understand time variable gravity field effects on altimetric orbits and reference frame issues (ITRF2013). This study is still under the ESA CCI initiative.

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Joint Working Group 1.4: Strategies for Epoch Reference Frames

Chair: Manuela Seitz (Germany)

Overview

The objectives of the Joint Working Group 1.4 are the realization of global short-term reference frames (epoch reference frames) and the development of strategies for their application for datum realization (alignment) of regional short-term reference frames. Epoch reference frames have a lot of advantages compared to ITRF, even if their long-term stability does not reach the level of ITRF stability. It is recommended that epoch reference frames shall be provided as add-ons to ITRF solutions.

The JWG has 13 members from eight countries. The work of the group is presented in 15 publications and 18 presentations. Additionally, the Website (http://www.dgfi.badw.de/index.php?id=403) improves the visibility of the activities of the Working Group. The work of the JWG is strongly linked to the activities of the IERS WG Combination on observation level (COL). During the last four years two COL meetings are organized in Munich, in May 2012 and in May 2013.

Computation of epoch reference frames

The computation of Epoch Reference Frames is - like the ITRF computation - based on the combination of the space geodetic techniques VLBI, SLR, GNSS and DORIS. This combination can be done at different levels of the Gauß-Markov adjustment model (Seitz, 2012). We perform the combination at the level of normal equations and at the level of observations in order to identify the individual strengths of these combinations methods. The flowchart for the computation of weekly epoch reference frames at the normal equation level is given by Fig.1.4.1.

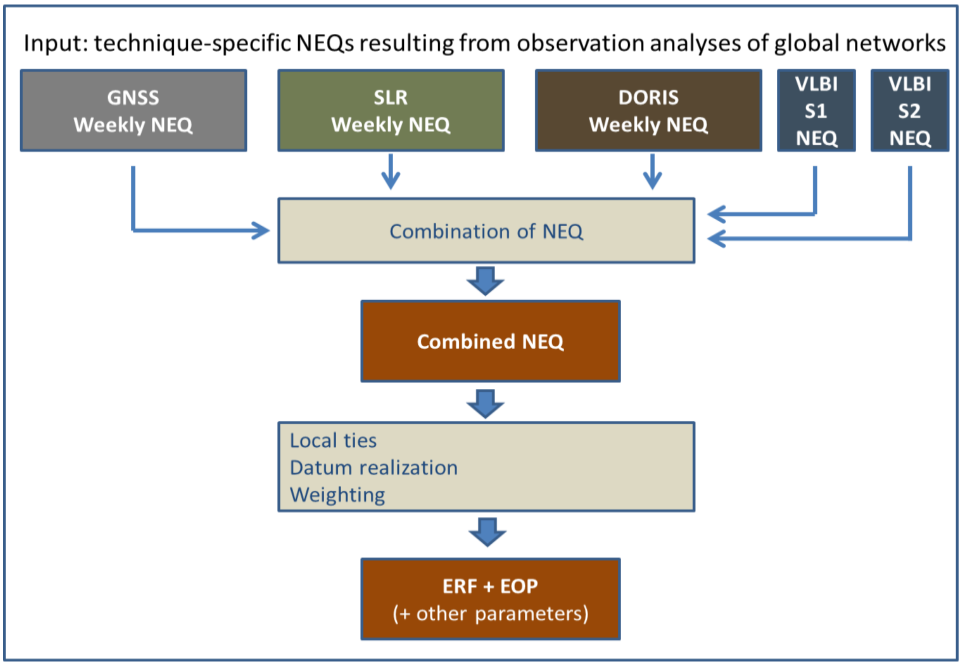

Figure 1.4.1: Strategy for the computation of epoch reference frames developed and applied at DGFI.

Weekly normal equations of the satellite techniques are combined first and then the VLBI normal equations are included session by session. The combined parameters are station positions, terrestrial pole coordinates, LOD and nutation rates. In a second step also gravity field coefficients are adjusted consistently. The most important steps in the combination, which are also central components of the research activities, are the introduction of local tie information, the weighting of the techniques and the datum realization.

The following research activities were performed with respect to the computation of epoch reference frames and the improvement of their accuracy and stability:

- *Improvement of datum realization for weekly SLR solutions by including 10 spherical SLR satellites (Bloßfeld et al. 2015b)*
  In addition to LAGEOS1 and 2, in particular LARES contributes significantly to the de-correlation of estimated parameters and hence to an improved determination of the geodetic datum. Figure 1.4.2. shows the RMS of weekly translation and scale parameters for the LAGEOS only, the three satellite and a 10 satellite solution. ILRS now also plans to include LARES in the routinely product generation.
- *Combination of SLR, GNSS and VLBI for the computation of weekly reference frames*
  The resulting station positions and EOP are compared to a multi-year TRF solution (ITRF). The non-linear station motions - not considered in ITRF and mainly caused by non-tidal atmospheric, hydrologic and oceanic loading but also by local effects - has an impact on the consistently estimated EOP series. Clear annual and semi-annual signals with amplitudes of up to 39.4 μas could be identified in the EOP difference series of ITRF and epoch reference frames (Bloßfeld et al. 2014).
- *Impact of time interval of epoch reference frames on datum stability*
  In order to improve the stability of datum realization for epoch reference frames (which does not reach the ITRF level of stability) different solution series are computed with a temporal resolution of one week, two weeks and four weeks. The analysis of the different datum parameter series shows that the RMS improves with increasing time interval but anyway all series represent the annual signal very well (Bloßfeld et al. 2015a). Therefore, from the view of datum realization a four-weeks solution should be preferred. But, the approximation of the station motions becomes more imprecise increasing the time interval and therefore, the ideal time interval must be defined depending on the main application of epoch reference frames.
- *Extending parameterization of epoch reference frames by temporal-highly resolved gravity field coefficients*
  The simultaneous estimation of TRF, EOP and gravity field coefficients is one of the goals of GGOS. For this task, SLR plays an important role, as it is the only technique which allows for the determination of all of these parameter groups with reliable accuracy (Bloßfeld, 2015c). It could be shown that the combination of 10 SLR satellites leads to a clear de-correlation of the estimated parameters in the SLR solutions and the combination with GNSS further reduces the correlations between the translation and orientation of the solution due to the good global distribution of the GNSS network (Bloßfeld 2015).
- *Combination of GNSS and SLR at the observation level*
  The studies related to the combination at the observation level were performed mainly at the University of Berne (AIUB) and the Bundesamt für Kartographie und Geodäsie (BKG) and are linked to the activities of the IERS Working Group on Combination at the Observation Level (COL). Therefore GNSS and SLR observations to GNSS satellites are combined and TRF, orbits and EOP are estimated consistently. The results show that the

origin (centre-of-mass derived from SLR observations) can be transferred very well in the combined TRF solution even if no local ties at co-location sites are used. This allows for a validation of local ties on the Earth.

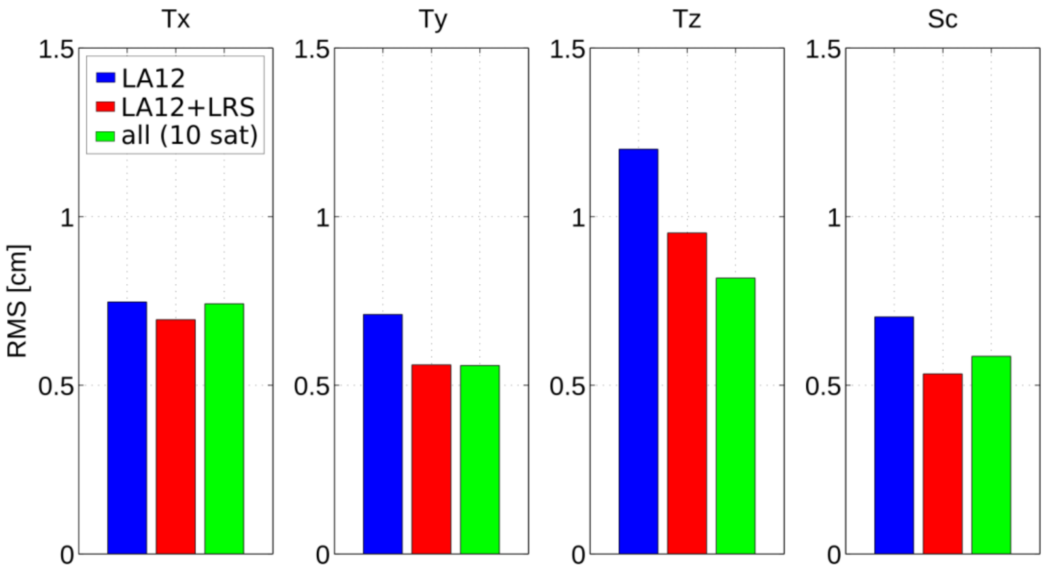

Figure 1.4.2: RMS of weekly translation and scale parameters of three different SLR solutions w.r.t. SLRF2008. Blue: LAGEOS1 and 2, Red: LA1, 2 and LARES, Green: 10 satellite solution. While the inclusion of LARES improves the RMS values significantly, only for z-translation a further improvement could be shown using all 10 satellites.

In summary the results of the research activities show that

- Datum realization for epoch reference frames can be improved by using an SLR solution which includes at least LARES in addition to LAGEOS1 and 2,
- The time series of weekly epoch reference frames approximate the complete station motion (linear and non-linear part) very well,
- The neglect of non-linear station motions in long-term reference frames affects the consistently estimated EOP-series by annual and semi-annual signals (Bloßfeld et al. 2014),
- Epoch reference frames do not provide such a high long-term stability as long-term reference frames. With regard to the geodetic datum four-weeks solutions show the highest stability. But non-linear station motions are characterized by short-term effects, which can be approximated better with a weekly or even shorter resolution,
- The integration of 10 spherical SLR satellites in the SLR solution and the combination of the techniques allow for a simultaneous estimation of TRF, EOP and gravity field coefficients in epoch reference frame solutions with high accuracy,
- The weekly combination at the observation level of GNSS and SLR (via satellite co-location) leads to very promising results, which allow the transfer of the SLR-derived centre-of-mass of the Earth to GNSS station network with very high accuracy and for a validation of the local ties at ground sites.

The advantages and disadvantages of epoch reference frames compared to ITRF are:

- Epoch reference frames approximate non-linear station motion very well.
- Highly resolved TRF, EOP and gravity field coefficients can be estimated consistently with reliable accuracy (GGOS goal).

- Annual and semi-annual geocenter variations can be derived with high accuracy from four-week epoch reference frames.
- EOP are not affected by non-linear signals in station motions.

Application of epoch reference frames

Regional GNSS-based epoch reference frames are meanwhile standard within the International GNSS Service (IGS), e.g., for Europe (EUREF) or Latin America and the Caribbean (SIRGAS) and are important in particular for real-time applications. To realize the geodetic datum of the regional epoch reference frames, they are aligned to the ITRF or long-term IGS solutions. Since these long-term solutions do not consider non-linear station motions - which are fully included in the epoch-wise estimated station positions -, the alignment is in particular affected by the seasonal signals in the station positions, which are mainly caused by atmospheric and hydrological mass load changes but also by very local – sometimes unknown – effects. Therefore, the weekly SIRGAS solutions are now aligned to the weekly IGS solution. This improves the consistency of the time series of weekly SIRGAS solutions significantly and demonstrates the importance of epoch reference frames.

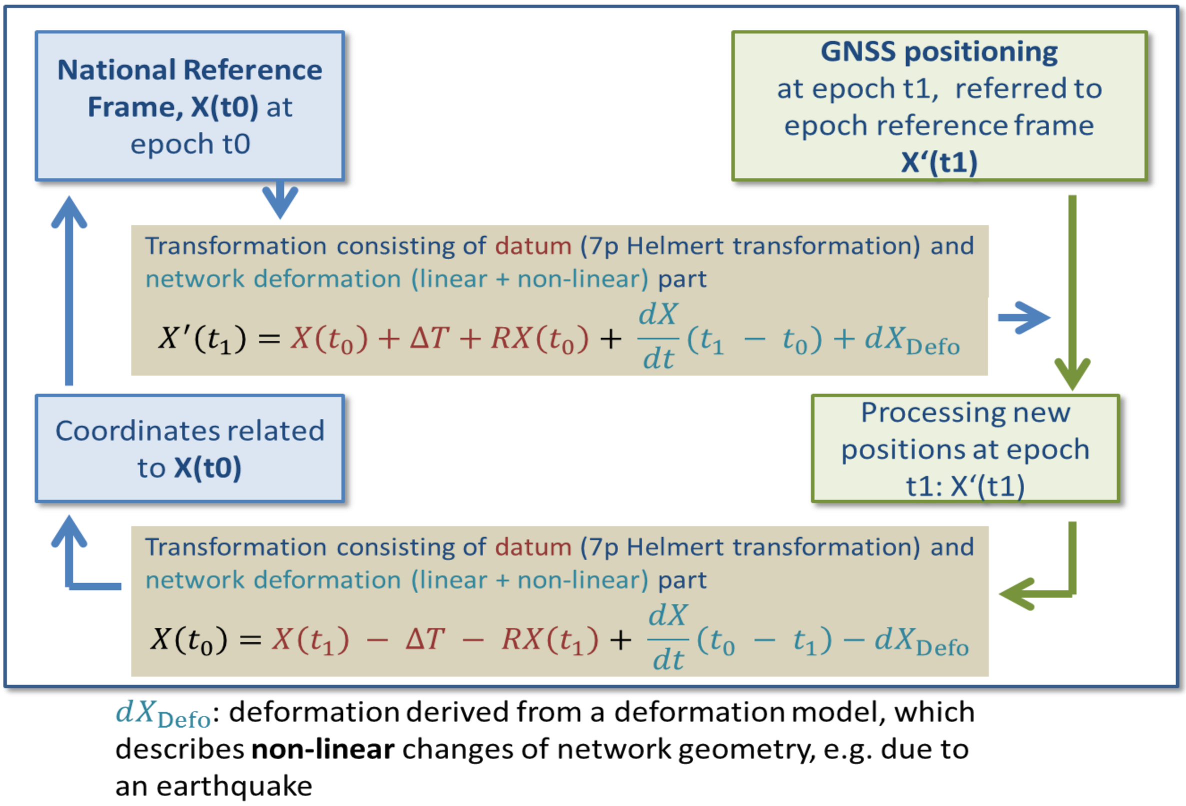

Figure 1.4.3: Transformation between epoch reference frames and national frames for regions affected by deformations. The approach considers also the transformation of positions of new stations into the national frame.

For GNSS-applications, which should be related to a national reference frame, a transformation between the global or regional reference frame, in which the GNSS positions are obtained, and the national frame have to be performed. The reference epochs of the frames often differ by some years. The transformation is in particular problematic for regions affected by seismic events, which usually induce large non-linear station motions. Figure

1.4.2 shows the developed concept of how a transformation between a regional epoch reference frame and a national reference frame (and vice versa) should be performed, including also the transformation of the positions of new stations into the national frame. Besides a 7-parameter similarity (Helmert) transformation, a deformation model is considered (Drewes and Heidbach, 2012), describing the deformations of the network in time.

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Commission 2 – Gravity Field

http://www.iag-commission2.ch

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

Structure

Sub-Commission 2.1:	Gravimetry and gravity networks
Sub-Commission 2.2:	Spatial and temporal gravity field and geoid modelling
Sub-Commission 2.3:	Dedicated satellite gravity missions
Sub-Commission 2.4:	Regional geoid determination
Sub-Commission 2.4a:	Gravity and geoid in Europe
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Sub-Commission 2.4c:	Gravity and geoid in North and Central America
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Sub-Commission 2.4e:	Gravity and geoid in Asia-Pacific
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Sub-commission 2.5:	Satellite altimetry
Sub-commission 2.6:	Gravity and mass displacements
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Joint Working Group 2.1:	Comparisons of absolute gravimeters
Joint Working Group 2.2:	Absolute gravimetry and absolute gravity reference system
Joint Working Group 2.3:	Assessment of GOCE geopotential models
Joint Working Group 2.4:	Multiple geodetic observations and interpretation over Tibet
Joint Working Group 2.5:	Physics and dynamics of the Earth's interior from gravimetry
Joint Working Group 2.6:	Ice melting and ocean circulation from gravimetry
Joint Working Group 2.7:	Land hydrology from gravimetry
Joint Working Group 2.8:	Modelling and inversion of gravity - solid Earth coupling
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

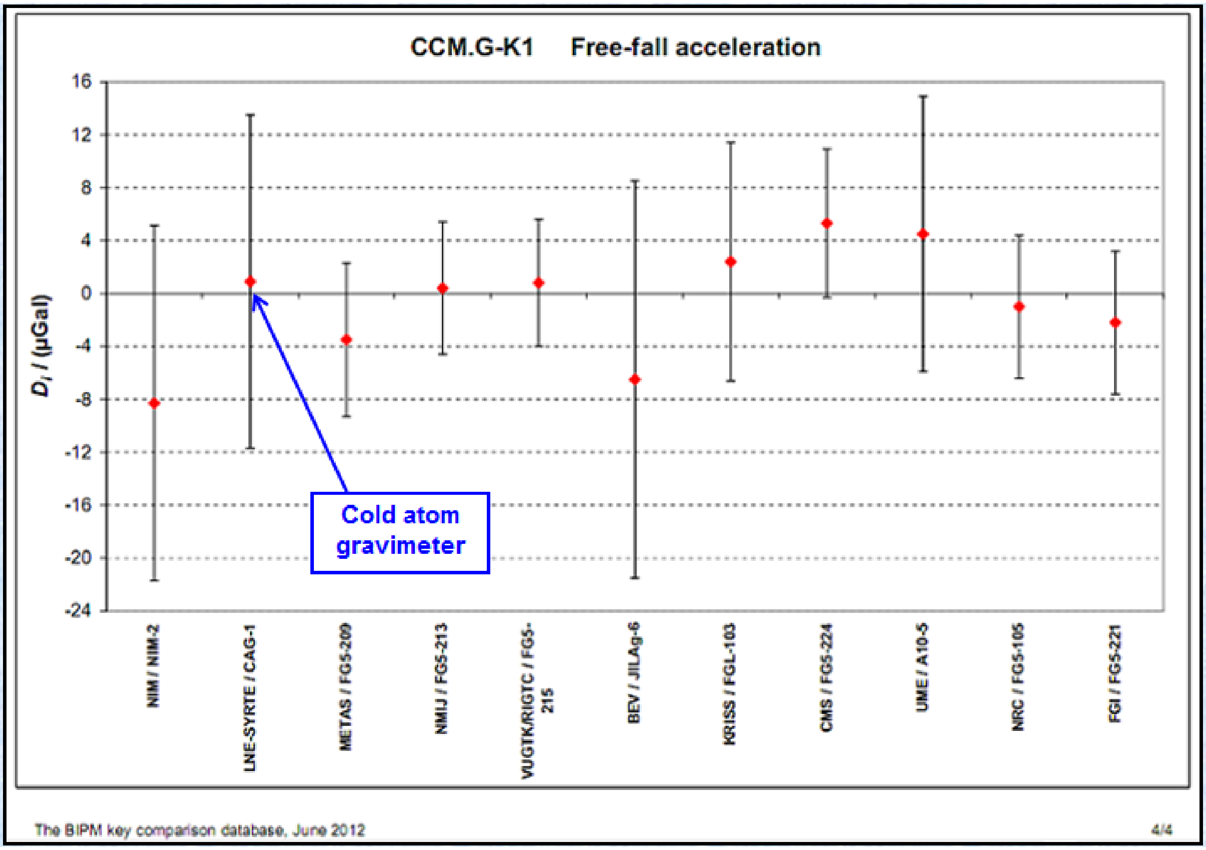

Fig. 1. The results of Key comparison CCM.G-K1 (2009, BIPM, Sèvres, France).

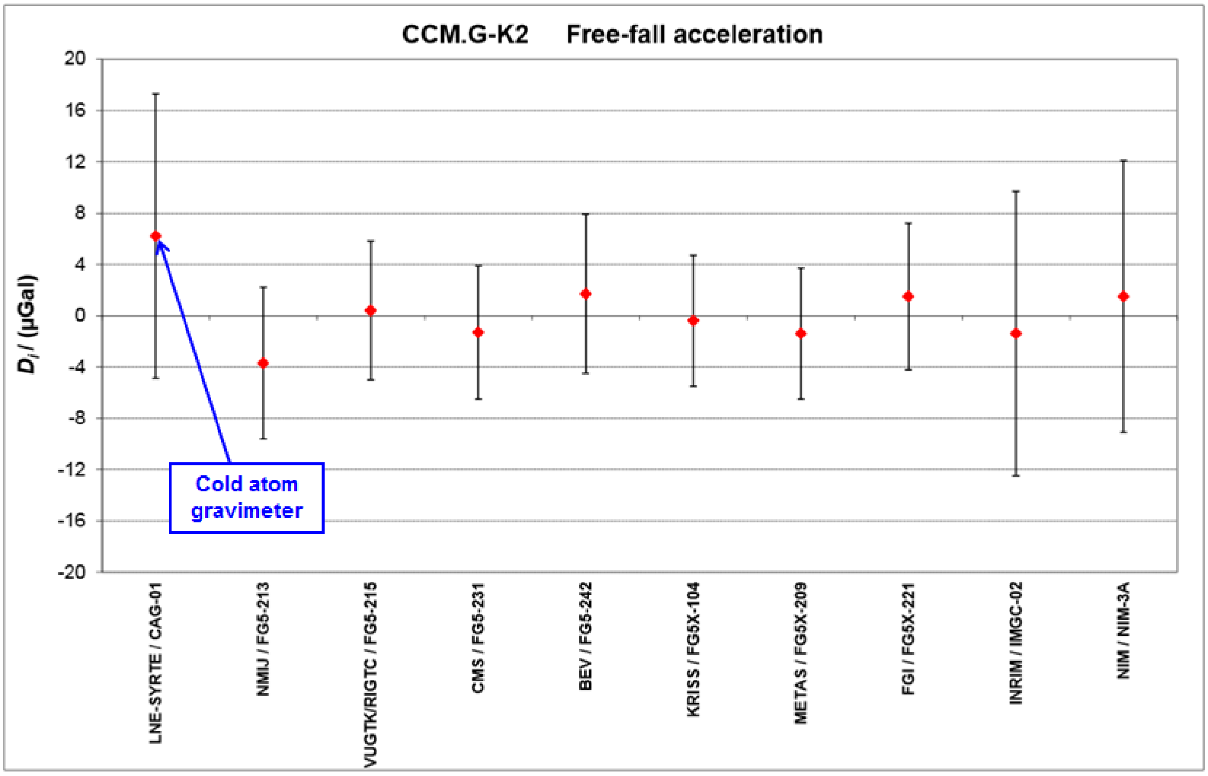

Fig. 2. The results of Key comparison of absolute gravimeters CCM.G-K1 (2013, Walferdange, Luxembourg).

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).

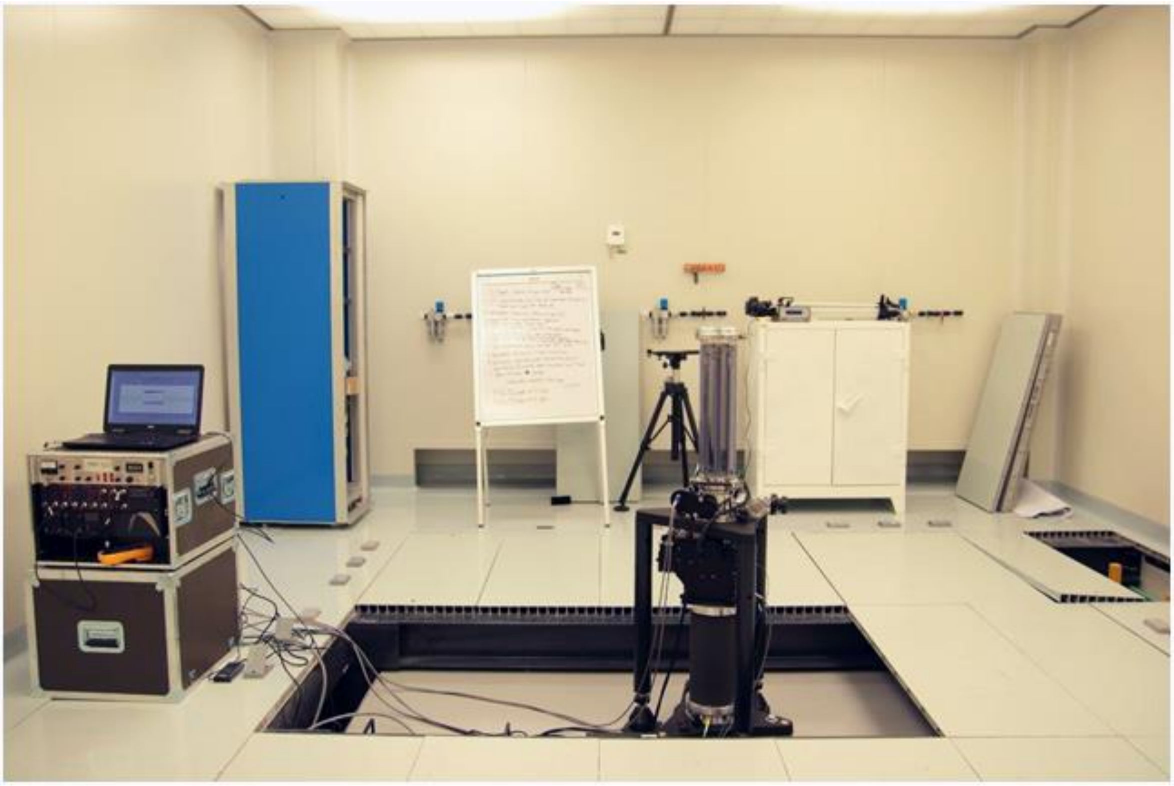

Fig. 3. A gravimetric site in the national metrology institute of Mexico CENAM.

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.

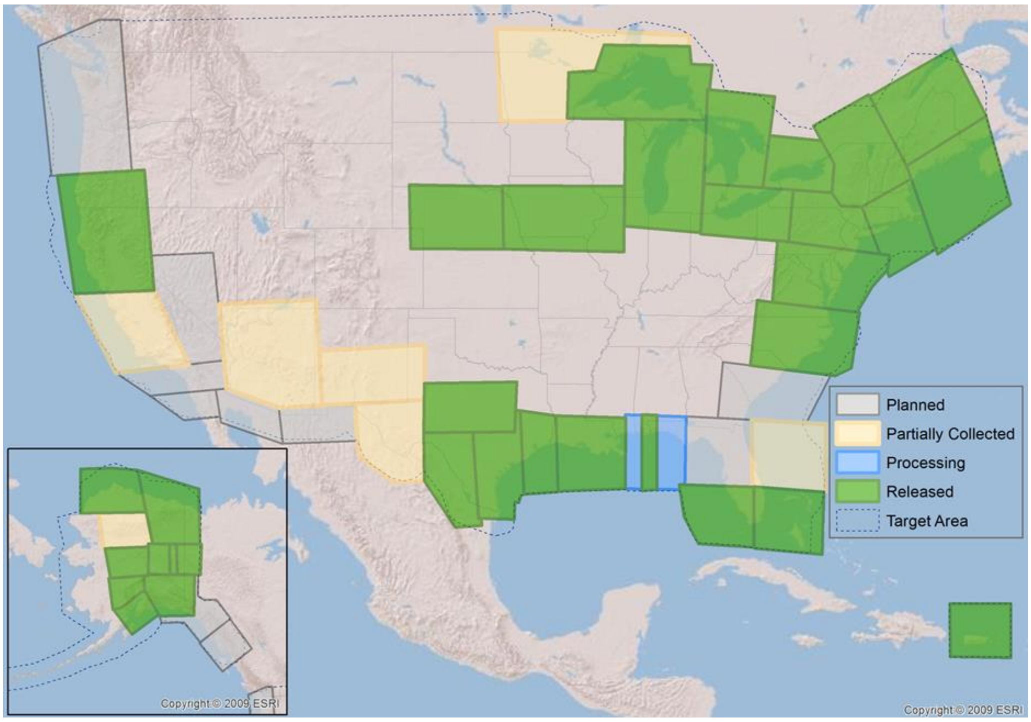
New Vertical Datum (USA Canada)

- 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.

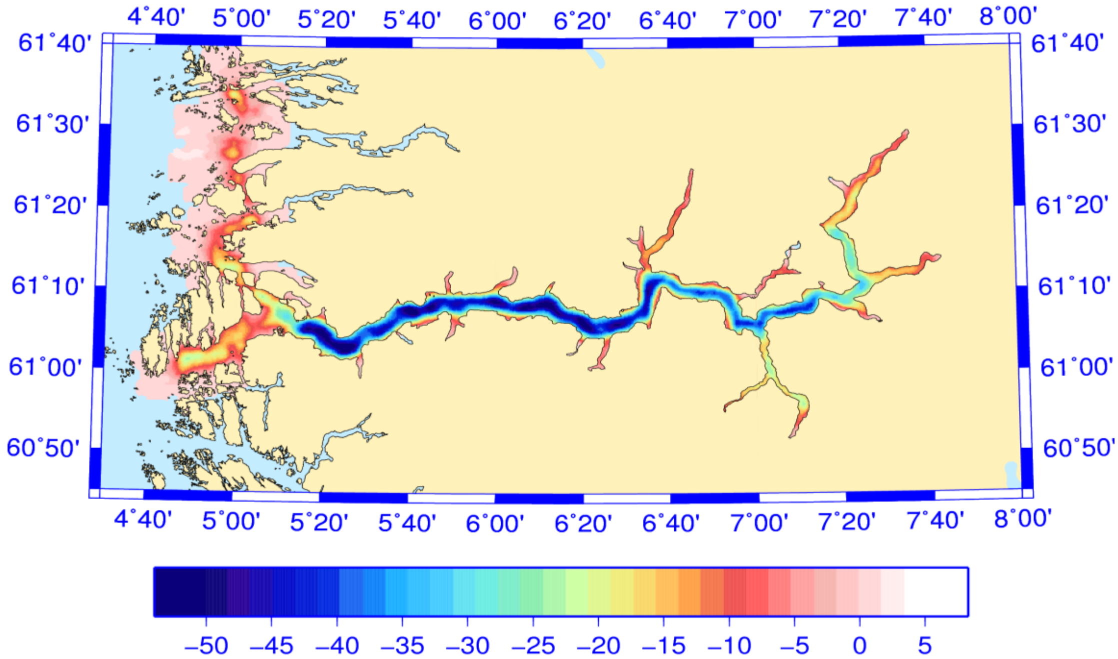

Fig. 1. Gravity signal from the Sognefjorden (units mGal)

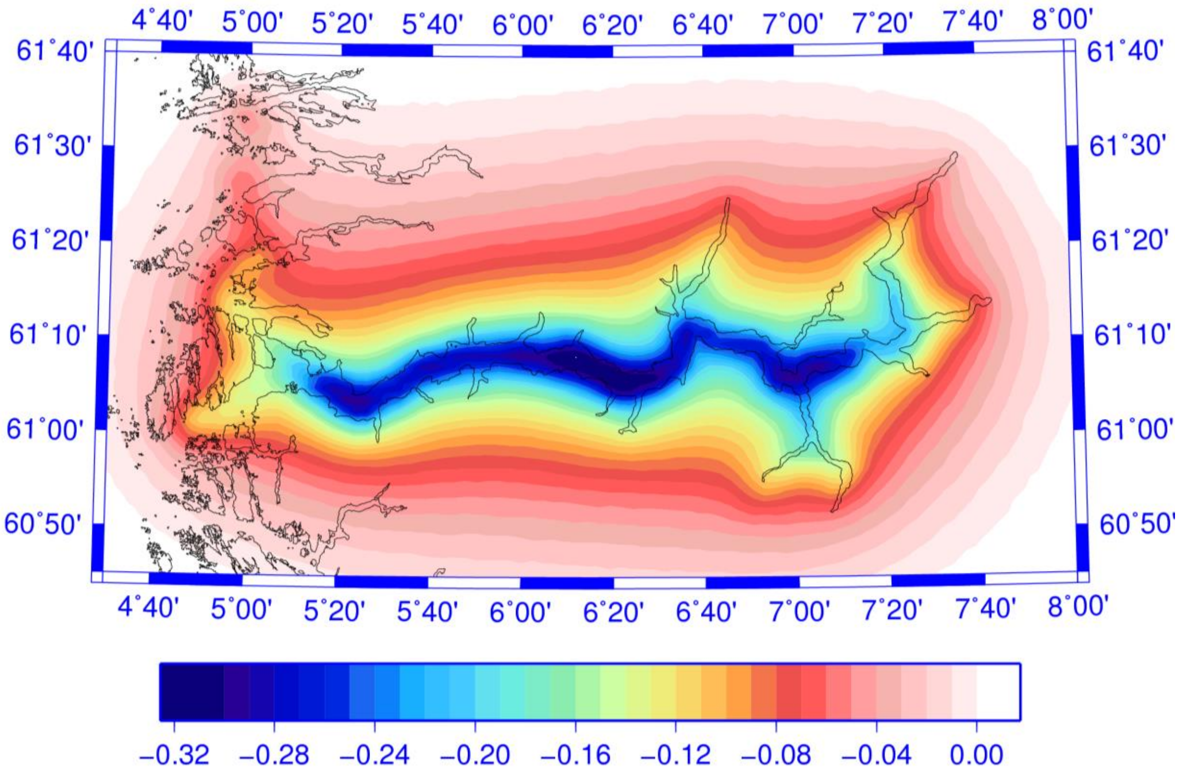

Fig. 2. Effect on the geoid when including the marine gravity data shown in Fig. 1 (units mGal)

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 – RosAeroSystems" (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 & 2.

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.

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.

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).

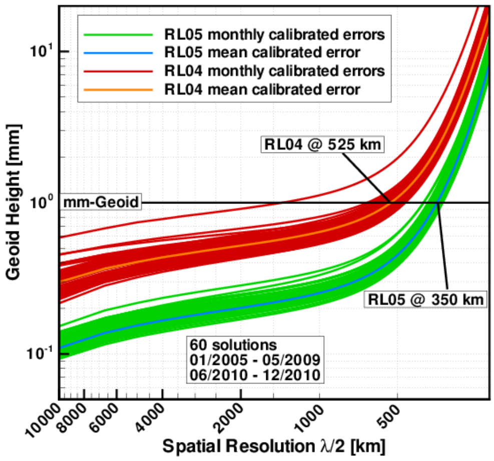

Figure 1: Degree variances of calibrated GRACE errors

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.

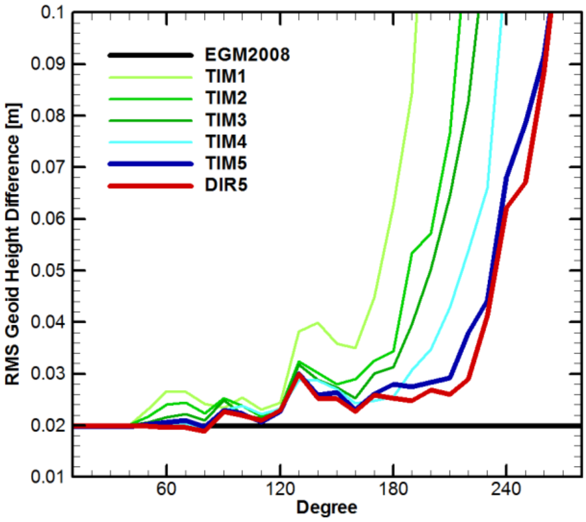

Figure 2: Rms of geoid height differences in Germany

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 iono-sphere 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.

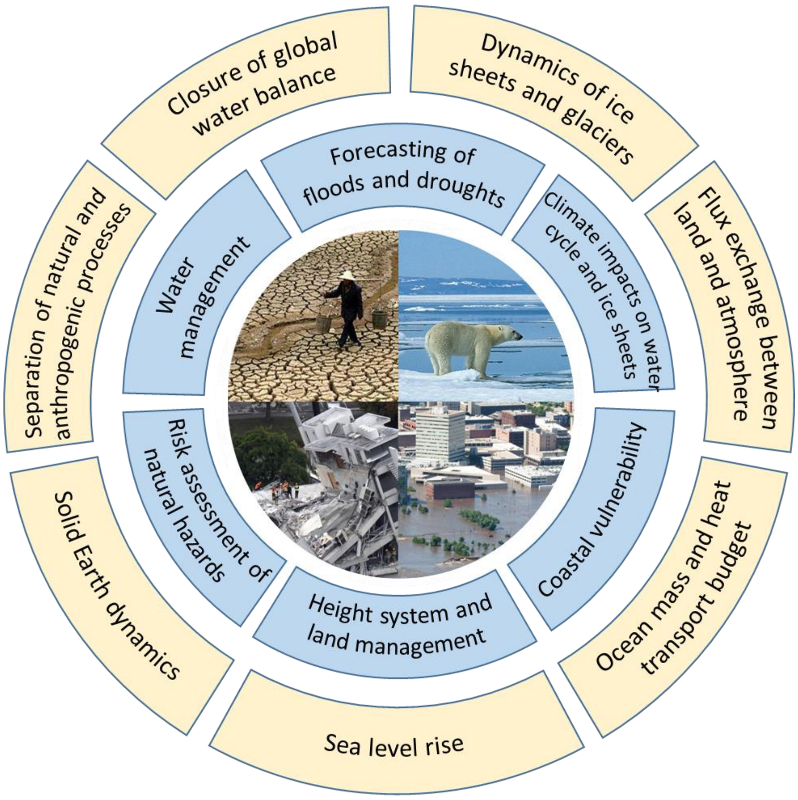

Figure 3: Main scientific (yellow) and societal (blue) objectives addressed by a future sustained satellite gravity observing system.

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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.

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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.

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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.

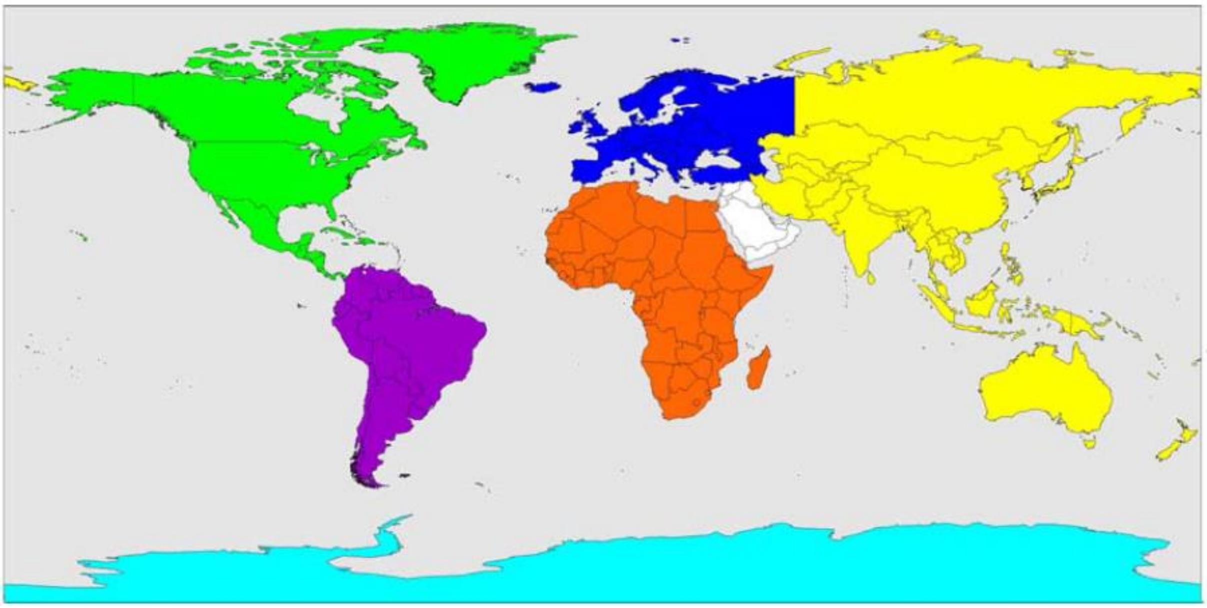

Figure 1: Coverage of the regional sub-commissions

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 database 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),

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

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.

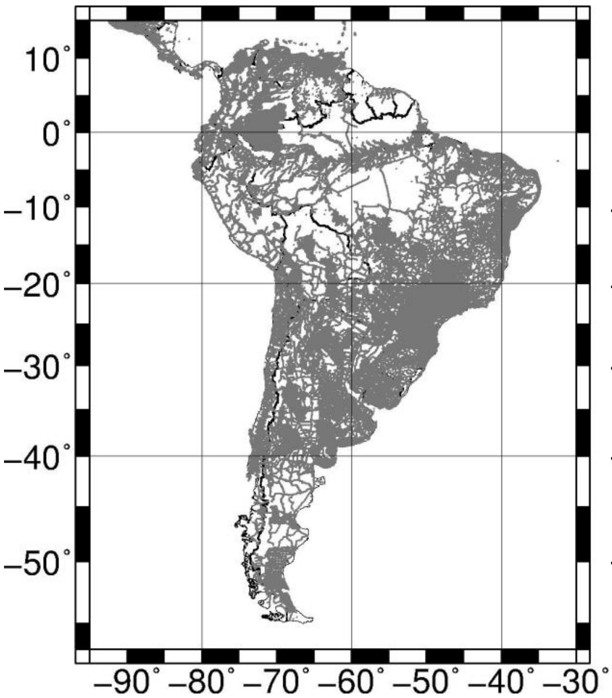

Figure l: South America gravity data

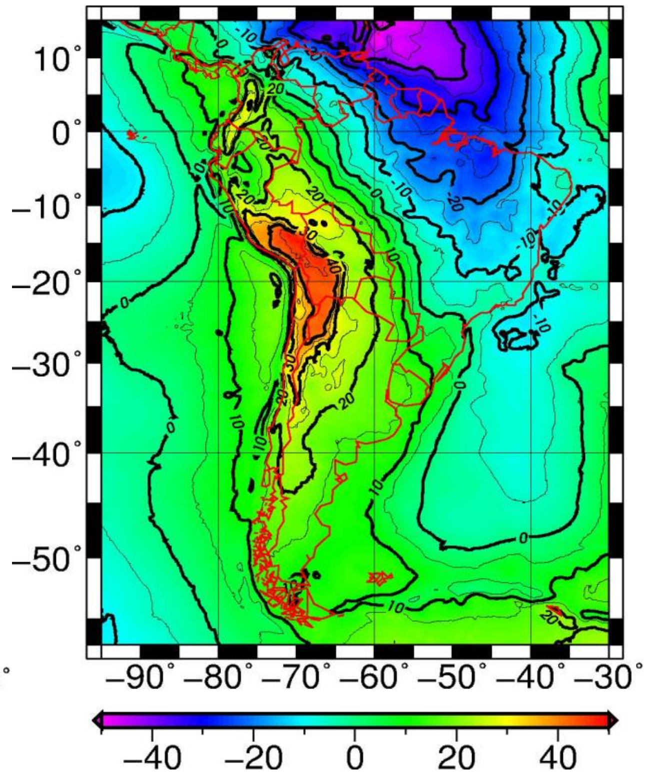

Figure 2: South America geoid model

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

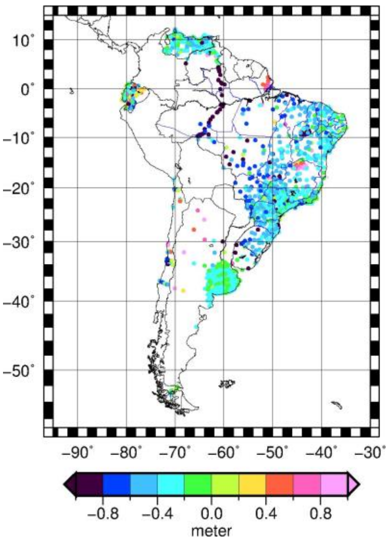

Figure 3 - Distribution of the GPS/BMs and illustration of the differences between GPS/BM geoidal heights and EIGEN6C4 (max. degree) height anomalies.

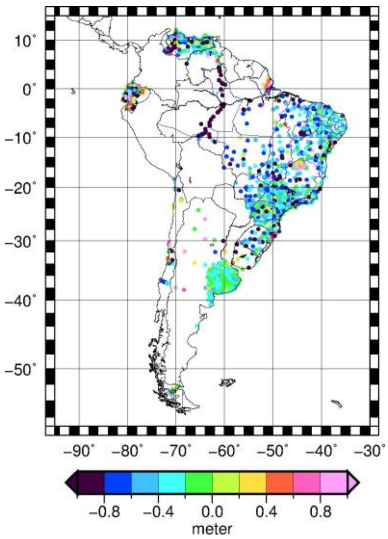

Figure 4 - Distribution of the GPS/BMs and illustration of the differences between GPS/BM geoidal heights and DIR_R5 (max. degree) height anomalies.

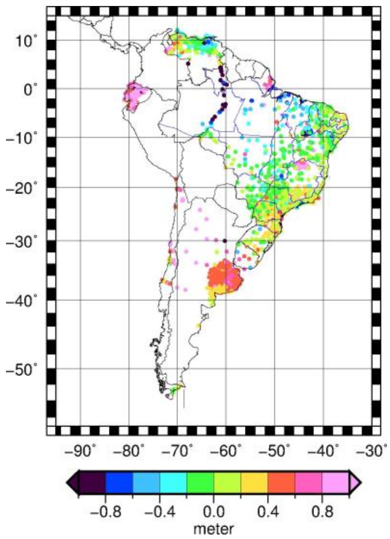

Figure 5 - Distribution of the GPS/BMs and illustration of the differences between GPS/BM and GEOID2014 geoidal heights.

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.

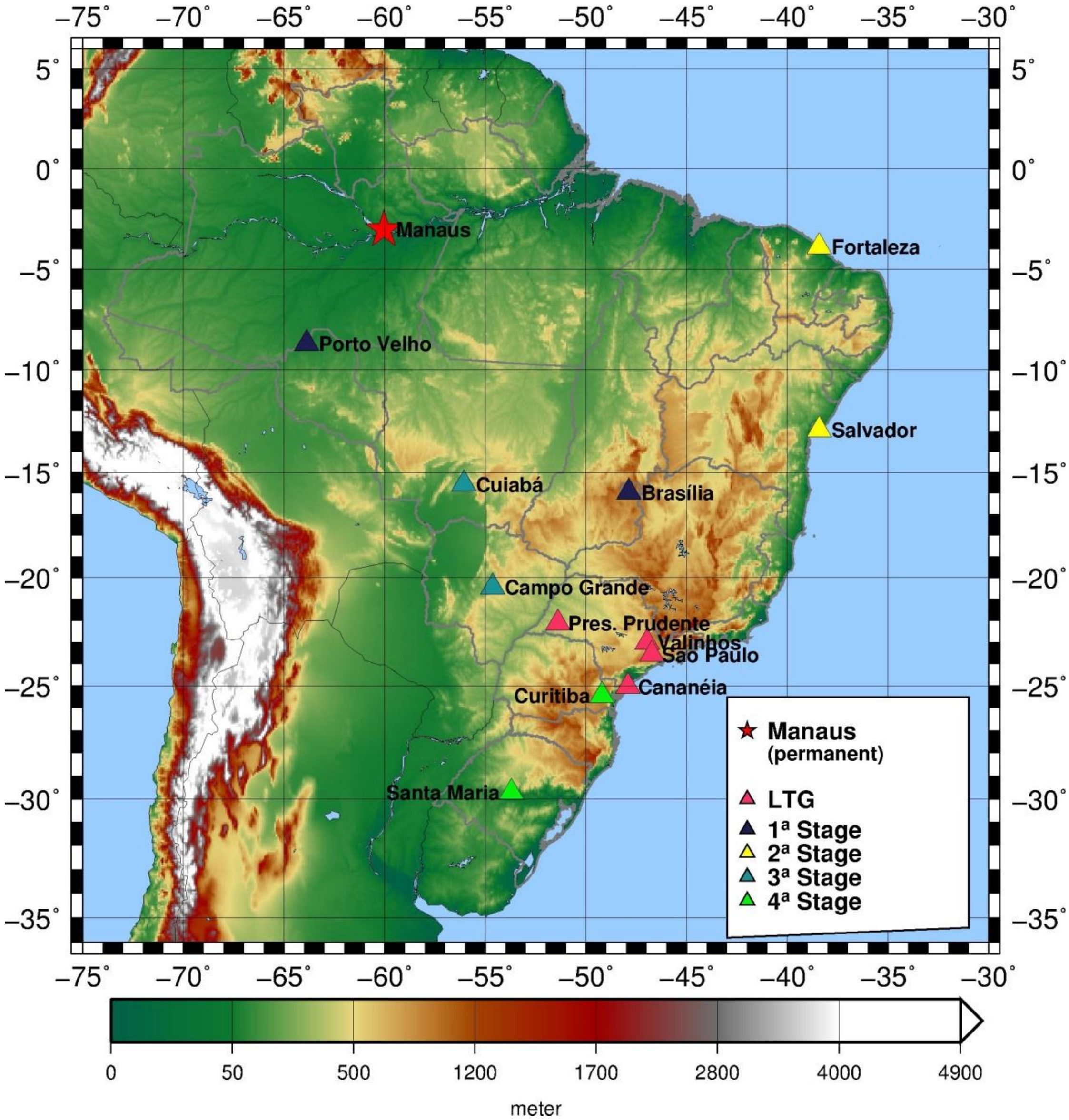

Figure 6 - Distribution of sites to be observed for Earth tides.

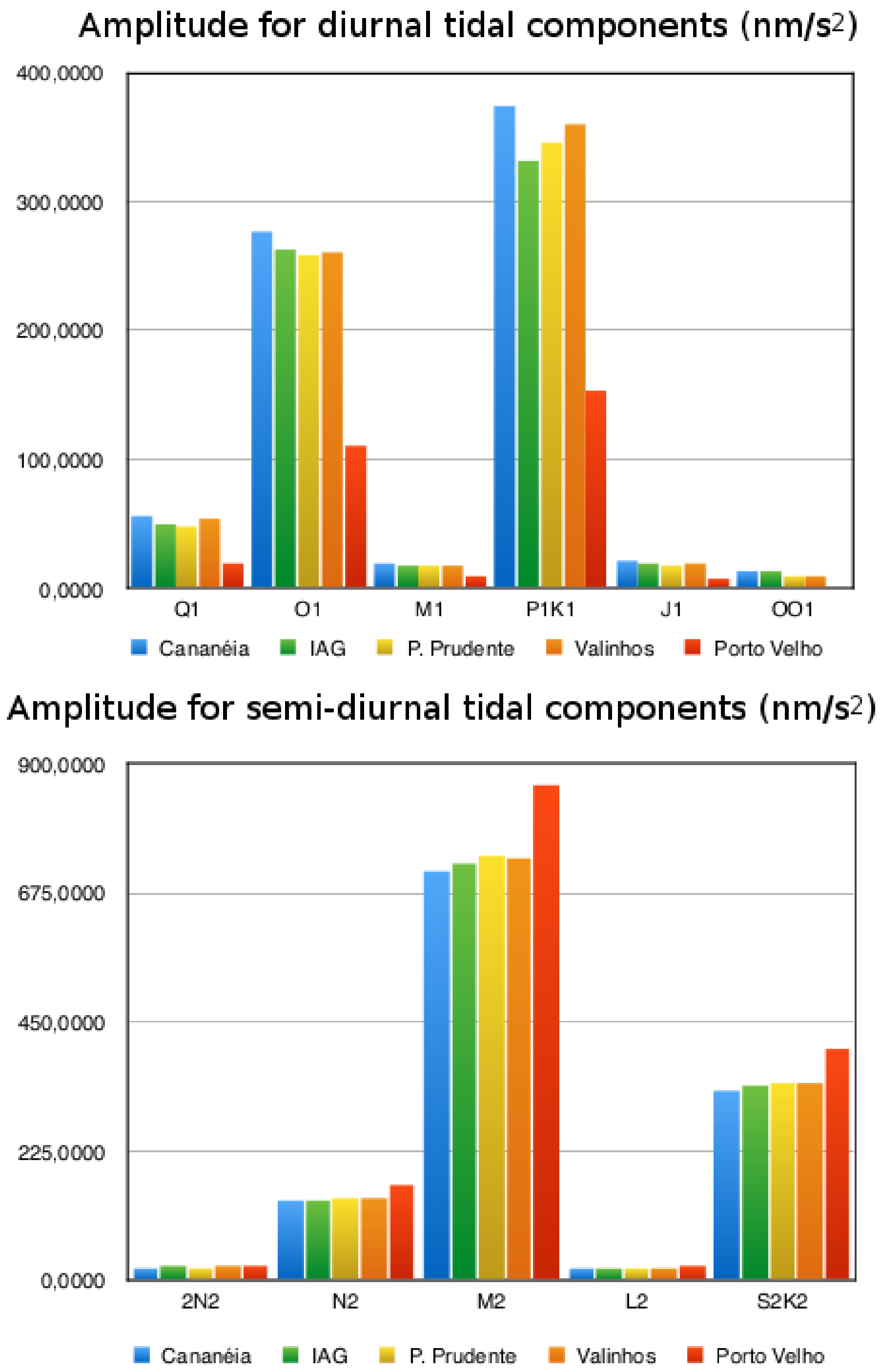

Figure 7 - Results for 5 stations already observed.

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.

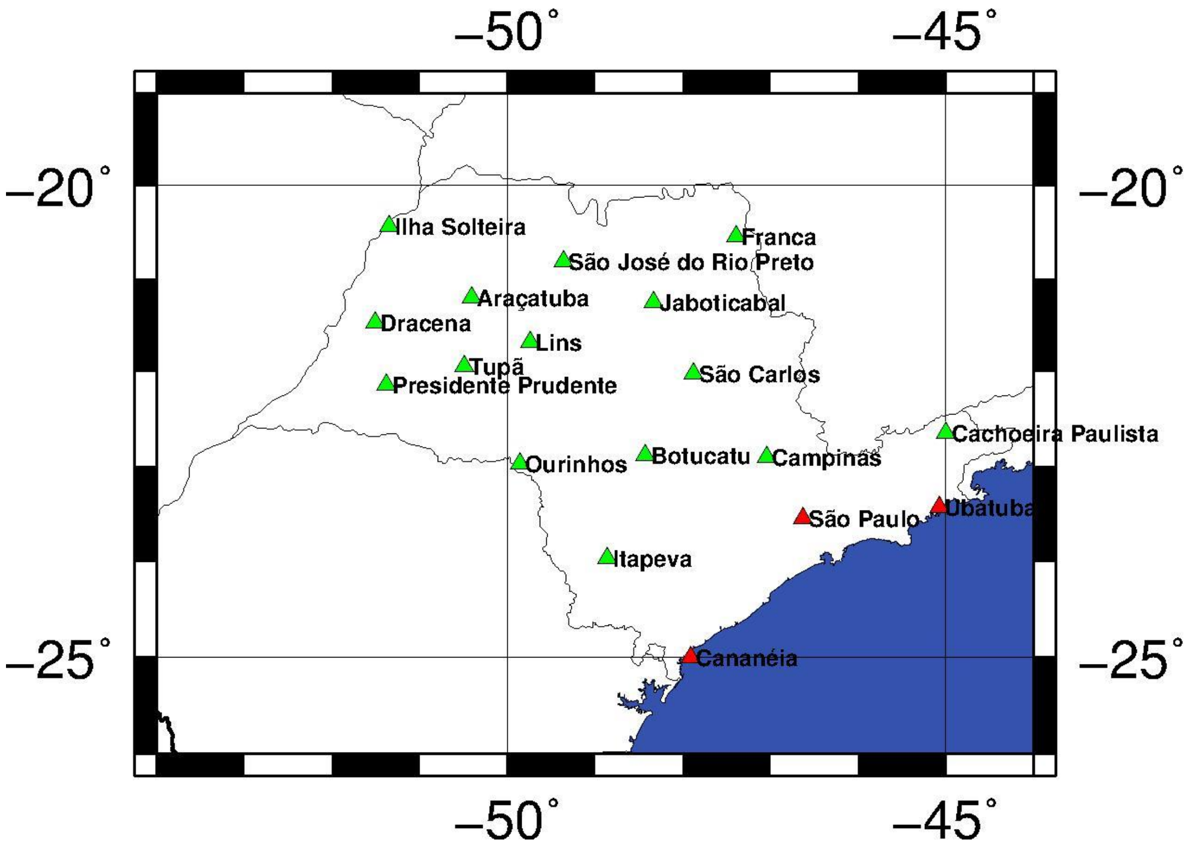

Figure 9 - Absolute gravimetric station in São Paulo State.

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.

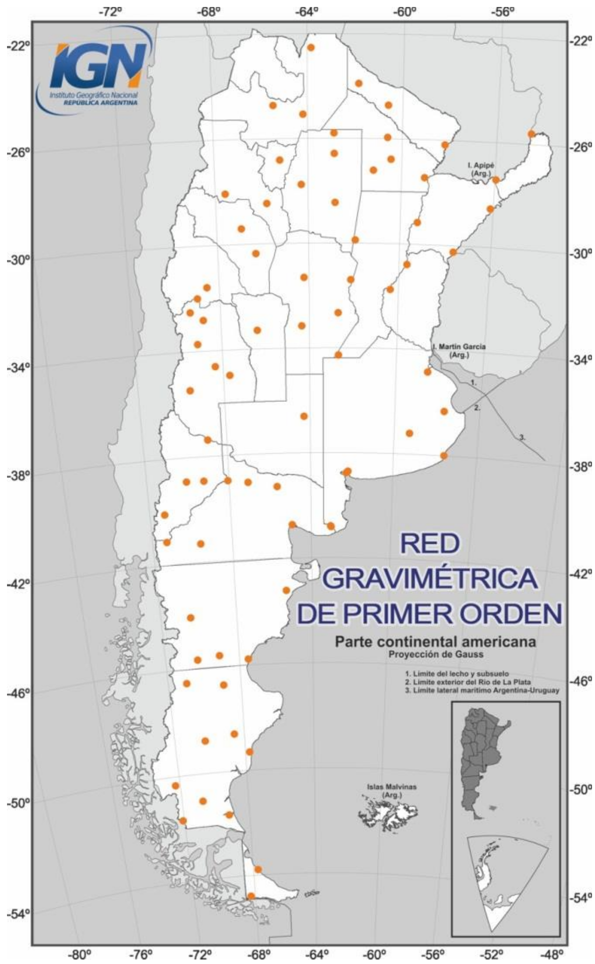

Figure 10: BACARA gravity network

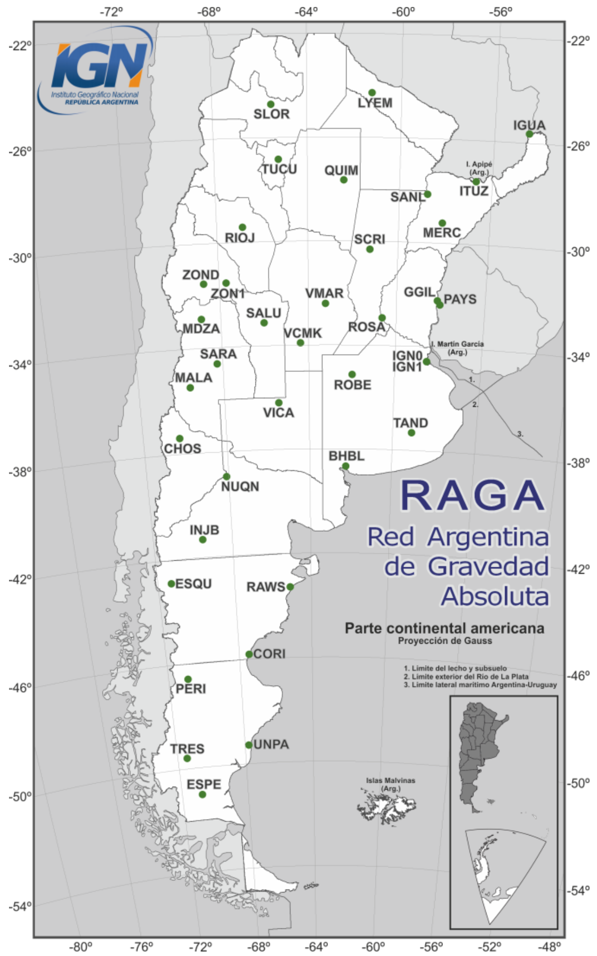

Figure 11: Absolute gravity network

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.

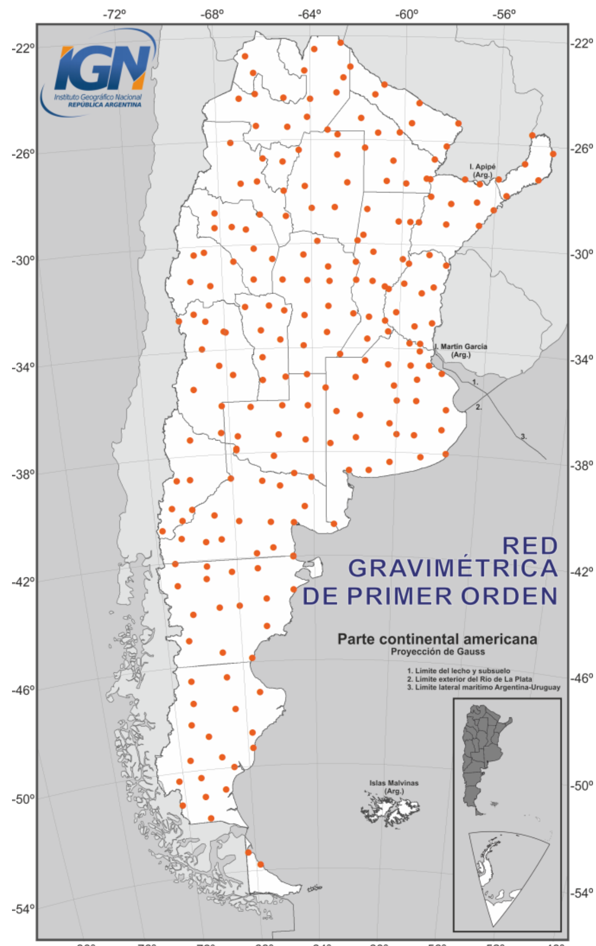

Figure 12: new first-order gravity network

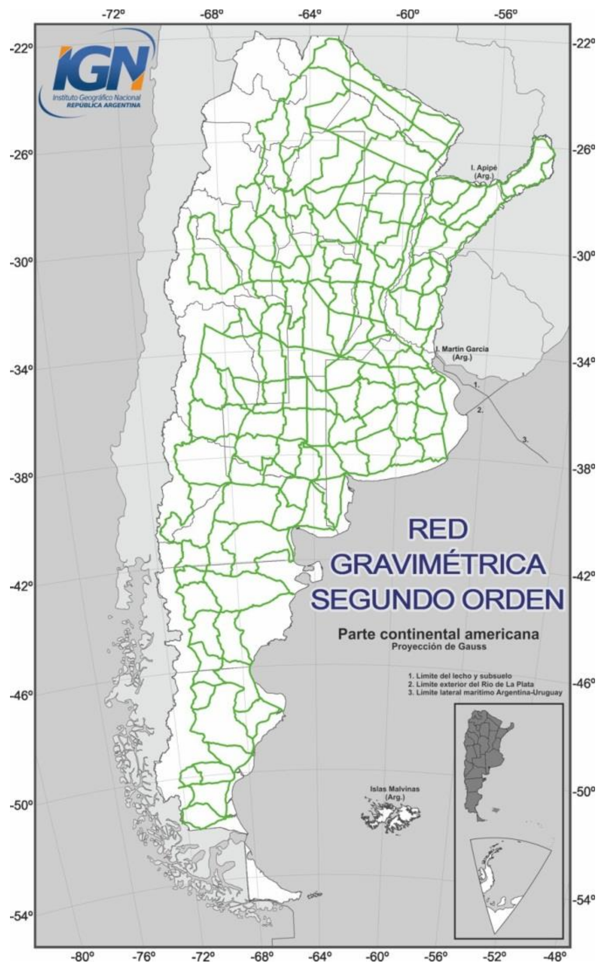

Figure 13: second-order gravity network

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

Chair: David Avalos (Mexico)

Steering Committee

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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

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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.

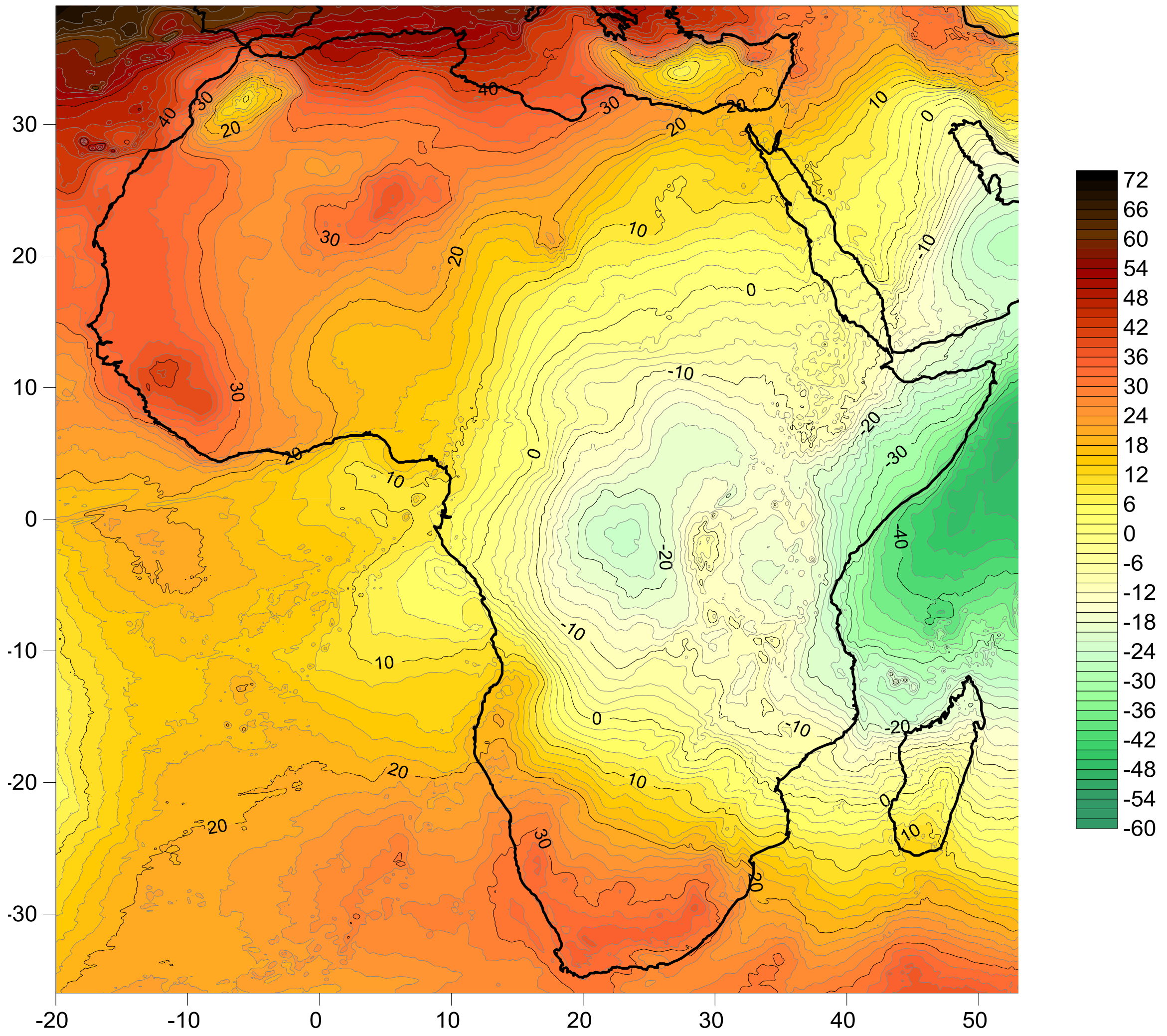

Figure 1: The African geoid model AFRgeo2015 (after Abd-Elmotaal et al., 2015c).

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

Abd-Elmotaal, H. (2014a) Egyptian Geoid using Ultra High-Degree Tailored Geopotential Model. Proceedings of the 25th International Federation of Surveyors FIG Congress, Kuala Lumpur, Malaysia, June 16–21, 2014, (peer reviewed paper), URL: http://www.fig.net/pub/fig2014/papers/ts02a/TS02A_abd-elmotaal_6856.pdf.

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.

Abd-Elmotaal, H. (2015b) Validation of GOCE Models in Africa. Newton's Bulletin, 5 (submitted).

Abd-Elmotaal, H., Abd-Elbaky, M. and Ashry, M. (2013) 30 Meters Digital Height Model for Egypt. VIII Hotine-Marussi Symposium, Rome, Italy, June 17-22, 2013.

Abd-Elmotaal, H. and Ashry, M. (2013) The 3″Digital Height Model for Egypt – EGH13. 8th International Conference of Applied Geophysics, Cairo, Egypt, February 25–26, 2013.

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.

Abd-Elmotaal, H. and Makhloof, A. (2014b) Combination between Altimetry and Shipborne Gravity Data for Africa. 3rd International Gravity Field Service (IGFS) General Assembly, Shanghai, China, June 30 – July 6, 2014.

Abd-Elmotaal, H., Makhloof, A. and Ashry, M. (2014) Experiments with Different Techniques for Combination of Gravity Field Wavelength Components for Geoid Determination in Egypt. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 27 – May 2, 2014.

Abd-Elmotaal, H. and Kühtreiber, N. (2014a) The Effect of DHM Resolution in Computing the Topographic-Isostatic Harmonic Coefficients within the Window Technique. Studia Geophysica et Geodaetica, Vol. 58, 41–55, DOI: 10.1007/s11200-012-0231-6.

Abd-Elmotaal, H. and Kühtreiber, N. (2014b) Automated Gross Error Detection Technique Applied to the Gravity Database of Africa. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 27 – May 2, 2014.

Abd-Elmotaal, H., Seitz, K., Abd-Elbaky, M. and Heck, B. (2015a) Tailored Reference Geopotential Model for Africa. International Association of Geodesy Symposia Journal, Vol. 143, DOI: 10.1007/1345_2015_84.

Abd-Elmotaal, H., Seitz, K, Kühtreiber, N. and Heck, B. (2015b) Establishment of the Gravity Database for the African Geoid. International Association of Geodesy Symposia Journal, DOI: 10.1007/1345_2015_51.

Abd-Elmotaal, H., Seitz, K, Kühtreiber, N. and Heck, B. (2015c) African Geoid Model AFRgeo2015. IUGG2015, Prague, Czech Republic, June 22 - July 2, 2015.

Benahmed Daho S.A., Goughali M. (2013) A refined geoid model for Algeria using EGM2008 and the satellite altimetry-derived marine gravity anomalies in Algeria. Communication accepted for presentation in IAG General Assembly – Potsdam - Germany (Gravity Field Determination and Applications / Regional gravity and geoid studies).

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).

Bell, R. E., Ferraccioli, F., Creyts, T. T., Braaten, D., Corr, H., Das, I., Damaske, D., Frearson, N., Jordan, T., Rose, K., Studinger, M., Wolovick, M. (2011): Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base, *Science*, 331 (6024), 1592-1595, doi: 10.1126/science.1200109

Bingham, R. G., Ferraccioli, F., King, E. C., Larter, R. D., Pritchard, H. D., Smith, A. M., Vaughan, D. G. (2012): Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts, *Nature*, doi:10.1038/nature11292

Cochran, J. R., and R. E. Bell. (2012) Inversion of IceBridge gravity data for continental shelf bathymetry beneath the Larsen Ice Shelf, Antarctica. *Journal of Glaciology*, 58(209), 540-552, doi: 10.3189/2012JoG11J033.

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Ferraccioli, F., et al. (2013): New airborne-gravity and satellite gravity views of crustal structure in Antarctica, Presentation G54A-05, AGU Fall Meeting, San Francisco, 9-13 December 2013.

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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Jordan, T., F. Ferraccioli, N. Ross, M. Siegert, H. Corr, P. Leat, R. Bingham, D. Rippin, and A. le Brocq (2013): Inland extent of the Weddell Sea Rift imaged by new aerogeophysical data, *Tectonophysics*, 585, 137–160, doi: 10.1016/j.tecto.2012.09.010.

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).

Rogister, Y.; Hothem, L.; Nielsen, J. E.; Bernard, J.-D.; Hinderer, J.; Forsberg, R.; Wilson, T.; Capra, A.; Zanutta, A.; Winefield, R.; Collett, D. (2013): Observations with FG5 and A10 absolute gravimeters on Ross Island and in Terra Nova Bay in November-December 2011. Presentation EGU2013-11511, EGU General Assembly, Vienna, 7-12 April 2013.

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

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Scheinert, M. et al. (2012): GEOHALO: Geodetic-geophysical flight mission over the Mediterranean using the "High Altitude and Long Range Research Aircraft" (HALO), Pres., IAG Symposium "Gravity, Geoid and Height Systems", Venice, 9-12 October 2012

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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Schwabe, J., M. Scheinert (2014): Improved geoid solution for the Weddell Sea region. PANGAEA data archive, doi: 10.1594/PANGAEA.816380. Supplement to: Schwabe, J. and Scheinert, M. (2014).

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.

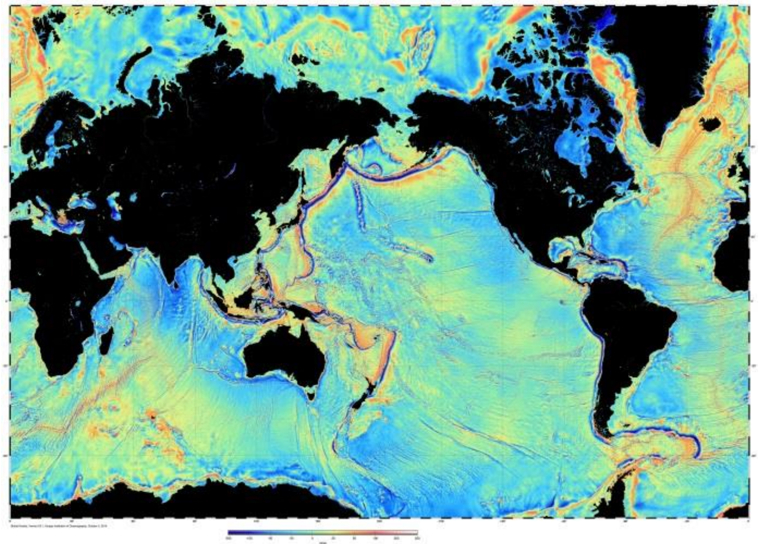

Figure 1. The latest global map of marine gravity - version 23.1 by Sandwell et al. (2014, http://topex.ucsd.edu/grav_outreach/)

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.

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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.

Publications

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Conference Papers

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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.

Jin, S.G., and F. Zou, Land-ocean leakage effects on glacier melting estimation in Antarctica from GRACE measurements, The 26th International Union of Geodesy and Geophysics (IUGG) General Assembly, 22 June -2 July 2015, Prague, Czech.

Jin, S.G., G.P. Feng, O. Andersen, and J. Sanchez Reales, Uncertainties of MDT and geostrophic currents estimated from GOCE and satellite altimetry: A case study in China's Marginal Seas, Proceeding of the 5th International GOCE User Workshop, 25-28 November 2014, Paris, France, pp. (Invited)

Avsar, N.B., B. Erol, S.H. Kutoglu, and S.G. Jin, Investigation of the Sea Level Rise and Its Impacts on the Coastal Areas for Black Sea, XXIV International Symposium on Modern Technologies, Education and Professional Practice in Geodesy and Related Fields, 6-7 November, 2014, Sofia, Bulgaria.

Feng, G.P., and S.G. Jin, Glacier melting contributions to global mean sea level change from satellite gravimetry, Proceeding of Asia-Pacific Remote Sensing Symposium, October 13-17, 2014, Beijing, China.

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Hassan, A.A., and S.G. Jin, Water storage and level variations in Lake Nasser (Africa) from satellite gravimetric and Landsat data, Proceeding of International Gravity Field Service (IGFS) General Assembly (IGFS2014), June 30-July 6, 2014, Shanghai, China, pp.

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Zou, F., and S.G. Jin, Land-ocean leakage errors in satellite gravity measurements using forward modeling, Proceeding of the 3rd International Workshop on Earth Observation and Remote Sensing Applications (EORSA 2014), June 11-14, 2014, Changsha, China, pp. 19-23, doi: 10.1109/EORSA.2014.6927841.

Jin, S.G., and X.G. Zhang, Time-varying gravity field from GPS observations: Evaluations and Applications, 6th CPGPS Forum, January 9-11, 2014, Xuzhou, Jiangsu, China. (Invited)

Jin, S.G., Time-varying gravity field from GNSS and LEO satellite observations and its applications, International Workshop on the Earth's structure and dynamics from geodetic and geophysical observations, December 6, 2013, Wuhan, China. (Invited)

Jin, S.G., and F. Zou, Recent melting of Greenland's glaciers observed by InSAR and satellite gravimetry, Proceeding of Progress In Electromagnetics Research Symposium (PIERS), 12-15 August, 2013, Stockholm, Sweden.

Feng, G., S.G. Jin, and F. Zou, Melting of ice-sheet in the Tien-Shan Mountains observed by satellite gravity measurements, International Conference on Geoinformatics, June 20-22, 2013, Kaifeng, China.

Jin, S.G., Y. Barkin, and W. Shen, Observation evidences on the northward drift of the Earth's core from space geodesy, Japan Geoscience Union Meeting, May 19-24, 2013, Makuhari Messe, Japan.

Hassan, A., and S.G. Jin, Water cycle and climate signals in Africa observed by satellite gravimetry, Proceeding of the 35th International Symposium on Remote Sensing of Environment (ISRSE35), April 22-26, 2013, Beijing, China.

Jin, S.G., and G.P. Feng, Glacier melting in Tibet observed from satellite gravity measurement, International Conference on Cryosphere: Changes, Impacts and Adaptation, November 10-12, 2012, Sanya, China.

Jin, S.G., Observing and understanding the Earth system from space, Redbud Forum on Global Change Science, Tsinghua University, November 1, 2012, Beijing, China.

Jin, S.G., and G.P. Feng, Interannual variations of glacier melting in the Antarctic from satellite gravimetry, Annual Conference of China Polar Science, October 24-27, 2012, Hangzhou, China.

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Jin, S.G., What can Space Geodesy do? Recent Results and Challenges, Forum on Geomatics Science and technology, 12-14 October 2012, Lanzhou, China

Jin, S.G., and X.G. Zhang, Excitations of length-of-day variations determined from GPS, SLR and GRACE, IAU XXVIII General Assembly, 20-31 August, 2012, Beijing, China, pp.

Zhang, T., and S.G. Jin, Evaluation of glacial isostatic adjustment uplift rates in the Tibetan Plateau from satellite gravimetry, International Symposium on Space Geodesy and Earth System, August 18-20, 2012, Shanghai, China.

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Jin, S.G., Low degree gravitational changes and large scale mass transport from GPS, SLR and GRACE, International Symposium on Space Geodesy and Earth System, Aug. 18-20, 2012, Shanghai, China.

Hassan, A., and S.G. Jin, GRACE detection of water storage variation in Africa and its response to climate events, Proceeding of International Symposium on Space Geodesy and Earth System, Aug. 18-20, 2012, Shanghai, China, pp.

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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.

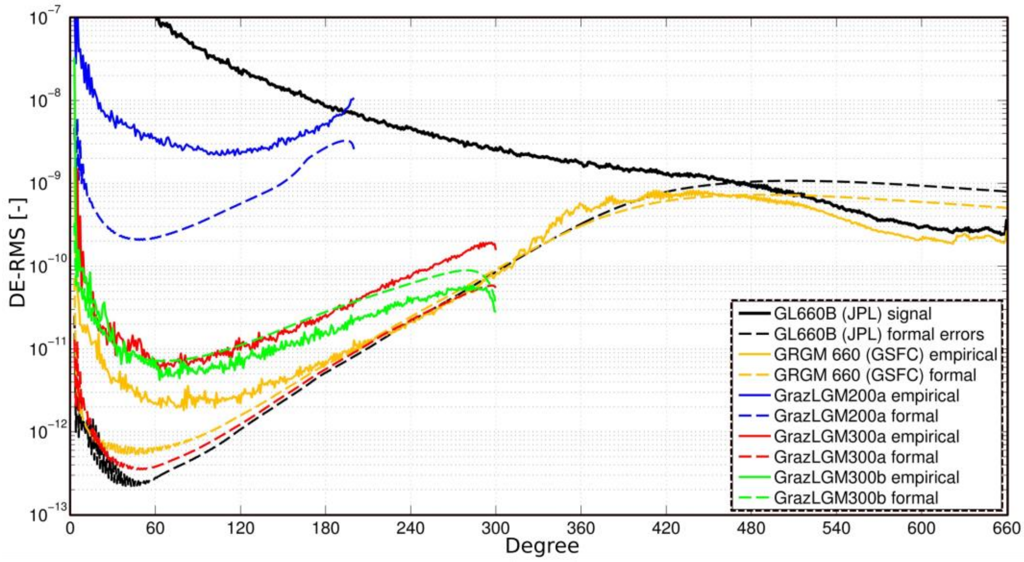

Figure 1. RMS values per spherical harmonic degree for different GRAIL gravity field solutions based on data collected during the primary mission phase (March 1 to May 29, 2012); figure taken from Krauss S., Klinger B., Baur O., Mayer-Gürr T. (2015) Development of the lunar gravity field model GrazLGM300b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

Biolcati E, Svitlov S, Germak A (2012). Self-attraction effect and correction on three absolute gravimeters, Metrologia, 49, 560–566.

Francis O et al. (2013). The European Comparison of Absolute Gravimeters 2011 (ECAG-2011) in Walferdange, Luxembourg: results and recommendations. Metrologia, 50, 257-268.

Francis O et al. (2015). CCM.G-K2 key comparison. Metrologia, 52, 07009.

Jiang Z et al. (2012). The 8th International Comparison of Absolute Gravimeters 2009: the first Key Comparison (CCM.G-K1) in the field of absolute gravimetry, Metrologia, 49, 666–684.

Nagornyi V D, Zanimonskiy Y M and Zanimonskiy Y Y (2011). Relativity, Doppler shifts and retarded times in deriving the correction for the finite speed of light: a comment on ‘Second-order Doppler-shift corrections in free-fall absolute gravimeters’, Metrologia, 48, 437-441.

Pálinkáš V, Liard J and Jiang Z (2012). On the effective position of the free-fall solution and the self-attraction effect of the FG5 gravimeters, Metrologia, 49, 552-559.

Rothleitner Ch and Francis O (2011). Second-order Doppler-shift corrections in free-fall absolute gravimeters, Metrologia, 48, 187-195.

Rothleitner Ch and Svitlov S (2012). On the evaluation of systematic effects in atom and corner-cube absolute gravimeters, Phys. Lett. A, 376, 1090–5.

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 cooperation 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

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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) Sept. 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
- Jean-Paul Boy (University of Strasbourg), jeanpaul.boy@unistra.fr
- 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

Bibliography of working group members

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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.

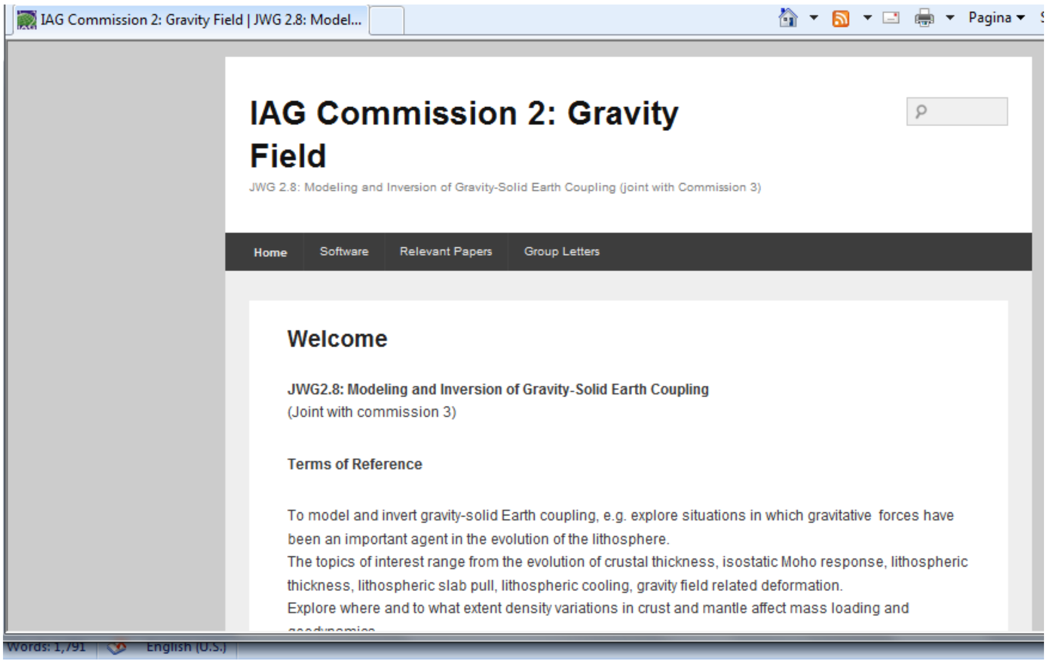


Figure l: Welcome page of the IAG 2.8 homepage, which includes a depository of software, relevant-publications-list and the possibility of making discussions.

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

CCM – IAG Strategy for Metrology in Absolute Gravimetry

Role of CCM and IAG

Urs Marti, President of 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

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 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.

[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/
[7] http://www.ggos.org/
[8] http://www.igfs.net/

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).

[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

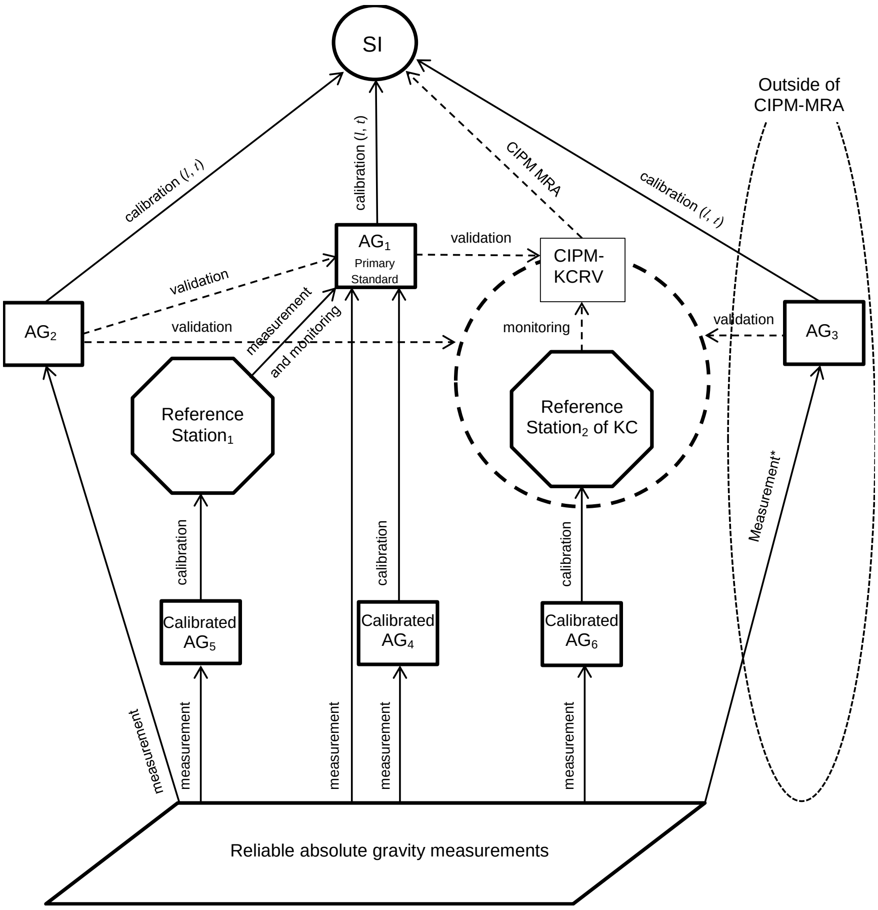
The absolute gravimeter has independent traceability to the SI unit of time (frequency) through the calibration of the frequencies of the laser and reference clock.

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.

[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

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 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.



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.

[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*

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].

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[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

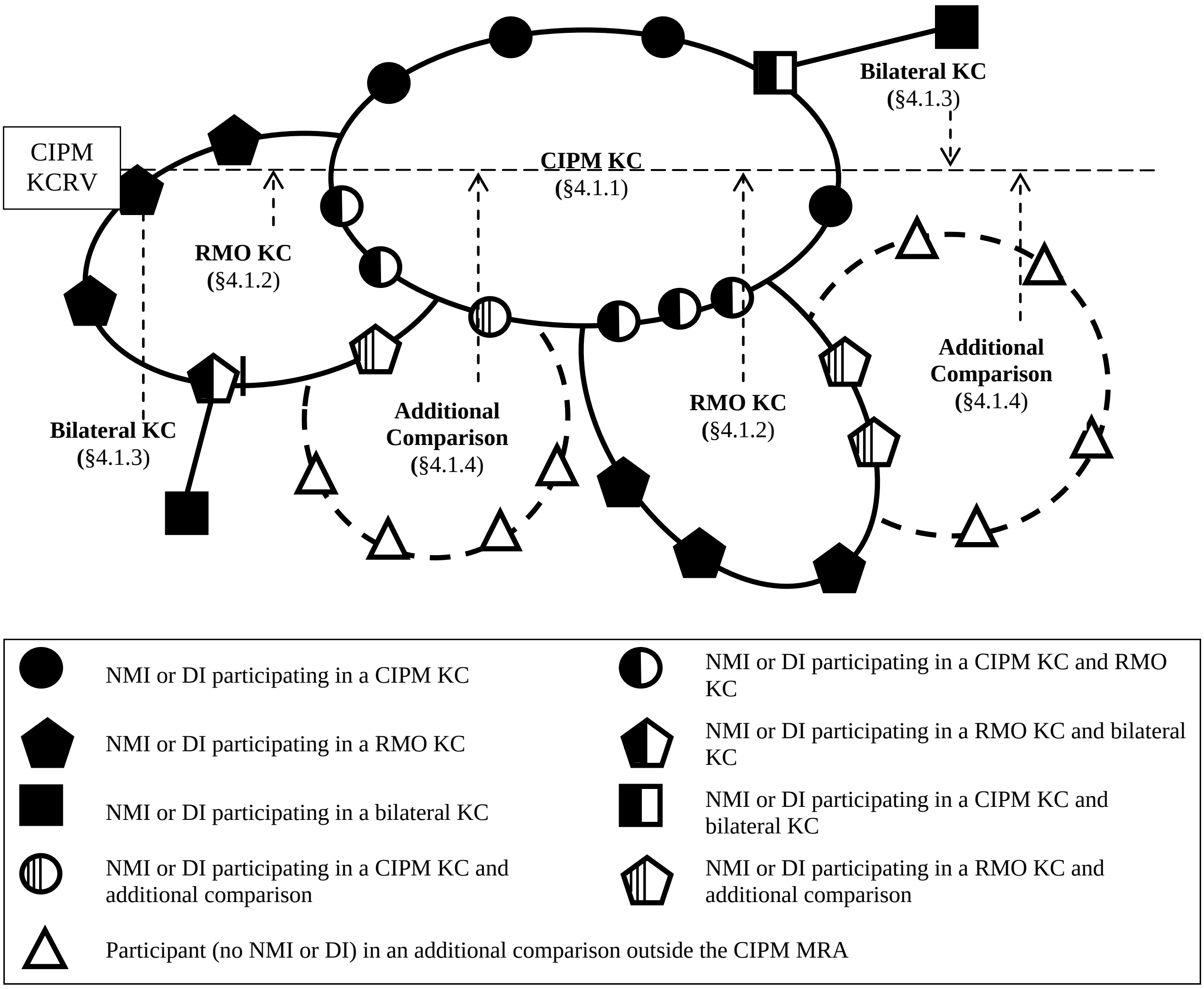

Figure 2: Scheme of some example of structure for Key Comparisons and other comparisons, according to §§4.1.1 - 4.1.4. To be noted that all comparisons have the same reference value, that is the CIPM-KCRV (through the links between comparisons).

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.

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[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

Reference to section	Method	Report	Procedure
4.1	Independent traceability to the SI units of time and frequency		
4.1.1	CIPM key comparison		
4.1.2	Regional key comparison	Final report into KCDB	Validation
4.1.3	Bilateral key comparison		
4.1.4	Additional comparisons linked to CIPM MRA	Final report into IAG AGrav DB	
4.2	Calibration by the comparison (against a reference)		
4.2.1	Comparison against a reference gravimeter	Calibration certificate	Calibration of a DUT
4.2.2	Comparison against a gravity value of a reference station	Calibration certificate	
4.3	Measurement certificate for the characterization of a gravity site	Measurement certificate	Measurement

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.

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.

[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

Commission 3 – Earth Rotation and Geodynamics

http://euler.jpl.nasa.gov/IAG-C3

President: Richard Gross (USA)
Vice President: Aleksander Brzezinski (Poland)

Structure

Sub-Commission 3.1:	Earth tides and geodynamics
Sub-Commission 3.2:	Crustal deformation
Sub-Commission 3.2a:	Global crustal deformation
Sub-Commission 3.2b:	Regional crustal deformation
Sub-Commission 3.3:	Earth rotation and geophysical fluids
Sub-Commission 3.4:	Cryospheric deformation
Sub-Commission 3.5:	Tectonics and earthquake geodesy
Joint Study Group 3.1:	Gravity and height change intercomparison
Joint Working Group 3.1:	Theory of Earth rotation

Overview

Geodynamics is the science that studies how the Earth moves and deforms in response to forces acting on the Earth, whether they derive from outside or inside of our planet. This includes the entire range of phenomena associated with Earth rotation and Earth orientation such as polar motion, length of day, precession and nutation, the observation and understanding of which are critical to the transformation between terrestrial and celestial reference frames. It includes tidal processes such as solid Earth and ocean loading tides, and crust and mantle deformation associated with tectonic motions and isostatic adjustment.

Commission 3 studies the entire range of physical processes associated with the motion and the deformation of the solid Earth. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research in this broad arena.

Sub-Commission 3.1 (Earth Tides and Geodynamics) addresses the entire range of tidal phenomena including its effect on Earth rotation. Sub-Commission 3.2 (Crustal Deformation) addresses the entire range of global and regional crustal deformation including intraplate deformation, the earthquake deformation cycle, aseismic phenomena such as episodic tremor and slip, and volcanic deformation. Sub-Commission 3.3 (Earth Rotation and Geophysical Fluids) addresses the space-time variation of atmospheric pressure, seafloor pressure and the surface loads associated with the hydrological cycle, and Earth's (mainly elastic) responses to these mass redistributions. Sub-Commission 3.4 (Cryospheric Deformation) addresses the Earth's instantaneous and delayed responses to ice mass changes, including seasonal (cyclical) mass changes and progressive changes associated with climate change. This group also studies postglacial rebound at all spatial scales and the elastic deformation taking place in the near-field of existing ice sheets and glaciers. Sub-Commission 3.5 (Tectonics and Earthquake Geodesy) addresses the integration of space and terrestrial approaches for studying the kinematics and mechanics of tectonic plate boundary zones, and in particular of the Eurasian/

African/Arabian boundary zone. Joint Study Group 3.1 is concerned with the comparison of ground and space gravity measurements with geometric measurements of surface deformation. IAU/IAG Joint Working Group 3.1 is concerned with developing fully consistent theories of the Earth's rotation that will meet the current and expected future accuracy requirements of the user community.

Sub-Commission 3.1: Earth Tides and Geodynamics

Chairs: Spiros Pagiatakis (Canada), Janusz Bogusz (Poland)

Sub-Commission 3.1 addresses the entire range of Earth tidal phenomena, both on the experimental as well as on the theoretical level. Earth tide observations have a very long tradition. These observations led to the discovery of the Earth's elasticity which allows deformation and variations in Earth orientation and rotation parameters. The phenomena responsible for these variations include the full range of periodic and non-periodic phenomena such as Earth tides and ocean tidal loading, atmospheric dynamics as well as plate tectonics and intraplate deformation. The periods range from seismic normal modes over to the Earth tides and the Chandler Wobble and beyond. Thus, the time scales range from seconds to years and for the spatial scales from millimetres to continental dimensions.

17th International Symposium on Earth Tides

Sub-Commission 3.1 organizes a symposium on Earth tides that is held every 4 years or so. The 17th International Symposium on Earth Tides was held in Warsaw, Poland during 15-19 April 2013. The theme of this Earth Tides Symposium (ETS) was "Understand the Earth". The Earth Tides Symposia are evolving to include all topics of interest to Commission 3 and ETS 2013 provided an opportunity to discuss not only tidal processes such as solid Earth and ocean loading tides but also crust and mantle deformations associated with tectonic motions, glacial isostatic adjustment, as well as the entire range of phenomena related to Earth rotation. There were 70 participants at the Symposium with 82 abstracts submitted and presented in 6 sessions. The proceedings of ETS 2013 were published as a special issue of the Journal of Geodynamics (volume 80, October 2014) with more technical papers as well as the resolutions being published in BIM (Bulletin d'Information des Marées Terrestres) No. 148 which is available electronically at http://www.eas.slu.edu/GGP/BIM_Recent_Issues/.

18th International Symposium on Geodynamics and Earth Tides

Recently, the multidisciplinary approach in geodynamics research has been increasing as well as the range of temporal and spatial scales on which geodynamic phenomena can be observed by modern instrumentation and monitoring systems. In order to take this development into account, the name of the "International Symposium on Earth Tides" has been changed to "International Symposium on Geodynamics and Earth Tides" and will be organized in this form for the first time at the 18th International Symposium on Geodynamics and Earth Tides that will be held in Trieste, Italy during 5-9 June 2016. The symposium will be open for a wide range of scientific problems in geodynamics research. Interactions of geophysical fluids with Earth tides phenomena and observations will be a specific focus and includes:

- Tidal and non-tidal loading in space geodetic and subsurface observations
- Permanent and dynamic effects of Earth tides on the geodetic reference system
- Using tides and ocean tidal loading with modern geodesy to probe Earth structure
- Variations in Earth rotation, gravity field and geocenter due to mass redistributions
- Subsurface fluid movement through geodetic and gravity observation
- Fluid pressure changes due to Earth tides
- Stress and deformation changes due to injected fluids
- Earth tides, mass movements and deformation at volcanoes
- Tidal forcing of plate movement

- Tidal effects on geodetic satellites as GOCE, GRACE, …
- Innovations in instrumentation for gravity and deformation observation
- Innovations in software, data analyses and prediction methods of loading and tides
- Induced seismicity
- Tides in planets

More information about the symposium can be found at <http://www.lithoflex.org/g-et/>.

Paul Melchior Medal

The Paul Melchior Medal, formerly known as the Earth Tides Commission Medal, is awarded to a scientist for her/his outstanding contribution to international cooperation in Earth tides research. It was awarded for the fifth time to Houtze Hsu (China) and presented to him on April 18, 2013 at the 17th International Symposium on Earth Tides in Warsaw, Poland. Previous recipients of the medal have been Paul Melchior (Belgium), Hans-Georg Wenzel (Germany), John Goodkind (USA), and Bernard Ducarme (Belgium) and Tadahiro Sato (Japan).

Sub-Commission 3.2: Crustal Deformation

http://iagsc32.fgi.fi/

Chair: Markku Poutanen (Finland)

There are many geodetic signals that can be observed and are representative of the deformation mechanisms of the Earth's crust at different spatial and temporal scales. These include the entire range of tectonic phenomena including plate tectonics, intraplate deformation, the earthquake deformation cycle, aseismic phenomena such as episodic tremor and slip, and volcanic deformation. The time scales range from seconds to years and from millimeters to continental dimension for the spatial scales.

Space geodetic measurements provide nowadays the means to observe deformation and movements of the Earth's crust at global, regional and local scales. This is a considerable contribution to global geodynamics by supplying primary constraints for modeling the planet as a whole, but also for understanding geophysical phenomena occurring at smaller scales.

Gravimetry, absolute, relative and nowadays also spaceborne, is a powerful tool providing information to the global terrestrial gravity field and its temporal variations. Superconducting gravimeters allow a continuous acquisition of the gravity signal at a given site with a precision of 10^{-10}. This is important in order to be able to detect and model environmental perturbing effects as well as the weak gravity signals associated with vertical crustal movements of the order of mm/yr. These geodetic observations together with other geophysical and geological sources of information provide the means to understand the structure, dynamics and evolution of the Earth system.

Sub-Commission 3.2 addresses the entire range of global and regional crustal deformation including intraplate deformation, the earthquake deformation cycle, aseismic phenomena such as episodic tremor and slip, and volcanic deformation. The Sub-Commission is divided into two Sub-Sub-Commissions, 3.2a on Global Crustal Deformation and 3.2b on Regional Crustal Deformation.

International Symposium on Geodesy for Earthquake and Natural Hazards

Sub-Commission 3.2 organized an International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH) that was held in Matsushima, Miyagi, Japan during 22–26 July 2014. Various large-scale natural disasters, such as earthquakes, tsunamis, volcano eruptions, hurricanes, landslides, etc., repeatedly endanger human lives in many parts of the world. During the first decade of the 21st century, in spite of our developing technologies, more than 700 thousand people were killed by large earthquakes. The 2011 Tohoku earthquake and tsunami was one of those tragic events.

In order to mitigate natural hazards, monitoring changes in the Earth's lithosphere as well as the atmosphere is indispensable. Recent geodetic techniques, such as GNSS, SAR, satellite gravity missions, etc., have a significant contribution in that aspect.

In GENAH 2014, 130 researchers from 16 countries in related fields of geodesy gathered to discuss the role of geodesy in disaster mitigation and how groups with different techniques can collaborate toward such a goal. The symposium was held in Matsushima, a town on the Pacific coast of northeastern Japan that was heavily damaged by the 2011 tsunami.

The proceedings of GENAH 2014 will appear as volume 145 of the IAG Symposia series that is published by Springer. More information about GENAH 2014 can be found at <http://genah2014.jpn.org/>.

Software Comparison Campaign

Sub-Commission 3.2a is organizing a software comparison campaign to test different approaches for computing far-field coseismic deformation. At least two distinct approaches have been used for these calculations in the past, but a careful software comparison has never been done before. We are using a common fault model and earthquake model, and are assessing how closely these approaches agree, and also how much accurate spherical layered models differ from the simple halfspace models commonly used by many. Assuming that good agreement between software packages is found, we will follow-up with other tests to assess the sensitivity of different earth models and fault models, with a long-term goal of being able to provide realistic estimates and uncertainties of far-field coseismic displacements from earthquakes on an ongoing basis.

Sub-Commission 3.3: Earth Rotation and Geophysical Fluids

Chairs: Maik Thomas (Germany), Jianli Chen (USA)

Charter

Geophysical fluid dynamics in atmosphere, hydrosphere, and outer core are related to large-scale mass transports causing observable geodynamic effects on broad time scales. These effects are reflected in small variations of the fundamental geodetic observables, i.e., the Earth's shape, its rotation, its gravity field, and geocenter shifts. Since all these parameters of the Earth are measured by various space- and ground-based geodetic techniques to increasing, unprecedented accuracy, these integral measures can principally be used to study global mass transport processes and the Earth's dynamic response, and, thus, to investigate geophysical aspects of global change. However, due to the integral character of geodetic observations and restrictions concerning resolution in time and space, the interpretation of the observational data and their utilization in Earth system sciences require complementary methods from theory and modeling. Variations of angular momenta and related torques, gravitational field coefficients, and geocenter shifts due to geophysical fluid dynamics are the relevant quantities, and some of them are already used to constrain state-of the-art models.

Objectives

The objective of the Sub-Commission 3.3 on Earth Rotation and Geophysical Fluids is to serve the scientific community by supporting research and data analysis in areas related to variations in Earth rotation, gravitational field and geocenter, caused by mass re-distribution within and mass exchange among the Earth's fluid sub-systems, i.e., the atmosphere, ocean, continental hydrosphere, cryosphere, and core along with geophysical processes associated with ocean tides and the hydrological cycle.

Activities during 2011–2015

Sub-Commission 3.3 follows the program defined by Commission 3. Moreover, Sub-Commission 3.3 interacts with the partner organizations and services, in particular with the Global Geophysical Fluids Center (GGFC) of the International Earth Rotation and Reference Systems Service (IERS) and its components, i.e., the operational Special Bureaus for the Atmosphere (SBA), Oceans (SBO), Hydrology (SBH), and the Special Bureau for Combination.

Moreover, the activities of Sub-Commission 3.3 are closely related to the new Joint Working Group on Theory of Earth Rotation (Chair: J. M. Ferrándiz) set up by IAG and the International Astronomical Union (IAU) in 2013. The main purpose of this Joint Working Group is the promotion of the development of theories of Earth rotation that are fully consistent and agree with observations of Earth rotation parameters.

The investigation of mass redistribution due to geophysical fluid dynamics and their impact on Earth's rotation, its shape, and gravity field is an ongoing very active research area. In order to promote the exchange of ideas and results as well as of analysis and modeling strategies, special sessions at the annual Fall Meetings of the American Geophysical Union in San Francisco, USA, at the annual General Assemblies of the European Geosciences Union in Vienna, Austria, at the conferences of the series Journées Systèmes de Référence Spatio-Temporels, and at the IAG 2013 Scientific Assembly in Potsdam, Germany, have been convened during the period. Furthermore, Sub-Commissions 3.1, 3.2, 3.2a, 3.2b, and 3.3 will participate in and co-organize the next Geodynamics and Earth Tides Symposium to be held in Trieste, Italy, in 2016 that will focus on *Earth system sensing, scientific enquiry and discovery*.

Sub-Commission 3.3 is an active participant in the Global Geophysical Fluids Center (GGFC) of the IERS and attended the topical workshops of the GGFC held 2012 and 2015 in Vienna, Austria. These meetings particularly focused on the assessment of remaining errors in current environmental models and ideas for overcoming these limitations. The highlights of the meeting were summarized in several recommendations supporting the provision of data sets that can reliably be used in geodetic and geophysical data analysis. In addition, members of Sub-Commission 3.3 are significantly involved in the generation of several operational data sets provided by the GGFC Operational Product Centers. These are, for instance, time series of global atmospheric, oceanic, and hydrological angular momentum consistently derived from four different atmospheric data sets, or three-dimensional displacements due to spatio-temporal variations of surface loading. Regularly updated and available in near-real time, these time series provide an important basis for numerous studies relevant for the Earth's variable rotation and its underlying physical mechanisms.

Sub-Commission 3.3 also contributes to the goals of IAG's Global Geodetic Observing System (GGOS). Due to the overlapping of the tasks, close contacts exist in particular to the activities of the GGOS Working Group on *Contributions to Earth System Modeling*, with the chair of Sub-Commission 3.3 being the head of this GGOS Working Group. One of the major goals of the Working Group is the preparation of a physically consistent system model for simulation of Earth rotation and gravity field variability due to geophysical fluid dynamics. The current foci of the activities are the realization of mass conservation within the modular system model, the improvement of model based short-term predictions of Earth rotation parameters, and the development of strategies for the separation of temporal variations of Earth rotation, gravity and geoid into individual causative processes related to geophysical fluid dynamics.

Sub-Commission 3.4: Cryospheric Deformation

Chairs: Matt King (Australia), Shfaqat Abbas Khan (Denmark)

Terms of Reference

Past and present changes in the mass balance of the Earth's glaciers and ice complexes induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Of principal interest is geodetic observations that validate, or may be assimilated into, models of glacial isostatic adjustment (GIA) and/or constrain models of changes in present-day ice masses through measurements of elastic rebound. Using geometric measurements alone, elastic and GIA deformations cannot be separated without additional models or observations. Reference frames of GIA models do not allow direct comparison to measurements in an International Terrestrial Reference Frame and ambiguity currently exists over the exact transformation between the two. Furthermore, there is no publicly available and easy-to-use tool for model computations of elastic effects based on observed elevation/mass changes over the spatial scales of interest (small valley glaciers to large ice streams) and including gravitational/rotational feedbacks. This SC will focus on resolving these technical issues and work on dissemination of these measurements within the glaciological community (notably IACS).

A steering group of 25 was established, with their expertise being a mixture of geodetic observation, geophysical modelling and glaciological observation. Members of the sub-commission include: M. Bevis, J. Davis, R. Dietrich, E. Ivins, J. Freymueller, I. Howat, P. Whitehouse, R. Riva, V. Barletta and X. Wu.

Activities 2011–2015

International Symposium on Reconciling Observations and Models of Elastic and Viscoelastic Deformation due to Ice Mass Change

Sub-Commission 3.4 organized this symposium with the objective of enabling this interaction and creating new collaborations through the discussion of the results of scientific studies focused on visco-elastic deformation of the solid Earth due to ice (un)loading. The symposium brought together those working on observation and modeling of cryospheric change and solid earth response to further our understanding of the Earth system. The symposium was held in Ilulissat, Greenland during 30 May –2 June 2013. Over 50 abstracts were submitted and presented in 4 sessions. Nearly 60 scientists were in attendance across the fields of geodesy, seismology, GIA modeling and glaciology and about one third were early career scientists. Significant funding was obtained from IAG, SCAR SERCE, EGU, NSF, DynaQlim and Danish Technical University which largely supported travel of early career researchers to the meeting

REAR: a program for computing the regional elastic response of the Earth to surface loading
The sub-commission called for expressions of interest for those who would be willing to publically release code for high-resolution modeling of elastic deformation associated with changes in surface loading. As a result, the Regional Elastic Rebound Calculator (REAR) was released [*Melini et al.,* 2015]. REAR runs on any UNIX environment with a Fortran compiler, including Windows systems running the Cygwin layer. The REAR source code package and a detailed User guide are available from <http://hpc.rm.ingv.it/rear>. REAR comes under a GNU General Public License.

GIA Modelling 2015 Conference and Elastic Modelling workshop

This workshop was held in Fairbanks, Alaska May 25-29, 2015. It brought together those working on ice load reconstructions, modeling of (visco-) elastic processes and comparison to relative sea level and geodetic observations (e.g. GRACE, GPS, ICESat, CRYOSAT II) in order to further refine our understanding of past to present ice/ocean load changes, and the characteristics of the solid Earth under time-varying loads, in order to advance our understanding of past ice sheet and sea level changes, of the structure and rheology of earth, and of exactly what geodetic measurements are measuring. About 35 abstracts were received mainly from researchers based within Europe and the USA.

Relevant peer-reviewed publications by sub-commission members

Barletta, V.R., L.S. Sorensen and R. Forsberg 2013. Scatter of mass changes estimates at basin scale for Greenland and Antarctica. *Cryosphere*, **7**(5): 1411-1432.

Bevis, M., J. Wahr, S.A. Khan, F.B. Madsen, A. Brown, M. Willis, E. Kendrick, P. Knudsen, J.E. Box, T. van Dam, D.J. Caccamise, II, B. Johns, T. Nylen, R. Abbott, S. White, J. Miner, R. Forsberg, H. Zhou, J. Wang, T. Wilson, D. Bromwich and O. Francis 2012. Bedrock displacements in Greenland manifest ice mass variations, climate cycles and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(30): 11944-11948.

Bevis, M., A. Brown and E. Kendrick 2013. Devising stable geometrical reference frames for use in geodetic studies of vertical crustal motion. *Journal of Geodesy*, **87**(4): 311-321.

Compton, K., R.A. Bennett and S. Hreinsdottir 2015. Climate-driven vertical acceleration of Icelandic crust measured by continuous GPS geodesy. *Geophysical Research Letters*, **42**(3): 743-750.

Groh, A., H. Ewert, M. Fritsche, A. Ruelke, R. Rosenau, M. Scheinert and R. Dietrich 2014. Assessing the Current Evolution of the Greenland Ice Sheet by Means of Satellite and Ground-Based Observations. *Surveys in Geophysics*, **35**(6): 1459-1480.

Groh, A., H. Ewert, R. Rosenau, E. Fagiolini, C. Gruber, D. Floricioiu, W.A. Jaber, S. Linow, F. Flechtner, M. Eineder, W. Dierking and R. Dietrich 2014. Mass, Volume and Velocity of the Antarctic Ice Sheet: Present-Day Changes and Error Effects. *Surveys in Geophysics*, **35**(6): 1481-1505.

Groh, A., H. Ewert, M. Scheinert, M. Fritsche, A. Ruelke, A. Richter, R. Rosenau and R. Dietrich 2012. An investigation of Glacial Isostatic Adjustment over the Amundsen Sea sector, West Antarctica. *Global and Planetary Change*, **98-99**: 45-53.

Gunter, B.C., O. Didova, R.E.M. Riva, S.R.M. Ligtenberg, J.T.M. Lenaerts, M.A. King, M.R. van den Broeke and T. Urban 2014. Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change. *Cryosphere*, **8**(2): 743-760.

Ivins, E.R., T.S. James, J. Wahr, E.J.O. Schrama, F.W. Landerer and K.M. Simon 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research-Solid Earth*, **118**(6): 3126-3141.

King, M.A. 2013. Progress in modelling and observing Antarctic glacial isostatic adjustment. *Astronomy & Geophysics*, **54**(4): 33-38.

King, M.A. and C.S. Watson 2014. Geodetic vertical velocities affected by recent rapid changes in polar motion. *Geophysical Journal International*, **199**(2): 1161-1165.

Lange, H., G. Casassa, E.R. Ivins, L. Schroeder, M. Fritsche, A. Richter, A. Groh and R. Dietrich 2014. Observed crustal uplift near the Southern Patagonian Icefield constrains improved viscoelastic Earth models. *Geophysical Research Letters*, **41**(3): 805-812.

Melini, D., P. Gegout, M. King, B. Marzeion, and G. Spada (2015), REAR: a program for computing the regional elastic response of the Earth to surface loading, EOS, in press.

Nield, G.A., V.R. Barletta, A. Bordoni, M.A. King, P.L. Whitehouse, P.J. Clarke, E. Domack, T.A. Scambos and E. Berthier 2014. Rapid bedrock uplift in the Antarctic Peninsula explained by viscoelastic response to recent ice unloading. *Earth and Planetary Science Letters*, **397**: 32–41.

Nield, G.A., P.L. Whitehouse, M.A. King, P.J. Clarke and M.J. Bentley 2012. Increased ice loading in the Antarctic Peninsula since the 1850s and its effect on Glacial Isostatic Adjustment. *Geophysical Research Letters*, **39**: L17504.

Nielsen, K., S.A. Khan, G. Spada, J. Wahr, M. Bevis, L. Liu and T. van Dam 2013. Vertical and horizontal surface displacements near Jakobshavn Isbrae driven by melt-induced and dynamic ice loss. *Journal of Geophysical Research-Solid Earth*, **118**(4): 1837-1844.

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Rietbroek, R., M. Fritsche, C. Dahle, S.-E. Brunnabend, M. Behnisch, J. Kusche, F. Flechtner, J. Schroeter and R. Dietrich 2014. Can GPS-Derived Surface Loading Bridge a GRACE Mission Gap? *Surveys in Geophysics*, **35**(6): 1267-1283.

Sasgen, I., H. Konrad, E.R. Ivins, M.R. Van den Broeke, J.L. Bamber, Z. Martinec and V. Klemann 2013. Antarctic ice-mass balance 2003 to 2012: regional reanalysis of GRACE satellite gravimetry measurements with improved estimate of glacial-isostatic adjustment based on GPS uplift rates. *Cryosphere*, **7**(5): 1499-1512.

Snay, R.A., J.T. Freymueller and C. Pearson 2013. Crustal Motion Models Developed for Version 3.2 of the Horizontal Time-Dependent Positioning Utility. *Journal of Applied Geodesy*, **7**(3): 173-90.

van der Wal, W., P.L. Whitehouse and E.J.O. Schrama 2015. Effect of GIA models with 3D composite mantle viscosity on GRACE mass balance estimates for Antarctica. *Earth and Planetary Science Letters,* **414**: 134-143.

Wahr, J., S.A. Khan, T. van Dam, L. Liu, J.H. van Angelen, M.R. van den Broeke and C.M. Meertens 2013. The use of GPS horizontals for loading studies, with applications to northern California and southeast Greenland. *Journal of Geophysical Research-Solid Earth*, **118**(4): 1795-1806.

Whitehouse, P.L., M.J. Bentley, G.A. Milne, M.A. King and I.D. Thomas 2012. A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International*, **190**(3): 1464–1482.

Sub-Commission 3.5: Tectonics and Earthquake Geodesy

Chair: Haluk Özener (Turkey)

Sub-Commission 3.5, Tectonics and Earthquake Geodesy (WEGENER group), aims to encourage cooperation between all geoscientists studying the Eurasian/African/Arabian plate boundary deformation zone with a focus on mitigating earthquake, tsunami, and volcanic hazards. Towards these ends, we organize periodic workshops and meetings with special emphasis on integrating the broadest range of Earth observations, sharing analysis and modelling approaches, and promoting the use of standard procedures for geodetic data acquisition, quality evaluation, and processing. WEGENER organizes dedicated meetings, arranges special sessions in other international meetings, organizes special issues in peer-reviewed journals, and takes initiative to promote and facilitate open access to geodetic databases.

Meetings Organized

16th General Assembly of WEGENER

WEGENER organizes bi-annual conferences to serve as high-level international forums in which scientists from all over the world share results, and strengthen collaborations between countries in the greater Mediterranean region and beyond. In this respect, the 16th General Assembly of WEGENER was organized in Strasbourg, France between 17 and 20 September 2012. The meeting was hosted by Institut de Physique du Globe et Ecole et Observatoire des Sciences de la Terre of the University of Strasbourg.

Around 100 scientists from all around the world attended the meeting. A total of 57 oral and 37 poster presentations were made. The meeting was conducted on six different topics in six sessions. Each session had its own oral and poster presentations. This gave the attendees the chance to participate in the sessions covering their research interests.

Information and experience in the use of geodetic methods for geodynamic studies such as GPS, InSAR, and terrestrial methods were shared in a wide range of applications from large scale studies such as the studies of continental boundaries to small scale studies such as local observations focusing on single faults. Invited talks enabled the attendees to keep up with the latest research of world leading scientists and the latest technological developments in instrumentation, analysis, modeling, and interpretation. The meeting was carried out in a workshop form, including extensive and inclusive discussions of the results and the methods presented within each session.

Detailed information about the 16th General Assembly of WEGENER can be found at <http://wegener2012.sciencesconf.org/>.

17th General Assembly of WEGENER

The 17th General Assembly of Wegener, on earth deformation and the study of earthquakes using geodesy and geodynamics, was held at the University of Leeds, UK, from 1-4 September 2014. The meeting gathered 110 scientists from across the planet for a week of intense scientific discussion, with the local organization led by Prof. Dr. Tim Wright, from the School of Earth and Environment at the University of Leeds.

The scientific program was put together by an international committee of 22 scientists (details on http://see.leeds.ac.uk/wegener), and consisted of sessions on Continental Faulting and the Earthquake Cycle, Subduction Zones, Geodetic Techniques, Geodynamics and Potential Fields, Surface Processes, Volcanic/Magmatic Processes, and Glacial Isostatic Adjustment and Sea Level.

In all, there were 42 oral presentations, including 7 keynote talks, and 56 poster presentations. Participants were from 14 countries, spread across 4 continents. Many of the participants stayed in Leeds for a field trip to Malham in the Yorkshire Dales, where they admired world-famous pristine limestone pavement, and the Mid-Craven Fault, and enjoyed the Yorkshire sunshine.

Full details of the presentations and photographs taken at the general assembly can be found at <http://see.leeds.ac.uk/wegener> and in the September 2014 Issue of the IAG Newsletter.

WEGENER Sessions in other Scientific Meetings

European Geosciences Union General Assembly 2011

During the EGU General Assembly 2011, a session titled "Geodesy and natural and induced hazards: Progress during 30 years of the WEGENER initiative" was convened by Susanna Zerbini, Robert Reilinger, and Mustapha Meghraoui. Eighteen oral talks were presented in two successive sessions. There were also 25 poster presentations. More detailed information can be found at <http://meetingorganizer.copernicus.org/EGU2011/session/7048>.

AGU Fall Meeting 2012

The 45th Annual Fall Meeting of the American Geophysical Union (AGU) was held in San Francisco, CA, USA in 2012 between 3 and 7 December. Being the largest worldwide conference in the geophysical sciences, the AGU Fall Meeting attracted more than 23,000 earth and space scientists, educators, students, and other leaders. Nearly 14,000 posters and more than 6,800 oral presentations were given in parallel sessions. More than 270 exhibitors also took place during the meeting. Besides these, numerous workshops, town halls and social and networking events took place during the organization. Thus, this meeting provided an ideal opportunity to highlight WEGENER's accomplishments to the Earth science community, and to develop synergies with other organizations such as EPN/EUREF, EPOS, CEGRN, and UNAVCO to further our mutual objectives of mitigating natural and anthropomorphic hazards.

A dedicated session titled "Geodesy and Natural and Induced Hazards: Progress During 32 Years of the WEGENER Initiative" was held during the AGU meeting. The session consisted of eight oral and fifteen poster presentations and attracted many international scientists' interests. The topics of the presentations were broad ranging from studies that focused on a single fault to large-scale studies of continental boundaries. Invited talks also took place during this session. One of the invited talks was given by David E. Smith who was awarded the 2012 Charles A. Whitten Medal of the AGU. Information and experiences about the use of geodetic technologies in geodynamic studies was shared and discussed within the session thus giving the attendees the chance to be aware of recent studies of the world leading scientists. This session was chaired by Haluk Ozener, Susanna Zerbini and Robert Reilinger. Details can be found at <http://www.agu.org/cgi-bin/sessions5?meeting=fm12&part=G52A> and at <http://www.agu.org/cgi-bin/sessions5?meeting=fm12&part=G53A>.

European Geosciences Union General Assembly 2014

In EGU 2014, a session titled "Present-day kinematics and tectonics of the Mediterranean Region: Implications for geodynamics and earthquake potential" was organized. There were 31 presentations. This session brought together geophysicists and geologists working on the present day deformation of the Mediterranean region to present and discuss these new constraints, as well as conceptual and quantitative model results for geodynamic and earthquake processes in this region. Details can be found at <http://meetingorganizer.copernicus.org/EGU2014/session/14738>.

European Geosciences Union General Assembly 2015

A session titled "Monitoring and modelling of geodynamics and crustal deformation: progress during 34 years of the WEGENER initiative" was organized and convened by Haluk Ozener, Susanna Zerbini and Mustapha Meghraoui in the EGU General Assembly 2015. Presentations emphasized multidisciplinary studies of Earth deformation using geodetic techniques (GPS, InSAR, LiDAR, space/air/terrestrial gravity, ground-based geodetic observations), complementary tectonic and geophysical observations, and modeling approaches focusing on the European-Mediterranean and Northern African regions. In total, 21 studies were presented in two successive sessions. More detailed information can be found at <http://meetingorganizer.copernicus.org/EGU2015/session/18028>.

Publications

Journal of Geodynamics Special Issue

A special issue of Journal of Geodynamics was arranged for WEGENER 2010. This special issue includes papers presented at the 15th General Assembly of WEGENER, held in Istanbul, Turkey, September 14–17, 2010. This biannual meeting was organized by the Bogazici University and hosted at the Albert Long Hall Conference Center. The 2010 WEGENER Conference brought together many experts from all around the world with a wide spectrum of Earth Sciences disciplines and provided an opportunity for the presentation of state-of-the-art results focusing on the "greater" Mediterranean region (Europe, Asia Minor, North Africa, and Arabia). There were 80 presentations at the meeting; this special issue includes a selection of 12 peer-reviewed manuscripts derived from these presentations. The papers in this volume reflect the application of new, as well as mature, space and terrestrial-based methods including, geodetic, gravimetric, radar technologies, environmental, and neotectonic observations and highlight the importance of integrated regional and global scale studies of the Earth System. A special paper describing some of the accomplishments of WEGENER and our new focus on Hazards was included in the Special Issue. Details can be found at <http://www.sciencedirect.com/science/journal/02643707/67>.

Other Activities

- An effort to identify a "WEGENER Supersite" was initiated by SC 3.5 members Susanna Zerbini and Meghan Miller, addressing one of the goals of SC 3.5. The supersite initiative is intended to solidify and extend international cooperation between WEGENER scientists, to provide broad access to invaluable data for constraining geodynamic processes, and to facilitate and stimulate the integrated exploitation of data from different techniques in the analysis and interpretation of geo-processes.

- Former WEGENER president, Susanna Zerbini was elected a member of the Scientific Advisory Committee for GEO-Supersites which will strengthen the ties between WEGENER and other international scientific organizations and reinforce cooperation with African and Arab countries as well as other international scientists studying these problems. We anticipate these developments will contribute to our understanding of the kinematics and dynamics of the Eurasian/African/Arabian plate boundary zone, will provide an improved physical basis for hazard mitigation, and will promote the growth of such research and geodetic expertise in these countries.
- International Symposium on Global Navigation Satellite Systems (ISGNSS-2013) was supported by our commission, which was held in Istanbul at 22-25 October 2013. More information about this can be found at <http://isgnss2013.beun.edu.tr/>.
- WEGENER Board Meetings were organized in conjunction with the AGU and EGU meetings.
- A report to the Technical Working Group of EUREF on WEGENER activities was submitted.
- A borehole strainmeter was installed in Istanbul, Turkey.
- Two creepmeters were installed on the North Anatolian Fault Zone, Turkey.
- A tide gauge and GNSS equipment were installed on Gough Island and seismic equipment on Marion Island.
- A permanent GPS network and a permanent broadband seismic network were established to study crustal deformation in the Ibero-Maghrebian region.
- Broadband Ocean Bottom Seismometers (OBS) were deployed in the Gulf of Cadiz-Alboran Sea area.
- Regional and on site Earthquake Early Warning System (ALERTES system) is being developed under a Spanish Research Ministry project.
- WEGENER participated in several research projects like EPOS, TOPOIBERIA, etc.
- Continuous GPS stations were installed in Saudi Arabia close to the Aqaba gulf.
- Several publications and presentations regarding WEGENER activities were prepared and given.

Upcoming Event

The WEGENER board decided that the 18th General Assembly will be held in Azores, the junction of three major tectonic plates: the North American Plate, the Eurasian Plate and the African Plate, in 2016 and will be organized by Prof. Dr. Rui Fernandes.

Relevant peer-reviewed publications by sub-commission members

2011

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Joint Study Group 3.1: Gravity and Height Change Intercomparison

http://www.srosat.com/iag-jsg/

Chair: Séverine Rosat (France)

Surface deformations are continuously recorded from space or from the ground with increasing accuracy. Vertical displacements and time-varying gravity are representative of various deformation mechanisms of the Earth occurring at different spatial and temporal scales. We can quote for instance post-glacial rebound, tidal deformation, hydrologic loading, co-seismic deformation and volcanic deformation. The involved time scales range from seconds to years and the space scales range from millimeters to continental dimension. Large-scale deformations are well monitored by space geodetic measurements from monthly spatially averaged GRACE measurements while local deformation are precisely monitored by daily GPS or VLBI solution and sub-daily gravimeter data at a site. The intercomparison of the space- and ground-gravity measurements with vertical surface displacements enable us to infer more information on the structure, dynamics and evolution of the Earth system. In particular, the transfer function of the Earth at various time-scales related to the elastic and visco-elastic properties of the Earth are a focus of activity.

Joint Study Group 3.1 on Gravity and Height Change Intercomparison is joint between Commission 1 on Reference Frames, Commission 2 on Gravity Field and Commission 3 on Earth Rotation and Geodynamics and is reporting to Commission 3. The activities of the Joint Study Group concern the comparison of ground and space gravity measurements with geometric measurements of surface deformation. The motivation of this Joint Study Group is to study surface deformation by comparing site displacement observations with both ground- and space-based gravity measurements. Issues that will arise when comparing site displacement with gravity measurements are differences in spatial and temporal scales and differences in sensitivity.

Summary of activities during 2011–2015

The Joint Study Group participated in the 17th Earth Tides Symposium that was held in Warsaw, Poland during 15–19 April 2013 by convening a session on *Gravity and Height Changes: Comparison with GPS*.

A review on the difficulties and techniques to compare space/ground gravity and height changes was also presented at the 17th Earth Tides Symposium.

A bibliography of relevant papers has been compiled and is available at <http://www.srosat.com/iag-jsg/papers.php>.

Load Love numbers, which are necessary to compare space/ground gravity and vertical displacement measurements of surface deformation, were computed for a PREM-like model and are available at <http://www.srosat.com/iag-jsg/loveNb.php>.

Finally, a project has been initiated on the comparison of GPS vertical displacements and surface gravity changes (from Superconducting Gravimeters) at co-located sites. A first comparison is performed concerning the noise characteristics of GPS and gravity data. This work is done in collaboration with Janusz Bogusz and will be presented at the next IUGG meeting in Prague in 2015: "Correlation at noise level between GPS and gravity data" by J. Bogusz, S. Rosat and A. Kłos.

Joint Working Group 3.1: Theory of Earth Rotation

Chair: Jose Ferrándiz (Spain)

The purpose of the International Astronomical Union / International Association of Geodesy (IAU/IAG) Joint Working Group (JWG) on Theory of Earth Rotation is to promote the development of theories of Earth rotation that are fully consistent and that agree with observations and provide predictions of the Earth orientation parameters (EOPs) with the accuracy required to meet the needs of the near future as recommended by, for example, IAG's Global Geodetic Observing System. Recent efforts have not led to improvements in the accuracy of theoretical models of the Earth's rotation that approach the required millimetre level, so there is a strong need to develop such theories to meet the current and future accuracy of the observations.

A main objective of the JWG is to assess and ensure the level of consistency of EOP predictions derived from theories with the corresponding EOPs determined from analyses of the observational data provided by the various geodetic techniques. Consistency must be understood in its broader meaning, referring to models, processing standards, conventions etc. In addition, clearer definitions of polar motion and nutation are needed for both their separation in observational data analysis and for use in theoretical modelling.

The derivation of comprehensive theories accounting for all relevant astronomical and geophysical effects and able to predict all EOPs is sought. In case more than one theory is needed to accomplish this, their consistency should be ensured. Searching for potential sources of systematic differences between theory and observations is encouraged, including potential effects of differences in reference frame realization. Theoretical approaches must be consistent with IAU and IAG Resolutions concerning reference systems, frames and time scales.

There are no *a priori* preferred approaches or methods of solution, although solutions must be suitable for operational use and the simplicity of their adaptation to future improvements or changes in background models should be considered. The incorporation into current models of corrections stemming from newly studied effects or improvements of existing models may be recommended by the JWG when they lead to significant accuracy enhancements.

Activities during 2011–2015

The JWG was established in 2013 and is just starting to organize its activities. Since the subject of the JWG is quite broad, three Sub-Working Groups (SWGs) have been formed: (1) Precession/Nutation chaired by Juan Getino of Spain, (2) Polar Motion and UT1 chaired by Aleksander Brzezinski of Poland, and (3) Numerical Solutions and Validation chaired by Robert Heinkelmann of Germany. The subjects of SWG 1 and 2 are self-explanatory. The subject of SWG 3 is numerical theories and solutions, relativity and new concepts, and validation by comparisons among theories and observational series.

Guidelines for the operation of the JWG have been drafted, a web site for the JWG has been developed and can be found at <http://web.ua.es/en/wgther>, and meetings of the JWG have been held in conjunction with the:

- 2013 IAG Scientific Assembly in Potsdam, Germany.
- 2013 Journées Systèmes de Référence Spatio-Temporels in Paris, France.
- 2014 EGU General Assembly in Vienna, Austria.
- 2014 AGU Fall Meeting in San Francisco, California.
- 2015 EGU General Assembly in Vienna, Austria.

Presentations about the JWG and its activities have been given at the:

- 2013 IAG Scientific Assembly in Potsdam, Germany.
- 2013 Journées Systèmes de Référence Spatio-Temporels in Paris, France.
- 2013 AGU Fall Meeting in San Francisco, California.
- 8th IVS General Meeting in Shanghai, China.
- 2014 EGU meeting in Vienna, Austria.
- 2014 Journées Systèmes de Référence Spatio-Temporels in St. Petersburg, Russia.
- 2014 AGU Fall Meeting in San Francisco, California.

Reports of many of the meetings and copies of the presentations can be found on the JWG's web site at <http://web.ua.es/en/wgther>.

Commission 4 – Positioning and Applications

http://www2.ceegs.ohio-state.edu/IAG-Comm4

President: Dorota Grejner-Brzezinska (USA)
Vice President: Allison Kealy (Australia)

Structure

Sub-Commission 4.1: Alternatives and backups to GNSS
Sub-Commission 4.2: Geodesy in geospatial mapping and engineering
Sub-Commission 4.3: Remote sensing and modelling of the atmosphere
Sub-Commission 4.4: Applications of satellite and airborne imaging systems
Sub-Commission 4.5: High-precision GNSS algorithms and applications
Sub-Commission 4.6: GNSS-reflectometry and applications

Overview

The primary mission objective of Commission 4 is to promote research that leverages current and emerging positioning techniques and technologies to deliver practical and theoretical solutions for engineering, scientific and mapping applications. Commission 4 carries out its work in close cooperation with the IAG Services and other IAG entities, as well as via linkages with relevant entities within scientific and professional sister organizations. In fact, Commission 4 has the representatives of the International Federation of Surveyors (FIG), International Society for Photogrammetry and Remote Sensing (ISPRS) and the Institute of Navigation (ION) on its Steering Committee.

Recognizing the central role of GNSS in providing high accuracy positioning information today and into the future, Commission 4 maintains a focus on developing tools that enhance and assure the positioning performance of GNSS-based positioning solutions for a range of geodetic and other scientific and engineering applications. A significant part of Commission 4 activities is oriented towards the development of theory, strategies and tools for modeling and/or mitigating the effects of interference, signal loss and atmospheric effects, as they apply to precise GNSS positioning technology. In addition, technical and institutional issues necessary for developing backups to GNSS, integrated positioning solutions, automated processing capabilities and quality control measures, are also being addressed. Commission 4 also deals with geodetic remote sensing, using Synthetic Aperture Radar (SAR), Light Detection And Ranging (LiDAR) and Satellite Altimetry (SA) systems for geodetic applications.

A major goal of Commission 4 over the 2011-2015 period was to promote research collaborations across various science and engineering disciplines, and to organize joint professional workshops and seminars. Examples of successful initiatives included (full listings of activities and publications can be found in the following sections):

- FIG/IAG WG 4.1.1/ISPRS, undertook a significant joint field campaign and follow-up data processing and analysis in the area of collaborative navigation, University of Nottingham, UK, May 14-18, 2012. This was a follow up of previous field campaigns held at The Ohio State University, USA and the University of New South Wales, Australia in 2011.

- IAG SC 4.2 and WG 4.2.1 actively participated in the organization of the International Symposium on Unmanned Airborne Vehicles for Geomatics, UAV-g 2011 held in Zurich, September 14-16 2011. The success of this event was repeated with active participation again at UAV-g 2013 held in Rostock, Germany, September 4-6.
- IAG Commission 4 and WG 4.2.1 sponsored and actively participated in "The 1st and 2nd International Summer School on Mobile Mapping Technology in 2012 and 2013, 11-15 June 2012 and 29-30 April, 2013 respectively at National Cheng Kung University (NCKU), Tainan, Taiwan.
- IAG Commission 4 sponsored and actively participated in "The 3rd International Summer School on Mobile Mapping Technology, Xiamen, China, April 27-29, 2015.
- IAG SC 4.2 and WG 4.2.1 sponsored and actively participated in the 8th International Symposium on Mobile Mapping Technology – MMT2013, 1–2 May, Tainan, 2013. President of IAG Commission 4. IAG SC 4.2 and WG 4.2.1 are currently organising the 9th International Symposium on Mobile Mapping Technology, MMT2015, to be held in Sydney, Australia, 9-11 December 2015, Website: www.mmt2015.org. A/Prof Jinling Wang, Chair of the IAG SC 4.2, is the Convenor/General Chair for the MMT2015.
- IAG WG 4.2.5 organised the Workshop on "Applications of Artificial Intelligence in Engineering Geodesy", 10-12 September 2012, Technical University of Munich, Munich, Germany.
- The Joint International Symposium on Deformation Monitoring, Hong Kong, China, 2-4 November 2011 was organised by IAG SC4.4 and FIG.
- The Global Navigation Satellite System (GNSS) School on "New GNSS Algorithms and Techniques for Earth Observations 2012 (nGATEo 2012)" was successfully held, 14-15 May 2012, Polytechnic University (PolyU), Hong Kong. Sponsored by IAG and organized by Dr. George Liu, Secretary of SC4.5.
- WG4.5.2 contributed to Inside GNSS Webinar on Precise Positioning Techniques.
- Commission 4 had a significant presence with roles such as program chair, track chair and session chairs, at the ION GNSS 2011, 2012, 2013 and 2014 conferences.
- SC4.5 organized the Croucher Summer Course on "New GNSS Algorithms and Techniques for Earth Observations", 26-31 May 2014, Hong Kong Polytechnic University, Hong Kong.

Significant Publications

- A special issue entitled 'Indoor Navigation and Tracking' Journal of Physical Communications (Vol. 13, Part A; http://www.sciencedirect.com/science/journal/18744907/13/part/PA) edited by Yu K., I. Oppermann, E. Dutkiewicz, I. Sharp and G. Retscher was published in 2014.
- A special issue entitled 'Ubiquitous Positioning and Navigation Systems' of the Journal of Applied Geodesy (Vol. 7, No. 4; http://www.degruyter.com/view/j/jag) edited by A. Kealy, G. Retscher and V. Schwieger was published in 2013.
- A special issue on the Second Joint International Symposium on Deformation Monitoring (JISDM), University of Nottingham edited by Xiaolin Meng, Yang Gao and Wujiao Dai Survey Review (Volume 46, Issue 339, November 2014).
- A special issue entitled 'Engineering Geodesy' of the Journal of Applied Geodesy (Vol. 8, No. 4; http://www.degruyter.com/view/j/jag) edited by G. Retscher was published in 2014.

Sub-Commission 4.1: Alternatives and Backups to GNSS

Chair: Günther Retscher (Austria)
Co-chair: Vassilis Gikas (Greece)

As most mobile positioning applications rely heavily on GNSS nowadays alternative approaches for location determination of users in GNSS denied environments, i.e., the so-called GNSS gap (e.g. in urban canyons or indoors), are needed. These alternatives and backups are the main focus of the Sub-Commission. The Working Groups of the Sub-Commission thereby focus on the use of multi-sensor systems and their integration. For ubiquitous positioning several technologies are researched and further developed. In this context Working Group 4.1.1 not only researches in the development of new ubiquitous positioning techniques but also lays its emphasis on collaborative positioning (or also referred to as cooperative positioning) CP and navigation using a variety of sensors on different platforms. These platforms include mobile vehicles, robots as well as pedestrians and most recently Unmanned Aerial Vehicles (UAV's). New emerging technologies, such as Wi-Fi, RFID, ZigBee, Bluetooth, cellular networks, UWB, Infrared, Ultrasonic, camera-based positioning, inertial sensors (accelerometers and magnetometer), as alternative to GNSS positioning are investigated by WG 4.1.3. In addition, the investigation of location technologies for smartphone positioning plays an important role in the interdisciplinary research conducted under the umbrella of Sub-Commission 4.1.

Major research fields of the SC included the development and enhancement of indoor positioning technologies. A special issue under the title 'Indoor Navigation and Tracking' of the Journal of Physical Communications (Vol. 13, Part A; http://www.sciencedirect.com/science/journal/18744907/13/part/PA) edited by Yu K., I. Oppermann, E. Dutkiewicz, I. Sharp and G. Retscher was published in 2014 containing the following papers:

Sharp I., K. Yu, Sensor-based Dead-reckoning for Indoor Positioning, pp. 4-16.

Moghtadaiee V., A. G. Dempster, Design Protocol and Performance Analysis of Indoor Fingerprinting Positioning Systems, pp. 17-30.

Cheng J., L. Yang, Y. Li, W. Zhang, Seamless Outdoor/Indoor Navigation with WIFI/GPS Aided Low Cost Inertial Navigation System, pp. 31-43.

Li Y., Optimal Multisensor Integrated Navigation Through Information Space- approach, pp. 44-53.

Yan J., K. Yu, L. Wu, Single Frequency Network based Mobile Tracking in NLOS Environments, pp. 54-67.

The SC started also for the first time cooperation with social scientists. Major addressed topics are ethical and political responsibilities of localization technologies for LBS and their impact on users of such services. User acceptance and usability including understandability, learnability and operability are a major focus in the investigations. The cooperation led to the preparation of a research proposal, which will be submitted in a second call under the title 'Mobility of the Future' advertised by the Austrian FFG (Österreichische Forschungsförderungsgesellschaft). A kick-off presentation of the cooperation at the LBS 2014 conference in Vienna, Austria, led to the following publication:

Obex F., G. Retscher (2014): Ethical and Political Responsibility in Location Based Services - The Need of Implementing Ethical Thinking in Our Research Field. in: Papers presented at the 11th International Symposium on Location-Based Services LBS 2014, November 26-28, 2014, Vienna, Austria, pp. 315-328.

Key projects undertaken by members of the SC include the following research fields.

- FIG/IAG/ISPRS Collaborative WG 4.1.1, *Ubiquitous Positioning*

  Field campaign and follow-up processing and analysis on Collaborative Navigation, University of Nottingham, UK, May 14-18, 2012

- EMPARCO (Efficient Management of PArking under Constraints)

  https://emparco.wordpress.com/

  Aims to develop solutions for the management of large-scale parking facilities and depots (for either passenger vehicles or commercial fleets) under constraints including near-capacity demand, temporally concentrated arrivals/departures, need for emergency evacuation.

  Project of the Laboratory of Geodesy, National Technical University of Athens (NTUA) under the lead of V. Gikas. D. Grejner-Brzezinska, OSU and G. Retscher act on the international advisory committee. Sponsor: ARISTEIA-II (Action's Beneficiary: General Secretariat for Research and Technology, GR), co-financed by the European Union (European Social Fund–ESF).

- SaPPART (Satellite Positioning Performance Assessment for Road Transport)

  http://www.sappart.net/

  Aims to develop a framework for the definition of service levels for GNSS and GNSS-augmented positioning terminals used in Intelligent Transportation Systems (ITS) and personal mobility applications, and the associated examination framework for certification purposes.

  Major involvement of the Laboratory of Geodesy, NTUA under the lead of V. Gikas. Sponsor: COST Action TU1302, EU RTD Framework Programme.

- Rowing Performance Assessment System

  Aims to develop an integrated data acquisition system (including GNSS, MEMS IMU, pressure cells, goniometers, biomechanical sensors, etc.) and advanced mathematical models for the analysis of movements of the rowing system for performance assessment and improvement of training.

  Project of the Laboratory of Geodesy, NTUA under the lead of V. Gikas. Sponsor: Greek Minister of Sports, Int. Rowing Federation.

- InKoPoMoVer (Intelligent Cooperative Positioning at Multimodal Public Transit Junctions)

  Aims at a better understanding of passenger movement at multimodal transit situations for providing improved passenger guidance. By combining Differential WLAN and RFID through Cooperative Positioning CP, algorithms can be generated, which considerably increase the accuracy of person tracking, allowing for the derivation of movement patterns. Addressing ethical and usability aspects will ensure user-friendly results.

  Project proposal of the Vienna University of Technology, Department of Geodesy and Geoinformation under the lead of G. Retscher.

In addition to previous projects, during the activity period, the Laboratory of Geodesy, NTUA has developed scientific software for: (a) vehicle trajectory extraction and comparisons, (b) sea trials analysis according to IMO guidelines based on GNSS and IMU. Also a back-pack personal navigator was built for pedestrian navigation use. Regarding future plans, the group aims at research in the hybrid/indoors environment for vehicles and pedestrians. The focus will be towards positioning and navigation using UWB and RFIDs – based on research funds, in the next months the Laboratory it shall equipped with such sensors.

The Sub-Commission 4.1 maintained a strong and active presence at the following international events through participation in coordinating workshops, scientific and organizing committees, delivering short courses and tutorial, publishing papers and presentations, session chairing, etc.

- LBS 2011, Vienna, Austria, Nov. 21-23, 2011
- PLANS 2012, Myrtle Beach, South Carolina, USA, Apr. 24-26, 2012
- FIG Working Week: May 6-10, 2012 in Rome, Italy
- ION GNSS, Nashville, Tennessee, USA, Sep. 17-21, 2012
- UPINLBS 2012, Helsinki, Finland, Oct. 3-4, 2012
- LBS 2012, Munich, Germany, Oct. 16-18, 2012
- IPIN 2012, Sydney, Australia, Nov. 13-15, 2012
- ION Pacific PNT 2013, Honolulu, Hawaii, USA, Apr. 22-25, 2013
- European Navigation Conference 2013, Vienna, Austria, Apr. 23-25, 2013
- 8th International Symposium on Mobile Mapping Technologies MMT 2013, Tainan, Taiwan, May 1-3, 2013
- IAG Scientific Assembly, Potsdam, Germany, Sep.2-6, 2013
- ION GNSS, Nashville, Tennessee, USA, Sep. 16-20, 2013
- IPIN 2013, Montbeliard-Belfort, France, Oct. 28-31, 2013
- LBS 2013, Shanghai, China, Nov. 21-22, 2013
- FIG General Assembly, Kuala Lumpur, Malaysia, June 16-21, 2014
- ION GNSS, Tampa, Florida, USA, Sep. 8-12, 2014
- RFID Conference, Tampere; Finland, Sep. 10-12, 2014
- IPIN 2014, Busan, Korea, Oct. 27-30, 2013
- UPINLBS 2014, Corpus Christi, Texas, USA, Oct. 20-21, 2014
- LBS 2014, Vienna, Austria, Nov. 26-28, 2014

Recent publications dealing with smartphone positioning:

Retscher G., E. Mok, T. Hecht (2013): Smartphone Altitude Determination Using Embedded Barometric Pressure Sensors. in: Papers presented at the 10th International Symposium on Location-Based Services LBS 2013, November 21-22, 2013, Shanghai, China, 3 pgs.

Retscher G., T. Hecht, E. Mok (2013): Location Capabilities and Performance of Smartphones for LBS Navigation Applications. in: Papers presented at the 8th International Symposium on Mobile Mapping Technology, May 1-3, 2013, Tainan, Taiwan.

Retscher G., T. Hecht (2012): Investigation of Location Capabilities of four Different Smartphones for LBS Navigation Applications. IEEE Xplore, 2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN), ISBN: 978-1-4673-1954-6, 6 pgs.

Retscher G. (2012): Wi-Fi Positioning with Smartphones. in: Papers presented at the 9th International Symposium on Location-Based Services LBS 2012, October 16-18, 2012, Munich, Germany, 9 pgs.

Mok E., G. Retscher, C. Wen (2012): Initial Test on the Use of GPS and Sensor Data of Modern Smartphones for Vehicle Tracking in Dense High Rise Environments. IEEE Xplore, 2012 Ubiquitous Positioning Indoor Navigation and Location Based Service (UPINLBS), ISBN: 978-1-4673-1909-6, 7 pgs.

Mok E., G. Retscher, D. Wang, L. Xia (2011): Use of Smartphones for Tracking and Trip Recording. in: Papers presented at the 8th International Symposium on Location-Based Services LBS 2011, November 21-23, 2011, Vienna, Austria, pp. 137-152.

Papers based on EMPARCO project:

Antoniou C., Gikas V., Papathanasopoulou V., Danezis C., Panagopoulos A., Markou I., Efthymiou D., Yannis G., Perakis H. (2015) "Localization and Driving Behavior Classification Using Smartphone Sensors in the Direct Absence of GNSS", Transportation Research Record, (accepted)

Gikas V., Antoniou C., Danezis C., Mpimis T., Perakis H., Papathanasopoulou V., Markou I. (2015) "Evaluating Smartphone Performance for Driving Event and Maneuver Reconstruction", 26th IUGG General Assembly, Prague, Jun. 22–Jul. 2

Antoniou C., Gikas V., Papathanasopoulou V., Danezis C., Panagopoulos A., Markou I., Efthymiou D., Yannis G., Perakis H. (2015) "Localization and Driving Behavior Classification Using Smartphone Sensors in the Direct Absence of GNSS", 94th TRB Annual Meeting Washington DC, USA, Jan. 11–15

Antoniou C., Papathanasopoulou V., Gikas V., Mpimis A., Markou I., Perakis H. (2014) "Monitoring Indoor Driver Behaviour Using Opportunistic Smartphone Sensor Data", ITS and Smart Cities 2014, Patra, Greece, Nov. 19–22

Antoniou, C., Gikas V., Papathanasopoulou V., Mpimis T., Markou I., Perakis H. (2014) "Towards Distribution-Based Calibration for Traffic Simulation", The IEEE Conf. on Intelligent Transportation Systems, Qingdao, China, Oct. 8–11

Antoniou, C., Papathanasopoulou V., Gikas V., Danezis C., Perakis H. (2014) "Classification of Driving Characteristics Using Smartphone Sensor Data", 3rd Symp. of the European Association for Research in Transportation, Leeds, UK, Sept. 10–12

Papers based on SaPPART project:

Gikas V., Gilliéron P-Y, Peyret F. (2015) "GNSS Accuracy and Integrity Issues in Transport and Mobility", 26th IUGG General Assembly, Prague, Jun. 22–Jul. 2

Clausen P., Skaloud J., Gilliéron P-Y, Perakis H., Gikas V., Spyroupoulou I. (2015) "Position Accuracy with Redundant MEMS IMU for Road Applications", European Navigation Conference, Bordeaux, France, Apr. 7–10

Peyret F. Gilliéron P-Y, Gikas V., et al. (2015) "Better use of Global Satellite Systems for Safer and Greener Transport" White Paper, COST Action: TU1302

Papers based on independent research:

Yigit C. O., Gikas V., Alcay S., Ceylan A. (2014) "Performance Evaluation of Short to Long Term GPS, GLONASS and GPS/GLONASS Post-Processed PPP", Survey Review, Vol. 46(336), pp 155–166

Danezis C., Gikas V. (2013) "An Iterative LiDAR DEM-Aided Algorithm for GNSS Positioning in Obstructed / Rapidly Undulating Environments", Advances in Space Research, Vol. 52(5), pp 865 – 878

Paradissis D., Gikas V. (2013) "GNSS for Sea Trials: Measuring Ship Controllability", GIM International, Vol. 37(2), pp 31–35

Gikas V., Mpimis A., Androulaki A. (2013) "Proposal for Geoid Model Evaluation from GNSS/INS-Leveling Data: Case Study along a Railway Line in Greece", Journal of Surveying Engineering, Vol. 139(2), pp 95–104

Gikas V., Stratakos J. (2012) "A Novel Geodetic Engineering Method for the Extraction of Road/Railway Alignments Based on the Bearing Diagram and Fractal Behavior", Transactions of Intelligent Transportation Systems, IEEE, Vol. 13(1), pp 115–126

Danezis C., Gikas V. (2012) "Performance Evaluation of A Novel Terrain-Aiding Algorithm for GNSS Navigation in Forested Environments", ION/GNSS, Nashville, Tennessee, USA, Sept. 17–21

Other Publications:

Gikas V., Karydakis P., Mpimis A., Piniotis G., H. Perakis (2015) "Structural Integrity Verification of a Cable-stayed Footbridge Based on FEM Analyses and Geodetic Surveying Techniques", Survey Review, http://dx.doi.org/10.1179/1752270614Y.0000000146

Gikas V. (2012) "3D Terrestrial Laser Scanning for Geometry Documentation and Construction Management of Highway Tunnels during Excavation", SENSORS, Vol. 12, pp 11249–11270

Gikas V. (2012) "Ambient Vibration Monitoring of Slender Structures by Microwave Interferometer Remote Sensing", Journal of Applied Geodesy, Vol. 6(3-4), pp 167–176

Gikas V., Karydakis P., Piniotis G, Mpimis T., Papadimitriou F, Panagakis A. (2014) "Design and Implementation of a Multi-Sensor Monitoring System for Structural Integrity Assessment: The Case of Attiki Odos, Pallini Cable-Stayed Bridge", IBSBI, Athens, Oct. 16–18

Gikas V., Karydakis P., Mpimis T., Piniotis G., Perakis H. (2014) "Nodestructive Load Testing of a Single-Span, Cable-Stayed Bridge: Testing, Instrumentation and Preliminary Results", FIG Congress, Kuala Lampur, Malaysia, June 16–21

Perakis H., Piniotis G, Mpimis A., Gikas V. (2014) "Experimental Investigation of GNSS, GBMI, DIC for Dynamic Structural Monitoring", 5th Nat. Metrology Conf., Athens, May 9–10

Gikas V., Karydakis P., Mpimis A., Piniotis G., Rodopoulos J. (2013) "Structural Integrity Verification of a Cable-stayed Footbridge Based on Conventional and Non-Conventional Geodetic Data", 2nd Joint Int. Symposium on Deformation Measurements, Nottingham, UK, Sept. 9–10

Piniotis G., Mpimis A., Gikas V. (2013) "Dynamic Testing and Output-Only Modal Analysis of a Bypass-Stack During Extreme Operating Conditions", 2nd Joint Int. Symposium on Deformation Measurements, Nottingham, UK, Sept. 9–10

Gikas V., Daskalakis S., Mpimis A. (2011) "Bridge-Vehicle Interaction Analysis Based on Microwave Radar Interferrometry: An Experimental Investigation of Evripos Cable-Stayed Bridge", Int. Conf. Innovations on Bridges and Soil-Bridge Interaction, Athens, Oct. 13-15

Gikas V., Daskalakis S. (2011) "Radar-based Measurements of the Oscillation Parameters of Large Civil Engineering Structures", 14th FIG Symp. on Deformation Monitoring and Analysis & 5th IAG Symp. on Geodesy for Geotechnical and Structural Engineering, Hong Kong, China, Nov. 2–4, 2011

Note: Further publications can be found under the respective Working Group.

Website of the Sub-Commission 4.1: http://info.tuwien.ac.at/ingeo/sc4/iag_sc41.htm

WG 4.1.1: Ubiquitous Positioning Systems

Chair: Allison Kealy (Australia)
Co-Chair: Günther Retscher (Austria)

In 2012 a major activity undertaken by members of the joint IAG Working Group WG 4.1.1 and FIG WG 5.5 was field experiments at the University of Nottingham from May 14 to 18, 2012. These revolved around the concept of collaborative navigation, and partially indoor navigation. Collaborative positioning is an integrated positioning solution, which employs multiple location sensors with different accuracy on different platforms for sharing of their absolute and relative localizations. Typical application scenarios are dismounted soldiers, swarms of UAV's, team of robots, emergency crews and first responders. The stakeholders of the solution (i.e., mobile sensors, users, fixed stations and external databases) are involved in an iterative algorithm to estimate or improve the accuracy of each node's position based on statistical models. For this purpose different sensor platforms have been fitted with similar type of sensors, such as geodetic and low-cost high-sensitivity GNSS receivers, tactical grade IMU's, MEMS-based IMU's, miscellaneous sensors, including magnetometers, barometric pressure and step sensors, as well as image sensors, such as digital cameras and Flash LiDAR, and ultra-wide band (UWB) receivers. The employed platforms in the tests include a train on the roof of the Nottingham geospatial building, mobile mapping vans, personal navigators from the Ohio State University and University of Nottingham.

In terms of the tests, the data from the different platforms are recorded simultaneously. The two personal navigators moved on the building roof, then trough the building down to where they logged data simultaneously with the vans, all of them moving together and relative to each other. The platforms logged data simultaneously covering various accelerations, dynamics, etc. over longer trajectories. First test results of the field experiments showed that a positioning accuracy on the few meter level could be achieved for the navigation of the different platforms.

Further information about the Working Group and the field experiments can be found at http://ubpos.net/. Measurement data from the campaign are freely accessible from this website.

The work of the group led to a great number of publications in the reporting period. An excerpt of the major publications is given below. In addition, a special issue under the title 'Ubiquitous Positioning and Navigation Systems' of the Journal of Applied Geodesy (Vol. 7, No. 4; http://www.degruyter.com/view/j/jag) edited by A. Kealy, G. Retscher and V. Schwieger was published in 2013 containing the following papers:

Sternberg H., F. Keller, T. Willemsen, Precise Indoor Mapping as a Basis for Coarse Indoor Navigation, pp. 231-246.

Cole A., J. Wang, A. Dempster, C. Rizos, VirtualLItes: Aided Single Epoch GPS Integer Ambiguity Resolution for Agricultural Land Vehicle Applications, pp. 247-256.

Beetz A., V. Schwieger, Automatic Lateral Control of a Model Dozer, pp. 257-270.

Bonenber L. K., C. Hancock, G. W. Roberts, Locata Performance in a Long Term Monitoring, pp. 271-280.

Jiang W., Y. Li, C. Rizos, J. Barnes, Flight Evaluation of a Locata-augmented Multisensor Navigation System, pp. 281-290.

Rabiain A. H., A. Kealy, M. Morelande, Tightly Coupled MEMS Based INS/GNSS Performance Evaluation During Extended GNSS Outages, pp. 291-298.

Li B., T. Gallagher, C. Rizos, A. Dempster, Using Geomagnetic Field for Indoor Positioning, pp. 299-308.

Major Publications:

Kealy A., G. Retscher, C. Toth, D. A. Grejner-Brzezinska (2014): Collaborative Positioning – Concepts and Approaches for More Robust Positioning. in: Papers presented at the XXV International FIG Congress, June 16-21, 2014, Kuala Lumpur, Malaysia, 15 pgs.

Retscher G. (2014): The Fourth Layer in Collaborative Navigation – Going Underground. in: Papers presented at the XXV International FIG Congress, June 16-21, 2014, Kuala Lumpur, Malaysia, 15 pgs.

Toth C., D. A. Grejner-Brzezinska, A. Kealy, G. Retscher (2014): Personal Navigation and Indoor Mapping: Performance Characterization of Kinect Sensor-based Trajectory Recovery. in: Papers presented at the XXV International FIG Congress, June 16-21, 2014, Kuala Lumpur, Malaysia, 12 pgs.

Kealy A., A. Hasnur-Rabiain, N. Alam, C. Toth, D. A. Grejner-Brzezinska, V. Gikas, G. Retscher (2013): Co-operative Positioning Algorithms and Techniques for Land Mobile Applications. in: Papers presented at the 8th International Symposium on Mobile Mapping Technology, May 1-3, 2013, Tainan, Taiwan, 6 pgs.

Kealy A., A. Hasnur-Rabiain, N. Alam, C. Toth, D. A. Grejner-Brzezinska, V. Gikas, C. Danezis, G. Retscher (2013): Cooperative Positioning using GPS, Low-cost INS and Dedicated Short Range Communications. in: Papers presented at ION Pacific PNT 2013, April 22-25, 2013, Honolulu, Hawaii, USA.

Kealy A., G. Retscher, A. Hasnur-Rabiain, N. Alam, C. Toth, D. A. Grejner-Brzezinska, T. Moore, C. Hill, V. Gikas, C. Hide, C. Danezis, L. Bonenberg, G. W. Roberts (2013): Collaborative Navigation Field Trials with Different Sensor Platforms. in: Papers presented at the 10th Workshop on Positioning, Navigation and Communication WPNC 2013, March 20-21, 2013, University of Applied Sciences Dresden, Germany, 6 pgs.

Kealy A., G. Retscher, N. Alam, A. Hasnur-Rabiain, C. Toth, D. A. Grejner-Brzezinska, T. Moore, C. Hill, V. Gikas, C. Hide, C. Danezis, L. Bonenberg, G. W. Roberts (2012): Collaborative Navigation with Ground Vehicles and Personal Navigators. IEEE Xplore, 2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN), ISBN: 978-1-4673-1954-6, 8 pgs.

Kealy A., G. Retscher, D. Grejner-Brzezinska, V. Gikas, G. Roberts (2011): Evaluating the Performance of MEMS based Inertial Navigation Sensors for Land Mobile Applications. Archives of Photogrammetry, Cartography and Remote Sensing, Vol. 22, ISSN 2083-2214, pp. 237-248.

WG 4.1.3: Emerging Technologies

Chair: Kefei Zhang (Australia)
Co-Chair: Lukasz Bonenberg (UK)

Working Group 4.1.3 and its associated key players from Australia and Europe have been active in the past 4 years in investigating emerging technologies for innovative positioning and tracking, theoretical frame, field evaluations and practical industrial applications. Nowadays numerous technologies such as Wi-Fi, RFID, ZigBee, Bluetooth, cellular networks, UWB, Infrared, Ultrasonic, camera-based positioning accelerometers and magnetometer positioning are employed for positioning and tracking. Each of these techniques has advantages and drawbacks. For example, Wi-Fi localization has relatively good accuracy but cannot be used in case of power outage or in the areas with poor Wi-Fi coverage. Magnetometer positioning or cellular network does not have such problems but they are not as accurate as localization with Wi-Fi. On the other hand, indoor tracking and positioning technologies have been one of the hot topics in the world and its rapid development has been predominantly driven by the huge potential commercial applications, especially Wi-Fi and smartphones based technologies. Wi-Fi and smartphones are getting more and more popular for tracking and positioning along with the fast growth of the Internet users and rapid development of e-commerce. Both industrial companies and government organizations have paid more and more attention to Wi-Fi's applications. Many industrial fields (e.g., retail industry, large shopping malls, airport operators, museums, university campus) have started to use Wi-Fi and smartphone as popular value-added tracking and positioning techniques to transform their business style and improve their customer services.

One of the emerging indoor positioning technologies is light-based positioning, in particular LED-based positioning technology. This presents a new trend of tracking and positioning. ByteLight announced that they had developed a GPS-like indoor positioning system that uses LED lighting to transmit location data to smartphones. ByteLight's positioning system works by controlling the pulses of LEDs so they work in a certain pattern. This pattern is not detectable to the human eye but can be picked up by the camera in a smartphone or tablet. Using the data gleaned from the LED modulation, the device works with Apps and performs client-side calculations to figure out where it is within the structure. Light-based positioning systems make it easy for shoppers to navigate retail stores and find products, managers and optimizes enterprise employee operations, turns mobile devices into tour guides within a museum or public building, and helps people find colleagues and booths while attending trade shows or other events – the applications for this technology are truly endless, said ByteLight CEO and cofounder Aaron Ganick.

Along with the development of the technologies, quite a few innovative algorithms have been proposed for the enhancement of the positioning solutions. This includes, for example, the crowdsourcing Radio Map method, dynamic fingerprinting method, cooperative localization technique, regular Infrastructure Topology proposed and the use of Signals of Opportunity etc. The current trend in this research arena is towards smart solutions pertaining to designated applications under specific environments.

Major Activities:

Participation in the initial working group proposing OFFCOM into ECC Report 128 Compatibility Studies Between Pseudolites And Services In The Frequency Bands 1164-1215, 1215-1300 And 1559-1610 MHz, September 2012

May 2012 Collaborative Navigation with Ground Vehicles and Personal Navigators, experiment in Nottingham, UK.

A series of UWB trials were conducted in the University of Nottingham in Dec. 2012 and RMIT University in April 2013 and July 2014.

Three major Australian universities (RMIT, University of Melbourne and UNSW) have worked together and established a dedicated Australian indoor positioning laboratory through major funding attracted from Australian Research Council and capital budget from both RMIT and University of Melbourne. The key researchers involved include K. Zhang (RMIT University), A. Kealy (University of Melbourne) and T. Gallagher and B. Li (UNSW). This laboratory is hosted in RMIT Design Hub Building in Melbourne and a large number of sensors systems have been procured. Several initial tests that involve smartphones and laptops as a mobile platform and UWB, USRP, RFID, Wi-Fi, magnetometers and INS as sensors were carried out.

An Australian Research Council project entitled with "TRIIBE - TRacking Indoor Information BEhaviour" was awarded to a team in RMIT University that involves researchers from geospatial, computer science and communication backgrounds. This project will research the passive tracking of user's mobile devices in indoor spaces correlating their spatial behaviour with their information needs to deliver personalised information. The project aims to create a system that enables owners of large buildings (for example, shopping malls, airports, universities) to better manage their spaces and services and provide value-added information to their customers.

The University of Nottingham team is working on the indoor positioning project using UWB, with external partner, which have feed into JISDM conference in Nottingham. If this initial study is successful I expect to establish a larger collaboration. Nottingham Geospatial Institute has a successful indoor positioning group and RMIT hosted Australian laboratory hopes to get further involved with them as well. Trials were conducted at the laboratory in July 2013 and 2014 with participation of G. Retscher.

Publications:

Chew P. (2015): Indoor positioning solutions guide, Building Management, Melbourne, Australia, Niche Media Pty Ltd. April-May 2015 edition, online published.

Rensheng, H. (2015): Trends of Science and Technology: Seven Popular Indoor Positioning Technologies. Retrieved 01 February, 2015, from http://www.wtoutiao.com/a/ 1498456.html.

Bai Y. B., S. Wu, G. Retscher, A. Kealy, L. Holden, M. Tomko, A. Borriak, B. Hu, H. R. Wu, K. Zhang (2014): A New Method for Improving Wi-Fi Based Indoor Positioning Accuracy. Journal of Location-Based Services LBS, Vol. 8, No. 3, November 2014, pp. 135-147, ISSN 1748-9725, DOI: 10.1080/17489725.2014.977362.

Bai Y. B., S. Wu, Y. Ren, K. Ong, G. Retscher, A. Kealy, M. Tomko, M. Sanderson, H. Wu, K. Zhang (2014): A New Approach for Indoor Customer Tracking Based on a Single Wi-Fi Connection. International Conference on Indoor Positioning and Indoor Navigation IPIN, October 27-30, 2014, Busan, South Korea, 7 pgs.

Bai Y. B., M. Williams, A. Borriak, A. Kealy, K. Zhang (2014): An Accuracy Enhancement Algorithm for Fingerprinting Method. Proceedings of the 2014 International Conference on Data Science and Advanced Analytics (DSAA 2014), November, 2014, Shanghai, China, http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=7050498, DOI 10.1109/DSAA.2014.7058060, pp110-114

Bartié M. A. (2014): Path Loss in free space. QSL.net. Retrieved 9 May, 2014, from http://www.qsl.net/pa2ohh/jsffield.htm.

CNNIC, C. I. N. I. C. (2014): CNNIC Released the 33rd Statistical Report on Internet Development in China. 33rd Statistical Report on Internet Development in China. Retrieved 3 February, 2014, from http://www1.cnnic.cn/AU/MediaC/rdxw/hotnews/ 201401/t20140117_43849.htm.

Costilla-Reyes O., K. Namuduri (2014): Dynamic Wi-Fi Fingerprinting Indoor Positioning System, Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 27th-30th October 2014, Busan, Korea.

Cullen G., et al. (2014): CAPTURE - Cooperatively Applied Positioning Techniques Utilizing Range Extensions, Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 27th-30th October 2014, Busan, Korea.

Fink A., H. Beikirch (2014): Refinement of Weighted Centroid Localization Using a Regular Infrastructure Topology, Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 27th-30th October 2014, Busan, Korea.

Han D., et al. (2014): Address-Based Crowdsourcing Radio Map Construction for Wi-Fi Positioning Systems, Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 27th-30th October 2014, Busan, Korea.

Jaswante S. A., M. M. Bartere (2014): Wi-Fi MIMO Emerging trend in Wireless Technology. International Journal of Computer Science and Mobile Computing 3(3): 557-561.

Nanmaran K., B. Amutha (2014): Situation Assisted Indoor Localization Using Signals of Opportunity, Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN), 27th-30th October 2014, Busan, Korea.

Ren Y., M. Tomko, K. Ong, Y. B. Bai, M. Sanderson (2014): The Influence of Indoor Spatial Context on User Information Behaviours, Proceedings of the ECIR'14 Information Access in Smart Cities Workshop (i-ASC 2014), 13 April, 2014, Amsterdam, Netherlands.

Cangeloso, S. (2013). ByteLight uses LEDs for indoor positioning. Retrieved 08 April, 2015, from http://www.extremetech.com/extreme/151068-forget-wifislam-bytelight-uses-leds-for-indoor-positioning.

Parramatta-City-Council (2013): Major Developments - Westfield Tower, Retrieved 6 June, 2014, from http://www.parracity.nsw.gov.au/work/economic_development/major_ developments.

Bonenberg L. K., G. W. Roberts, C. M. Hancock (2012): Using Locata To Augment GNSS In A Kinematic Urban Environment, Archives of Photogrammetry, Cartography and Remote Sensing, Vol. 22, ISSN 2083-2214, pp. 63-74.

Gunawan M, B. Li, T. Gallagher, A. G. Dempster, G. Retscher (2012): A New Method to Generate and Maintain a WiFi Fingerprinting Database Automatically by Using RFID. IEEE Xplore, 2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN), ISBN: 978-1-4673-1954-6, 6 pgs.

Mok E., F. Lau, L. Xia, G. Retscher, H. Tian (2012): Influential Factors for Decimetre Level Positioning Using Ultra Wide Band Technology. Survey Review, Vol. 44, No. 324, January 2012, pp. 37-44.

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Bonenberg L. K., G. W. Roberts, C. M. Hancock (2011): Using Locata to Augment GNSS, Civil Engineering Surveyor, GIS-GPS supplement, pp. 19-23.

Xia L., D. Wu, E. Mok, G. Retscher (2011): Adaptive Indoor Hybrid Positioning for LBS. in: Papers presented at the 8th International Symposium on Location-Based Services LBS 2011, November 21-23, 2011, Vienna, Austria, pp. 61-75.

Zhu M., G. Retscher, K. Zhang (2011): Integrated Algorithms for RFID-based Multi-sensor Indoor/Outdoor Positioning Solutions. Archives of Photogrammetry, Cartography and Remote Sensing, Vol. 22, ISSN 2083-2214, pp. 451-465.

WG 4.1.4: Imaging Techniques

Chair: Mohamed Elhabiby (Egypt and Canada)
Co-Chair: Jens-André Paffenholz (Germany)

Purpose

The major research aim is to fulfill the need for developing imaging techniques for different navigation problems. Vision Based Navigation (VBN) systems research work will cover two different research streams: the non-inertial vision navigation and the inertial-aided vision navigation approaches. Real time efficient implementation with fast computations extended the working group research activities to geo-computations, digital signal processing, non-linear optimization and image matching. The working group research work was connected to the navigation and geo-computational industry in general and UAV industry in specific.

Objectives and actions of the Working Group

- Integration between inertial systems and imaging technique using advanced search algorithms was investigated.
- Evaluation of estimating aircraft position and velocity from sequential aerial images.
- Real-time implementation of a vision based navigation algorithm which comprises both accuracy and effectiveness (meaning the cheapness of the sensors used, computational load and complexity).T
- Assessment on the relative position estimation based on stereo modeling of two sequential images.
- Evaluation of the absolute position estimation techniques through matching schemes using reference images
- Implementation of non-linear estimation for solving Collinearity equation for UAV Visual Based Navigation systems
- Implementation of the advanced imaging filtering techniques for edge detection and feature extraction
- Development of INS navigation system with map aiding for land based navigation
- Development of low cost INS system for helping with automatic LIDAR registration
- Development an indoor mapping system using integrated INS and 2D range finder for navigation and RGB-D for mapping
- Building an effective academic and industrial network worldwide that can help and promote the research activities of the working group.

Publications:

Attia M., Moussa A. and El-Sheimy N. (2013): Map Aided Pedestrian Dead Reckoning Using Buildings for Indoor Navigation Applications, Scientific Research Publishing, Vol.4, No.3 POS.

Attia M., A. Moussa and N. El-Sheimy (2012): Map Aided Pedestrian Dead Reckoning Using Buildings Information for Indoor Navigation Applications. Positioning 07/2013; 4(2):227-239. DOI: 10.4236/pos.2013.43023

Badawy, H., Alsubaie N., Elhabiby M. and El-Sheimy N. (2014): Registration of Time of Flight Terrestrial Laser Scanner Data for Stop-and-Go Mode, Conference: ISPRS Technical Commission I Symposium, At Denver, Colorado, USA, Volume: Volume XL-1.

Chiang Kai-Wei, Tsai M., El-Sheimy N., Habib A., Chu C. (2015): New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads, Sensors 01/2015; 15(3):6560-85. DOI: 10.3390/s150306560, Source: PubMed.

Mostofi N., Elhabiby M. and El-Sheimy N. (2014): Indoor Localization and Mapping Using Camera and Inertial Measurement Unit (IMU). DOI: 10.1109/PLANS.2014.6851507 Conference: IEEE/ION PLANS 2014, At Monterey, CA

Mostofi N., Moussa A., Elhabiby M. and El-Sheimy N. (2014): RGB-D Indoor Plane-based 3D-Modeling using Autonomous Robot. DOI: 10.5194/isprsarchives-XL-1-301-2014 Conference: ISPRS Technical Commission I Symposium, At Denver, Colorado, USA, Volume: XL-1. DOI: 10.1109/PLANS.2014.6851507 Conference: IEEE/ION PLANS 2014, At Monterey, CA

Shawky Elsharkawy A., M. Elhabiby, and N. El-Sheimy (2012): Curvelet Transform for Water Bodies Extraction from High Resolution Satellite Images. 8th international conference on electrical engineering, ICEENG-8, Cairo 29th -31st May 2012.

Shawky Elsharkawy A., M. Elhabiby, and N. El-Sheimy (2012): A New Integrated Pixel- and Object Based Techniques for Efficient Urban Classification using WorldView-2 Data. ISPRS congress, August 25th – September 1st ,2012, Melbourne, Australia.

Sheta B., Elhabiby M. M., and El-Sheimy N. (2012): Assessments of Different Speeded Up Robust Features (SURF) algorithm resolution for pose estimation of UAV. International Journal of Computer science and Engineering Survey., Vol.3, No.5, 27, 2012.

Sheta B., Elhabiby M. M., and El-Sheimy N., (2012): Assessment of Nonlinear Optimization and Speeded Up Robust Features (SURF) Algorithm for Estimating Object Space Transformation Parameters for Pose Estimation. GEOMATICA, 2012, Vol.66, No.4, p: 307-321

Sheta B., Elhabiby M. M., and El-Sheimy N., (2012): Low Cost Vision Based Navigation (VBN) System for UAV Navigation in GPS-denied Environments. International Journal of Computer science and Engineering Survey.

Sheta B., Elhabiby M. M., and El-Sheimy N., (2012): Assessments of Nonlinear Least Squares Methods for UAV Vision Based Navigation (VBN). ASPRS Annual Meeting 2012, Sacramento, California, USA, March 19-23, 2012.

Sheta B., Elhabiby M. M., and El-Sheimy N., (2012): Comparison and Analysis of Nonlinear Least Squares Methods for Vision Based Navigation (VBN) algorithms. ISPRS Congress 2012, Melbourne, Australia, August 25-September 1, 2012.

Concluding Remarks

The three Working Groups of SC 4.1 were very active in the last period as can be seen from the reports. Therefore we would like to continue our successful work in the next period.

Sub-Commission 4.2: Geodesy in Geospatial Mapping and Engineering

Chair: Jinling Wang (Univ. of New South Wales, Australia)
Co-Chair: Gethin Roberts (Univ. of Nottingham, UK)

Geodesy provides foundations for geospatial mapping and engineering. Modern geospatial mapping as a massive point positioning process has been evolving towards automatic operations, and at the same time, various engineering areas are increasingly relying on highly developed geospatial technologies to deliver improved productivities and safety with minimised negative environment impact. The Sub-Commission (SC) 4.2 have therefore coordinated research and other activities that address the broad areas of the theory and applications of geodesy tools in geospatial mapping and engineering, ranging from construction work, geotechnical and structural monitoring, precision farming, mining, to natural phenomena such as landslides and ground subsidence. Over the past four years, the SC4.2 has carried out its work in close cooperation with other IAG Entities, as well as via linkages with relevant scientific and professional organizations such as ISPRS, FIG, IEEE, ION, ISM. The objectives of this Sub Commission are:

- To develop and promote the use of new geospatial mobile mapping technologies for various applications.
- To develop and report the modelling and quality control framework for geo-referencing procedures
- To monitor research and development into new technologies that are applicable to the general field of engineering geodesy, including hardware, software and analysis techniques.
- To study advances in geodetic methods for precision farming, mining operations, and large construction sites.
- To study advances in monitoring and alert systems for local geodynamic processes, such as landslides, ground subsidence, etc.
- To study advances in the application of artificial intelligence techniques in engineering geodesy.
- To document the body of knowledge in the field of geospatial mapping and engineering geodesy, and to present such knowledge in a consistent frame work at symposia and workshops.

These objectives have been largely achieved and the website for the sub-commission was set up and maintained at http://www.sage.unsw.edu.au/iag-sc4.2. Over the past four years, the working groups have developed memberships as well as coordinated and participated in the professional activities towards the objectives of the sub-commission. This final report presents these activities.

WG 4.2.1 Mobile Mapping Technologies and Applications

Chair: J. Skaloud (Switzerland)
Co-Chair: K.-W. Chiang (Taiwan)

Mobile mapping technologies have been widely used to collect geospatial data for a variety of applications, for example, navigation and online geospatial information services. As mobile mapping sensors are becoming cheaper and easier to access, modeling and quality control procedures for major steps of mobile mapping should be further developed to ensure the reliability of geospatial data from mobile mapping systems. This working group conducted its work through coordinated activities among the members of the group as well as in collaborations with other professional organizations, such as ISPRS/FIG.

The IAG Sub Commission 4.2 and Working Group 4.2.1 actively participated in organization of the International Symposium on Unmanned Airborne Vehicles for Geomatics, **UAV-g 2011** held in Zurich, September 14-16 2011.

IAG Commission 4 and Working Group 4.2.1 sponsored and actively participated "The International Summer School on Mobile Mapping Technology in 2012 and 2013, 11-15 June 2012; 29-30 April, 2013, National Cheng Kung University (NCKU), Tainan, Taiwan.

Program Details: http://conf.ncku.edu.tw/mmt2013/course01.htm

The 2013 Summer School on Mobile Mapping Technology (MMT 2013) was held just before the MMT symposium. The courses of this summer school were focused on the themes of inertial navigation and multi sensor integration, mobile mapping systems, photogrammetric and LiDAR Technologies, and various applications. President of IAG Commission 4, Prof. Dorota A. Grejner-Brzezinska, and Co-Chair of IAG Working Group 4.2.1, Associate Professor Kai-Wei Chiang, were among the invited lecturers for the Summer School on MMT in Tainan, 2012/2013.

The IAG Sub Commission 4.2 and Working Group 4.2.1 have sponsored and actively participated The 8th International Symposium on Mobile Mapping Technology – **MMT2013**, 1 – 2 May, Tainan, 2013 (see the photo below).

The IAG Sub Commission 4.2 and Working Group 4.2.1 actively participated in the International Symposium on Unmanned Airborne Vehicles for Geomatics, UAV-g 2013 held in Rostock, Germany, September 4-6.

The chair of IAG Working Group 4.2.1 co-organized the European Calibration and Orientation Workshop, EuroCOW 2014 held in Calstelldefels, Spain, 12-14 February where he was responsible for the session on Integrated Systems for Sensor Geo-referencing and Navigation.

The IAG Sub Commission 4.2 and Working Group 4.2.1 has been organising The 9th International Symposium on Mobile Mapping Technology, MMT2015, to be held in Sydney, Australia, 9-11 December 2015, Website: www.mmt2015.org. A/Prof Jinling Wang, Chair of the IAG Sub Commission 4.2, is the Convenor/General Chair for the MMT2015.

Selected Publications:

Chiang, K.-W.; Duong, T.T.; Liao, J.-K.; Lai, Y.-C.; Chang, C.-C.; Cai, J.-M.; Huang, S.-C. (2012) On-Line Smoothing for an Integrated Navigation System with Low-Cost MEMS Inertial Sensors. *Sensors, 12(12)*, 17372-17389.

Chiang K-W, Tsai M-L, Chu C-H. (2012) The Development of an UAV Borne Direct Georeferenced Photogrammetric Platform for Ground Control Point Free Applications. *Sensors*,12(7):9161-9180.

Chiang K-W, Duong TT, Liao J-K. (2013) The Performance Analysis of a Real-Time Integrated INS/GPS Vehicle Navigation System with Abnormal GPS Measurement Elimination. *Sensors*, 13(8):10599-10622.

Chiang ,K.W., Duong ,T.T., Liao J.k.,(2013),* Performance of Real-Time Land-Based GPS-Aided MEMS Inertial Navigator with Interference from Reflected GPS Signals, *Sensors* **2013**, *13*(8), 10599-10622

*Chu, H.J**,*Tsai, G.J., Chiang ,K.W., Duong ,T.T.,**(2013),*** GPS/ MEMS INS data fusion and map matching in urban areas, *Sensors* **2013**, *13*(9), 11280-11288;

Lin C-A., Chiang,K-W. *Chu,C-H. (2013), The Performance Evaluation of Pure Inertial Navigation System Aiding from DTM for Land Vehicular Applications: ION GNSS 2013 Meeting, Nashville, Tennessee, USA*

Chu,C-H, Chiang,K-W., Lin C-A. (2013), The Performance Analysis of a Portable Mobile Mapping System with Different GNSS Processing Strategies: ION GNSS 2013 Meeting, Nashville, Tennessee, USA

Chu, C.H., and Chiang, K.W, *(2013),The Performance Analysis of a Portable Mobile Mapping System, 2013 International Symposium on Mobile Mapping Technologies, Tainan, Taiwan*

Guerrier, S., Waegli, A., Skaloud J., and Victoria-Feser M.-P. (2012) *Fault Detection and Isolation in Multiple MEMS-IMUs Configurations*, in IEEE Transactions On Aerospace And Electronic Systems, vol. 48, p. 2015-2031, 2012.

Kersting, A. P., Ayman, . F. H , Ki-In B. and Skaloud J (2012). *Automated approach for rigorous light detection and ranging system calibration without preprocessing and strict terrain coverage requirements*, in Optical Engineering -Bellingham- International Society for Optical Engineering-, vol. 51, num. 7, p. 076201-1 – 19

Li, X., Wang J., Liu, W., & Li, R. (2013) Geo-referenced 3D map: Concept & experiments. *8th Int. Symp. on Mobile Mapping Technology*, Tainan, Taiwan, 1-3 May. Paper 102

Skaloud J. and Schär P. (2012) *Automated Assessment of Digital Terrain Models Derived From Airborne Laser Scanning*, in PFG, vol. 2, p.0105-0114.

Wu, Y., & Wang J. (2013) Stochastic modeling of inertial errors for mobile mapping applications. *8th Int. Symp. on Mobile Mapping Technology*, Tainan, Taiwan, 1-3 May. Paper 48

P. Molina, I. Colomina, T. Victoria, J. Skaloud, W. Kornus, R. Prades and C. Aguilera: Searching lost people with UAVS: The system and results of the CLOSE-SEARCH project. XXII Congress of the International Society for Photogrammetry and Remote Sensing, Melbourne, Australia, August 25 - September 1, 2012.

Y. Stebler, S. Guerrier, J. Skaloud and M.-P. Victoria-Feser. A Framework for Inertial Sensor Calibration Using Complex Stochastic Error Models. ION/IEEE PLANS, Session A5, Myrtle Beach, SC, USA, April 2012.IEEE-ION Position Location and Navigation Symposium.

P. Molina, I. Colomina, P. Victoria, J. Skaloud, W. Kornus, R. Prades and C. Aguilera: Drones to the Rescue! Inside GNSS, vol. July/August, 2012.

R. Filliger, Y. Stebler, J. Skaloud and K. Hug. Autarktic and Inertial Measurement based Low-cost Reconstruction of Motorcycle forward Speed. Proceedings of the ENC GNSS 2013, Vienna, Austria, 2013.

M. Rehak, J. Skaloud, R. Mabillard, A Micro-UAV with the Capability of Direct. Georeferencing. UAV-g 2013, Rostock, Sep. 4-6.

S. Guerrier, R. Molinari, J. Skaloud and M.-P. Victoria-Feser. An algorithm for automatic inertial sensor calibration. ION GNSS+, Nashville, Tennessee, USA, September 16-20, 2013.

WG 4.2.2: Applications of Geodesy in Mining Engineering

Chair: A. Jarosz (Australia)
Co-Chair: J. Gao (China)

Geodesy has been playing an important role in mining operations from geospatial mapping, modern navigation and guidance technologies used in automation at various mine sites to special orientation and location procedures used in underground operations. This working group conducted its activities in close collaborations with other relevant international professional organizations, such as the International Society of Mining Surveying (ISM) and FIG.

Chair of IAG Working Group 4.2.2, Dr. Andrew Jarosz organised "2012 International Symposium on Mine Surveying and Mapping for Sustainable Mining", 9 August 2012, The Sebel Cairns, Queensland, Australia.

Program details can be found at: http://www.ism.rwth-aachen.de/images/upload/CommissionMeetings/Commission6/2012Commission6Announcement-Australia.pdf

Dr. A. Jarosz was the Chairman of the Scientific Committee, and Associate Professor Jinling Wang, Chair of IAG Sub-Commission 4.2 was a member of the Scientific Committee for the Symposium.

The IAG Sub Commission 4.2 and Working Group 4.2.2 actively participated in the work conference "Joint workshop on ubiquitous positioning and future development" of Sino-British Joint Research Centre of Spatial Information, held in Nottingham, British, 2013, September 12-15. The conference was dedicated in the concept of ubiquitous, the collection and management of data, the system integration and the marketization, and the committee talked about the planning of the future work. At the end of the meeting, the participants visited the pseudo-satellite positioning experimental platform of Nottingham University.

The seminar combining sensors of environment and disaster of the mining area was held at China University of Mining and Technology, 7, September, 2013. Beside the China University of Mining and Technology, Northeast University, Xian University of Science and Technology and Jiangxi University of Science and Technology participated this seminar. The seminar was dedicated to the affection of environment and human health because of the production of coal and electricity. The participants discussed technical issues related to monitoring of the environment and disasters, and visited the mining experiment area, mining area I, mining area II.

Selected Publications:

Li Zengke; Gao Jingxiang; Wang Jian; and Zhou Feng. Application of Geostatistics Model in Analysis of GPS Deformation Sequence. Geostatistics. 2012, Vol. 32, Issue (4): 99-10

WANG Bin; GAO Jing-xiang; HU Hong; ZHOU Feng.Quality Control Method of High-precision GPS Mesh Adjustment for Mine Area. 2012, 2012(03) 21-24.

ZHANG An-bing; GAO Jing-xiang; ZHANG Zhao-jiang. Deformation analysis and prediction of building above old mine goaf based on multiscale method. Rock and Soil Mechanics, 2012, 2012(03) 21-24.

WG 4.2.3: Geodetic technologies in Precision Farming

Chair: R. Bill (Germany)

Modern precision farming operations are highly dependent on high precision positioning, orientation and geospatial mapping, which are based on modern geodetic theory, techniques and services. This working group coordinated professional activities to look into major geodetic aspects in precision forming areas in various parts of world.

UAV-g 2013 conference

In the last years we saw ncreasing use of so-called unmanned aerial vehicles, UAV (aka UAS, RPAS), in photogrammetric and geoinformatics research and development. The bi-annual conference series "UAV-g - Unmanned Aerial Vehicles in Geomatics" addresses this extended field of research and the first conference, which took place in Zurich, Switzerland, in 2011 was a great success. In 2013 the conference was held in Rostock, Germany, from September 4 to 6.

In total, 230 participants from 35 countries followed the invitation of the chair for Geodesy and Geoinformatics at the Rostock University. There were 69 oral and 15 poster presentations, and as a special event on the Thursday, September 5, an airshow was organized on the airfield Barth. Here, 15 manufacturers, service providers and software companies demonstrated their systems.

IAG Sub Commission 4.2 members actively participated in this conference and were members of the Scientific Committee.

All conference papers appeared in the ISPRS archives, see http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-1-W2/. Selected publications have been be prepared for special issues of dedicated scientific journals (Photogrammetrie, Fernerkundung und Geoinformation (PFG) Volume 4-2014 and gis.SCIENCE Volume 1-2014).

IAG Sub Commission 4.2 members are involved in the preparation of the next UAV-g 2015 event in Toronto, August 30 - September 2, 2015. In parallel Dr. Grenzdörffer is the chairman of the ICWG I/Vb: Unmanned Vehicle Systems (UVS): Sensors and Applications of the

ISPRS. In this position he was participating at the Commission I mid-symposium, Ohio, USA 2014 of the ISPRS. Program details under: www.uav-g-2015.ca

Research projects

The chairman (and some members of the WG 4.2.3) have been involved in larger European research activities on web-based data infrastructures and services used in agricultural environment.

- Future Farm (2008-2010, http://www.futurefarm.eu): Meeting the challenges of the farm of tomorrow by integrating Farm Management Information Systems to support real-time management decisions and compliance to standards
- AgriXchange (2010-2012, http://agrixchange.eu/): Setup a network for developing a system for common data exchange in the agricultural sector.
- GeoWebAgri (2011-2012, http://geowebagri.eu/): Geospatial ICT infrastructure for agricultural machines and FMIS in planning and operation of precision farming
- FarmFUSE (2013-2016, http://www.farmfuse.eu/): Fusion of multi-source and multi-sensor information on soil and crop for optimised crop.

Individual research aspects of the group were related to precise positioning with low-cost GNSS (September, 2011, 2013), precise navigation and guidance, precise mapping as well interpretation of space-time heterogeneities in the field.

Prof. Bill and members of his team have been invited to write the chapter on "GIS in Agriculture" for the Springer Handbook of Geographic Information.

Selected publications:

Bill, R., Nash, E., Grenzdörffer, G. (2012): GIS in Agriculture. In: Kresse, W., Danko, D.M.: Handbook of Geographic Information. Springer. Page 795 - 819.

Behnke, R., Born, A., Salzmann, J., Timmermann, D., Bill, R. (2011): Combining Scalability and Resource Awareness in Wireless Sensor Network Localization. In: IEEE Conference on Computer Communications Workshops: IEEE INFOCOM 2011. Proceedings of the Third International Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN 2011). Page 531 - 536. gis.Science (2014): Special Issue UAS.Volume 1.

Grenzdörffer, G., Niemeyer, F., (2011) UAV Based BRDF Measurements of Agricultural Surfaces with PFIFFIKUS. In: Eisenbeiss, H. et al. [eds], *Int. Arch. Photogrammetry Remote Sens. Spatial Inf. Sci. Proceedings of the International Conference on Unmanned Aerial Vehicle in Geomatics (UAVg),* Zürich.

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Nash, E., Nikkilä, R., Wiebensohn, J., Walter, K., Bill, R. (2011): Interchange of Geospatial Rules - Towards Georules Interchange Format (GeoRIF)?. In: gis.Science. 24. Jahrgang, Nr. 3, S. 82 - 94.

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Nikkilä, R., Wiebensohn, J. Nash, E., Seilonen, I., Koskinen, K. (2012): A service infrastructure for the representation, discovery, distribution and evaluation of agricultural production standards for automated compliance control. In: Computer and Electronics in Agriculture. 80, Nr. 0, S. 80 - 88.

Peets, S., Mouazen, A., Blackburn, K., Kuang, B., Wiebensohn, J. (2012): Methods and procedures for automatic collection and management of data acquired from on-the-go sensors with application to on-the-go soil sensors. In: Computer and Electronics in Agriculture. 81, Nr. 0, S. 104 - 112. PFG (2014): Special issue on UAS. Volume 4.

Stempfhuber, W., Buchholz, M. (2011): High-End and Low-Cost RTK GNSS in Machine Control and Precision Farming Applications, FIG Working Week 2011 Bridging the Gap between Cultures, Marrakech, Morocco, 18-22 May 2011.

Stempfhuber, W. (2013): Geodätische Monitoringsysteme mit RTK Low-Cost-GNSS, tech 13 - Trends im Vermessungswesen: Aktuelle Trends und Herausforderungen in der Ingenieurgeodäsie

Wiebensohn, J., Sørensen, C.A.G. (2011): Aspects of the Farm Management Information System related to standards and regulations. In: Nordic Association of Agricultural Scientists (Hrsg.): Automation and System Technology in Plant Production: NJF Report. 7, 5. Herning, Denmark.

More details about this working group can be found at: http://www.iag-wg423-pf.auf.uni-rostock.de/

WG 4.2.4: Monitoring of Landslides & System Analysis

Chair: G. Mentes (Hungary)
Co-Chair: J. Guo (China)

Surface mass movements can cause a lot of damages. Forecasting landslides is of crucial importance due to the potentially serious consequences to the society. It is a difficult and complex task which needs understanding of the relationships between landslide generating processes (geological, geophysical, hydrological, meteorological, etc.) and movements of the sliding block and its surroundings. In addition to the continuous recording geophysical, hydrological, meteorological, etc. parameters, there is an urgent need for continuous 3D geodetic measurements to determine the complex movements of the landslide prone area to understand the kinematic and dynamic behaviour of landslides. There is only a chance to develop an early warning system in exact knowledge of the moving process of the landslide area and all of other physical parameters. According to these requirements the working group laid a special emphasis on the following research areas:

- detection of potential landslides on large scale
- an efficient and continuous observation of critical areas
- a knowledge-based derivation of real time information about actual risks in order to support an alert system

According to the research aims the group worked intensively on the next research areas:

1. Different terrestrial and space measurement techniques were combined for continuous observation of surface movements. As terrestrial geodetic measurement techniques new instruments and methods were developed and tested. Instead of geodetic measurements carried out in periodical campaigns a great stress was laid on the continuous geodetic measurements techniques to get data series directly comparable with continuously collected hydrological (water table, stream stage, pore pressure, etc.), meteorological (e.g. precipitation, temperature), etc. data series for the study of dynamic processes of landslides and to get more reliable and comprehensive information for development of early warning systems.
2. Use of terrestrial radar systems for slope monitoring, meanwhile we have an IBIS-L system.
3. Investigation on different satellite radar bands for the estimation of the "normal behaviour" of the region of interest.

4. A special stress was laid on the combination of monitoring data with a numerical model which represents the structure and the kinematic and dynamic behaviour of the slope. Landslide modelling with support vector machines
5. The effect of the vegetation on the slope stability was also intensively investigated.
6. Application combined PinSAR and GNSS technology for monitoring Landslide movements

Organization of workshops and conferences:

Organization of the section "Monitoring of Landslides & System Analysis" on "The World Multidisciplinary Earth Sciences Symposium– MESS 2015" in Prague (Czech Republic) during 7-11 September 2015.

IAG Sub Commission 4.2 and Working Group 4.2.4 actively participated in "The Second Joint International Symposium on Deformation Monitoring" (JISDM), 9-11 September 2013, University of Nottingham, Nottinham, UK.

IAG Sub Commission 4.2 and Working Group 4.2.4 will actively participate in the organization of the 3rd Joint International Symposium on Deformation Monitoring, March 30 to April 1, 2016, Vienna, Austria.

Some of the research projects which were /are carried out:

- P20137 KASIP - Knowledge-Based Alarm System with Identified Deformation Predictor Research project alpEWAS (Sudelfeld, Bayern): combined sensor network on landslide Anggenalm/Sulderfeld. Observation by PS Radarinterferometrie by DLR and Infoterra (EADS Astrium), GNSS+TPS.
- Landslide Hornbergle (Reutte Tirol): test measurements by gbSAR, combined campaign measurements by GNSS+TPS.
- EU FP7 Forschungsprojekt De-Montes (Deformation Monitoring by High Resolution Terrestrial Long Range Sensing) for further research of adoption of IATS and a combined photogrammetric/tahymetric/TLS measurement conception.
- OTKA K78332 Kinematic and dynamic models of landslides by means of geodetic observations along the high bank of the Danube at Dunaszekcső, Hungary
- OTKA K 81295 Development of measuring methods for detection of very small surface mass movements

Some selected references which represent the activity and the main research topics of the working group:

Bányai, L., Mentes, Gy., Újvári. G., Kovács, M., Czap, Z., Gribovszki, K., Papp, G., 2014: Recurrent landsliding of a high bank at Dunaszekcső, Hungary: Geodetic deformation monitoring and finite element modelling. GEOMORPHOLOGY 210: pp. 1-13.

Mentes, Gy., Bányai L., 2014. Observation of Landslide Movements by Geodetic and Borehole Tilt Measurements. In: Kopáčik, A., Kyrinovič, P., Štroner , M. (Eds). Proceedings of the 6th International Conference on Engineering Surveying INGEO 2014, Czech Technical University Prague, Faculty of Civil Engineering, 2014. Czech Republic, ISBN 978-80-01-05469-7. Prague, Czech Republic, April 3-4, 2014. TS2-4 Networks and GNSS application. pp. 53-58.

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Theilen-Willige B., Papadopoulou I.D., Savvaidis P., and Tziavos I.N. 2011: Use of Remote Sensing and GIS methods for mitigating the impact of earthquakes in cities, Proc. Inter. Congress "Natural Cataclysms and Global Problems of the Modern Civilization –GeoCataclysm 2011, Istanbul, Turkey.

Stergioudis A., Savvaidis P. and Lakakis K. 2011: Performance estimation of pixel-based classification algorithms in mixed environment areas, in Proc. "Modern technologies, education and professional practice in geodesy and related fields", 19th International Symposium, 03 - 04 November, Sofia.

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Mair am Tinkhof, K., Preh, A., Tentschert, E.-H., Eichhorn, A., Buhl, V., T. Schmalz, T., Rödelsperger, S., Zangerl, C. 2011: KASIP - Numerical Investigation of landslides amd combination with monitoring data Poster: 60. Geomechanik Kolloquium/Franz Pacher Kolloquium, Salzburg, Austria, 13.10.2011 - 14.10.2011

Rödelsperger, S., Läufer, G., Eichhorn, A., Gerstenecker, C. 2011: Near real-time monitoring concept of mass movements with ground based SAR Oral presentation: IUGG General Assembly, Melbourne, Australia, 28.06.2011 - 07.07.2011

Rödelsperger, S., Läufer, G., Eichhorn, A., Gerstenecker, C. 2011: Continuous monitoring of landslides with ground based SAR: A case study at Steinlehnen Oral presentation: EGU General Assembly, Vienna, Austria, 03.04.2011 - 08.04.2011

Mertl, S., Rödelsperger, S., Weginger, S. 2011: Seismic- and GBSAR monitoring of a rockslide. Poster: EGU General Assembly, Vienna, Austria, 03.04.2011 - 08.04.2011

Mentes, Gy., Bányai, L., Újvári, G., Papp, G., Gribovszki, K and Bódis, V.B. 2011: Recurring Mass Movements On The Danube's Bank at Dunaszekcső (Hungary) Observed by Geodetic Methods. Proceedings of the Joint International Symposium on Deformation Monitoring. Hong Kong, China, 2-4 November 2011. Session 3E: Applications in Geosciences on Local and Regional Scale II. 3E-04. 159.pdf

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WG 4.2.5: Applications of Artificial Intelligence in Geospatial Mapping and Engineering Geodesy

Chair: H. Neuner (Austria)

Co-Chairs: A. Reiterer (Germany) and U. Egly (Austria)

Artificial Intelligence (AI) has become an essential technique for solving complex problems in many applications. In the areas of geospatial mapping and engineering geodesy, knowledge-based systems are emerging. To develop reliable intelligent systems, this working group has focused on some critical issues ranging from the understanding of the nature of intelligence to the understanding of knowledge representation and deduction processes, eventually resulting in the construction of computer programs, which act intelligently.

IAG Working Group 4.2.5 organised the Workshop on "Applications of Artificial Intelligence in Engineering Geodesy", 10-12 September 2012, Technical University of Munich, Munich, Germany.

Program details can be found at:
http://www.geo.bv.tum.de/images/stories/AI_IATS_Flyer.pdf

Sub-Commission 4.3: Remote Sensing and Modelling of the Atmosphere

Chair: Marcelo Santos (Canada)
Vice-Chair: Jens Wickert (Germany)

SC 4.3 is composed of one Study Group and three Working Groups. Besides, Several of SC 4.3 members participate in the COST Action 1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)", which will be referred to below.

SG 4.3.1 Ionosphere Modelling and Analysis

Chair: Michael Schmidt (Germany),

Co-Chair: Mahmut O. Karslioglu (Turkey),

Members: Lung-Chih Tsai (Taiwan), Dieter Bilitza (USA), Denise Dettmering (Germany), Mahdi Alizadeh (Germany), C.K. Shum (USA), Kuo-Hsin Tseng (Taiwan), Norbert Jakowski (Germany), Robert Heinkelmann (Germany), Andrzej Krankowski (Poland), Pawel Wielgosz (Poland), Lee-Anne McKinnell (South Africa), Marco Limberger (Germany), Wenjing Liang (Germany), Shin-Chan Han (USA), Manuel Hernandez-Pajares (Spain), Claudio Brunini (Argentina), Benedikt Soja (Germany), Tatjana Gerzen (Germany), David Minkwitz (Germany), Eren Erdogan (Germany)

The general objective of this study group is the development of ionosphere models based on physics, mathematics and statistics. Within the next four years we will (1) focus on the development of appropriate parameter estimation and assimilation techniques based on the combination of different observation techniques. With respect to physical modeling we (2) will perform first steps by introducing physics-motivated functions such as the Chapman function into the parameter estimation process. Furthermore, we (3) will establish ionosphere models including near real-time applications by introducing Kalman filtering procedures. Other topics (4) are the development of densification strategies of global models using regional approaches as well as applications, e.g. the study of the L3 GNSS frequency

Research Activities related to topic (1):

- The main activity at GESA (LaPlata, Argentina) is focused on developing a suitable model and a numerical strategy for combining ionospheric information derived from different beacon satellites measurements to generate a global representation of the electron density. Ground-based GNSS measurements, VTEC estimations derived from satellite altimetry missions and electron density estimations derived from space-based GPS receivers, are consistently combined on the observation level to determine the parameters of the empirical functions that describe the 4-D (latitude, longitude, height and time) electron density distribution of the different ionospheric layers. Several years were analysed in order to assess the performance of the combination technique under low solar activity conditions.
- The focus of a study at DGFI-TUM (Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, Germany) is the evaluation of DORIS data for ionosphere modeling. Recently launched satellite missions such as JASON-2, Cryosat, HY-2A and Saral have DGXX instruments on board which allow for tracking continuous dual-frequency phase observations and, hence, the extraction of STEC. A single layer model approach has been used to derive VTEC where the spatio-temporal TEC distribution is described by mathematical B-spline functions. The validation of the derived VTEC was

carried out by comparisons with other models, for instance, the IGS GIMs and dual-frequency altimeter measurements from Jason-2 where significant improvements due to the combination of GPS and DORIS can be observed. At Wuhan University, with collaborations from OSU (Ohio State University) and DGFI-TUM, a new method for retrieval of the absolute VTEC is proposed to combine the GPS GIM and DORIS tracking data. Two steps are used. The first step is the parameters pre-estimation using the GIM data, followed by the parameter-update with the DORIS tracking data. In this study, the altimeter data from HY2A was used to validate the effectiveness of DORIS-GIM ionosphere model for nadir ionosphere corrections.

- The Satellite Geodesy Group at the Department of Geodesy and Geoinformation Science of TUB (Technische Universität Berlin) is effectively contributing to the aims IAG Study Group 4.3.1 in a variety of fields. In the field of combination, TUB is developing combined global maps of VTEC using various space geodetic techniques, e.g. GNSS, satellite altimetry, Formosat-3/Cosmic, etc.

Research Activities related to topic (2):

- At TUM, DGFI-TUM and DLR (German Aerospace Center) the electron density distribution within the ionosphere is described vertically by an adapted Chapman function which consists of an F2 Chapman profile and a plasmasphere layer. To account for the horizontal and the temporal behavior, the fundamental key parameters of this physics-motivated approach, such as the maximum electron density NmF2, the corresponding height hmF2 and the F2 scale height HF2, are each modeled by series expansions in terms of tensor products of localizing B-spline functions depending on longitude, latitude and time. For testing the procedure the model is applied to an appropriate region in South America, which covers relevant ionospheric processes and phenomena such as the Equatorial Anomaly. Due to their individual sensitivities with respect to the key parameters, different observation techniques are used and combined. Relevant validations have been carried out for STEC data from ground-based GPS and electron density profiles derived from GPS radio occultation on COSMIC, GRACE and CHAMP. Using the developed techniques ionospheric scenarios for a quiet and a perturbed ionospheric conditions were generated. The scenarios have been validated using independent space-based and ground-based measurements as well as independent ionosphere models in terms of TEC and electron density profiles. On the one hand, the reconstructed TEC are validated using independent TEC measurements from Topex/Poseidon mission. On the other hand, the electron density including the peak parameters NmF2 and hmF2 are validated by independent ionosonde observations and CHAMP reconstruction. In addition, global empirical TEC models such as NeQuick, NTCM and electron density parameter models NPDM and NPHM are used for comparisons.
- In the field of physics-motivated modeling of the ionospheric parameters, TUB has achieved global modeling of F2-peak electron density (NmF2) and F2-peak height (hmF2) by applying a combined electron density representation to the GNSS ionospheric observables. The electron density representation at TUB is comprised from combination of multi-layer Chapman function for the bottom-side and topside ionosphere, and Topside Ionosphere/Plasmasphere (TIP) model for the plasmaspheric contribution.
- Several aspects of ionospheric modelling have been refined and exploited during the period 2011-2015 from the UPC-IonSAT research group (see the corresponding papers at reference list mentioned below): (1) Electron density retrieval from GPS radio occultation measurements (Aragon-Angel et al. 2011), (2) Improvement of precise GNSS positioning by means of real-time ionospheric models (Juan et al. 2012), (3) Prediction of Global Ionospheric Maps (García-Rigo et al. 2012), (4) GNSS modelling of Medium Scale Travelling Disturbances, MSTIDs (Hernandez-Pajares et al. 2012a), (5) Indirect

measurement of solar EUV flux rate by means of RT global GNSS data (Hernandez-Pajares et al. 2012b) and (6) Higher order ionospheric modelling (Hernandez-Pajares et al. 2014). Moreover the production of real-time GIMs in the context of the RT-IGS project (Caissy et al. 2012) is also taking part of the efforts of UPC-IonSAT members. In this regard we can advance a significant improvement in our tomographic-kriging strategy, based on a Kalman filter implementation, thanks to the availability of +150 RT GNSS receivers worldwide distributed. In this context we are attaining global RT accuracies (when compared with independent JASON2 data for instance) similar to the precision of rapid GIMs (24 hours of latency) of most of the contributing ionospheric analysis centers to IGS.

- At Wuhan University, the 4D ionosphere tomography model is developed based on a pixel model. Firstly we impose a priori IRI model based on constraints by increasing the virtual observations between two pixel grids. Then, we establish a more robust connection between the grids using “loose” constraints, which improve the rank of inversion of the normal equation. The resulting 4D ionosphere model is shown to have more solution stability and more accurate estimated ionosphere parameters. The above 4D ionosphere modeling allows one to simultaneously retrieve gridded near-real time velocities of the ionosphere electron density, and the electronic density parameters.
- The International Reference Ionosphere (IRI) describes the monthly average behavior of the Earth’s ionosphere based on most of the accessible and reliable ground- and space-based observations of ionospheric parameters. With the ever-increasing dependence on space technology the IRI development is going beyond the monthly averages in order to provide a quantitative description of ionospheric day-to-day variability depending on altitude, time of day, time of year, latitude as well as solar and magnetic activity. The IRI team is also pursuing the development of the IRI Real-Time (IRI-RT) that uses assimilative algorithms or updating procedures to combine IRI with real-time data for a more accurate picture of current ionospheric conditions.

Research Activities related to topic (3):

- At METU (Middle East Technical University) studies have been performed on the non-parametric forward-backward stagewise algorithms MARS and BMARS for VTEC estimation; related results are published. Currently, iterative algorithms for tomographic reconstruction of the ionosphere using heterogenous data collected from ground and satellite based observations are investigated. The main purpose of the current research is to find flexible, efficient, accurate and stable reconstruction of the spatio-temporal ionospheric electron density in 4 dimensions based on multivariate adaptive regression B-Splines. Moreover, estimation of the instrumental biases of the satellites and receivers inside the algorithm or by a combination of parametric and non-parametric approaches will be investigated. Additionally, we are working on station based modeling of the ionospheric VTEC estimation using particle filters for near real time applications particularly during geomagnetic storms, since particle filters are effective algorithms for the estimation of nonlinear and non-Gaussian high dynamic systems. In parallel to the studies above, there is an ongoing research activity which consists of accurate and precise calibration of ionospheric delay measurements derived from GPS and GLONASS using different local ionosphere models for estimating Ground Based Augmentation System (GBAS) threat model parameters. In order to asses real-time integrity algorithms for CAT III GBAS precision landing, a software tool is being developed for simulating the multi-GNSS code and phase measurements inside the receivers of virtual ground stations and aircrafts within different GBAS architectures and atmospheric conditions. The software and simulated scenarios will not only be used to research and develop architectures and real-time integrity monitoring algorithms for GBAS but also be used to develop and asses the measurement pre-processing algorithms in addition to local, regional and global ionosphere modeling algorithms.The International Reference Ionosphere (IRI) describes the monthly average behavior of the Earth's ionosphere based on most of the accessible and reliable ground- and space-based observations of ionospheric parameters. With the ever-increasing dependence on space technology the IRI development is going beyond the monthly averages in order to provide a quantitative description of ionospheric day-to-day variability depending on altitude, time of day, time of year, latitude as well as solar and magnetic activity. The IRI team is also pursuing the development of the IRI Real-Time (IRI-RT) that uses assimilative algorithms or updating procedures to combine IRI with real-time data for a more accurate picture of current ionospheric conditions.

- The International GNSS Service (IGS) provides a variety of data products such as GNSS observations and satellite orbits with different latencies. These products can, for instance, be exploited for the production of high quality, near-real time ionosphere maps as needed in the scientific, educational and commercial sector. In addition to GPS and GLONASS data which can be accessed through the IGS, complementary techniques such as radar altimetry, DORIS or radio occultations can be included to improve the data coverage. Therefore, sequential methods for data pre-processing and filtering (e.g. Kalman filter) that are capable of running in near-real time may be applied to assimilate this data under consideration of the different characteristics concerning data precision, number and type. At DGFI-TUM, effort has been maintained to generate VTEC products with low latency through a continuously operating processing framework.
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Research Activities related to topic (4):

- For investigations about the solar corona's electron density using VLBI data (Soja et al., 2014a), the effect of the ionosphere needs to be corrected. Two approaches were followed, on the one hand estimating the ionospheric vertical electron content from VLBI data and on the other hand interpolating it from IGS global ionospheric models. The resulting electron density models of the solar corona from both approaches agreed well within their formal errors and also when compared to previous models derived from spacecraft tracking. Regional variations in the electron density and coronal mass ejections visible in coronagraph data could be linked to the VLBI data as well (Soja et al., 2014c).
- Development of the local ionosphere model over Central Europe based exclusively on precise carrier phase observations and its validation in precise positioning (Krypiak-Gregorczyk et al, 2013, 2014).
- Quality analysis of VRS (Virtual reference station) ionospheric corrections provided by the Polish part of the EUPOS (European Positioning System) (Krukowska et al. 2014). The ionospheric part of the VRS corrections was compared to the actual ionospheric delays derived from processing real GNSS observations at the test stations. Degradation of the corrections during ionospheric disturbances was demonstrated.

For the exchange of the scientific outcome within the Study Group we organized splinter meetings at the EGU General Assemblies in the years 2012 and 2015 in Vienna. As a further outcome Lung-Chi Tsai (NCU) organized in the framework of the IAG SG 4.3.1 the Session GFH-2 entitled as "Developments and/or applications of a multi-dimensional ionospheric electron density model" at the Asia-Pacific Radio Science Conference AP-RASC'13, September 3-7, 2013 in Taipei, Taiwan. Furthermore, in each of the last years an ionosphere session was placed in the Geodesy programme of the EGU, related to the ToR of the IAG SG 4.3.1. The sessions have been arranged and chaired by members of the SG. In the beginning of July 2015 the SGI Workshop will take place at the Technische Universität Berlin. This workshop will also be supported by members of the SG. In addition, many other conferences, symposia and workshops have been attended by members of the IAG SG 4.3.1 within the last four years.

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WG4.3.1 Standards for space weather products for geodetic and ionospheric studies

Chair: Andrzej Krankowski (Poland)

Members: Dieter Bilitza (USA), Manuel Hernandez-Pajares (Spain), Atilla Komjathy (USA), Michael Schmidt (Germany), Hanna Rothkaehl (Poland), Iurii Cherniak (Russia), Irina Zakharenkova (Russia)

Activities primarily associated with the IGS IONO WG. Starting a new official/operational product – TEC fluctuation changes over North Pole to study the dynamics of oval irregularities (carried out by UWM to be started as official/routine product after performance evaluation period).

Reports on activities

The objective of this WG is to suggest common international standards for the dissemination of space weather products used in geodesy and ionospheric studies. This WG works in close scientific collaboration with IGS, URSI and COSPAR IRI group.

Special session G5.5 and G5.1 "Monitoring and modelling of the ionosphere from space-geodetic techniques" was organized during General Assembly EGU 2012 and EGU 2013, respectively.

During the last IGS Workshop 2012 held at the University of Warmia and Mazury in Olsztyn, Poland from 23 – 27 July 2012 was also organized by members the special session "Atmospheric Delay Modeling and Applications" and the Ionosphere Working Group Splinter Session. After this IGS Workshop the following recommendations from IGS WG were prepared:

a) starting a new official/operational product – TEC fluctuation changes over North Pole to study the dynamic of oval irregularities (carried out by UWM to be started as official/routine product after performance evaluation period,
b) higher temporal and spatial resolution of IGS combined GIMs - the IAACs (UPC and JPL) agreed on providing their maps in IONEX format, with a resolution of 15 min, 1 degrees and 1 degrees in time, longitude and latitude respectively,
c) the new the IAAC from GNSS Research Center (GRC), Wuhan University, China
d) very close cooperation with IRI COSPAR group.

Recently the International Standardization Organization, ISO, recommends the International Reference Ionosphere (IRI) for the specification of ionosphere plasma densities and temperatures and indicates necessity for extending IRI to the plasmasphere's altitudes. At the IRI Workshop 2013 "IRI and GNSS", organized in Olsztyn, Poland, the IRI Working Group recommends to adjust IRI-Plas model to IRI 2012 version and adjust GPS TEC into IRI Real Time (IRTAM).

WG4.3.2 Inter-comparison and cross-validation of tomography models

Chair: Alain Geiger (Switzerland)
Co-Chair: Witold Rohm (Australia)

Members: George Liu(China), Michael Bender (Germany), Hugues Brenot (Belgium), Michal Kačmařík (Czech Rep.), Toby Manning (Australia)

Reports on activities

The IAG working group was established in spring 2012 and its aim is to address main deficiencies in the tomography model construction. In order to successfully achieve this objective, the members decided to split up the work into several logical steps, outlined below. Firstly identification of critical steps in GNSS tomography processing the discussion held mainly by e-mail resulted in following list (not exclusive): slant delay calculation based on DD or PPP solution, the model structure definition (voxel model, node model, outer model, nested models), inversion technique and linked with this topic constraints applications and finally the benefits and flaws of Least Squares approach or Kalman Filter approach. Therefore in multi-model solution these points will be reviewed carefully. Members decided that tomography solution should cover wet refractivity and integrated water vapour content; therefore both Slant Wet Delay (SWD) as well as Slant Integrated Water Vapour (SIWV) are to be utilised. This decision generated fair amount of coding works since not all models have the dual capability. The observations conversion (ZTD to SWD/SIWV) between models varies significantly and testing revealed bugs in some model codes. Secondly, the reference database covering meteorological parameters as well as ground based observations was established. It has been decided to use Numerical Weather Prediction data for state of Victoria in Australia and GNSS observations from the state's CORS network over a period of Mesoscale Convection System occurrence. Common Slant Delay data source have been established covering two types of data simulated (based on NWP data) and real world (based on ZTD estimation). Thirdly, common model setup (size, number and domain of the model) has been chosen as a proper way to establish reference for inter-comparison studies. Again, this decision involved large amount of work, not all models have the same flexibility in setting up the model structure, and some new functionalities had to be introduced. In meanwhile new members joined the group adding new interesting 2D tomography capability to the inter-comparison studies. Currently, all modifications to the model codes are finished and the WG is in the process of running simulations observations with different strategies, it will be followed by real a world experiment. The WG submitted an abstract of a paper based on the outcomes of this inter comparison study at the IAG General Assembly in Potsdam 2013 and will be published as a Journal Paper soon.

Results of inter-comparison campaign

Since 2013 the members of WG4.3.3 from have joined research group within the framework of COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC: http://gnss4swec.knmi.nl/). The group activities overlap with the tasks performed of working group WG2 "GNSS for Severe Weather Monitoring" of this project.

WG4.3.2 has recently had a workshop on the use of tomography in severe weather. A comparison campaign was set up and is underway. Severe weather case studies identification in 2014 in collaboration with meteorologists from University of Wroclaw, Workshop on application of GNSS tomography in severe weather studies (20 participants from 6 Universities), website: http://www.igig.up.wroc.pl/tomolab/.

WG4.3.3 Integration of GNSS atmosphere models with NWP models

Chair: Jaroslaw Bosy (Poland)

Co-Chair: Henrik Vedel (Denmark)

Members: Jonathan Jones (UK), Jan Dousa (Czech Republic), Rosa Pacione (Italy), Guergana Guerova (Bulgaria), Norman Teferle (Luxembourg), Shuli Song (China), Szabolcs Rozsa (Hungary), Yuei-An Liou (Taiwan), Ryuichi Ichikawa (Japan), Joseph Awange (Australia), Jean-Pierre Barriot (French Polynesia), Shuanggen Jin (China), Ambrus Kenyeres (Hungary), Ahmed Furqan (Luxembourg), Jan Kaplon (Poland), Gemma Bennitt (UK)

Report on activities

Activities through 2011 and 2012 involved in the problems: a) assimilation of GNSS data processing products in NWP models and validation and comparison of different of GNSS atmosphere models using NWP outputs. Determine the nature and extent meteorological data, that could be used by GNSS community to improve the atmosphere used in GNSS data processing in postprocessing and real time mode, b) use of GNSS atmosphere and NWP models in real-time positioning methods: RTK and PPP, and comparison of GNSS and meteorological and MWP products, c) development of GNSS data processing strategies for new tropospheric products to move for Near Real Time to Real Time availability.

Since 2012, started collaboration with members of E-GVAP The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk/ (represented by Henrik Vedel) in area of GNSS models assimilation in NWP models.

Since 2013 the most of members of WG4.3.3 have joined research group within the framework of COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC: http://gnss4swec.knmi.nl/). The group activities overlap with the tasks performed of working group WG1 "Advanced GNSS data processing techniques" and WG2 "GNSS for Severe Weather Monitoring" of this project.

In 2014 Jaroslaw Bosy (Chair of WG 4.3.3), Witold Rohm (Co-Chair of WG 4.3.2) and Pawel Wielgosz (Commission 4 Steering Committee member) initiated a project of European Joint Doctorate (EJD) programme an submitted on the January 2015 the proposal titled Multi-GNSS applications for Earth System monitoring (mGNSS-4ES) in the frame of Horizon 2020, call: MSCA-ITN-2015-ETN: Marie Skłodowska-Curie Innovative Training Networks (ITN-ETN). This activity has been supported by prof. Dorota D. Grejner-Brzezinska, President of IAG Commission 4 "Positioning and Applications" and Marcelo Santos and Jens Wickert, Chairs of Sub-Commission 4.3 "Remote Sensing and Modelling of the Atmosphere". Implementation of this project will allow in the future continuing research in the field of GNSS remote sensing of atmosphere (ionosphere, troposphere), geodesy and geodynamics (Muli-GNSS), ocean studies (GNSS RO and GNSS-R) and other activity areas of IAG Commission 4 with in connection with the activities carried out under GGOS.

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Selected conference presentations:

Ahmed F., Teferle F.N. and Bingley R.M.: First Zenith Total Delay and Integrated Water Vapour Estimates from the Near Real-Time GNSS Data Processing Systems at the University of Luxembourg. European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012;

Ahmed F., Teferle N., Bingley R. and Laurichesse D.: An Evaluation of the Accuracy of Real-Time Zenith Total Delay Estimates. European Geosciences Union General Assembly 2013, Vienna, Austria, 07-12 April 2013;

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Vedel H. and Amstrup B.: Impact of gb GNSS data in NWP, as case study. European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012;

COST Action 1206

As mentioned before, several SC4.3 members take part of the COST Action 1206 “Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)” (managed by Jonathan Jones, from UK Met).

The WG structure of the COST Action is:

- WG 1 Advanced GNSS data processing techniques
- WG 2 GNSS for Severe Weather Monitoring
- WG 3 GNSS for Climate Monitoring

Several meetings took place and there was also the 1st Summer school, September 9-13, in Golden Sands Ressort, Varna, Bulgaria.

Other Activities

Participation in another initiative GRUAN GCOS (Global Climate Observing System) Reference Upper Air Network. There is a GNSS component for atmosphere sounding as key component. Several CS4.3 members (Gunnar Elgered, Galina Dick, Jens Wickert) in the expert team GRUAN GNSS Precipitable Water Task Team. In the phase of installing data analysis center including data flows, etc. The GRUAN GNSS precipitable water (GNSS-PW) Task Team (TT) was established in summer 2010 as one of six GRUAN TTs. TTs are charged with addressing critical GRUAN requirements. Ground-based GNSS PW was identified as a Priority 1 measurement for GRUAN, and the GNSS-PW TT’s goal is to develop explicit guidance on hardware, software and data management practices to obtain GNSS PW measurements of consistent quality at all GRUAN sites.

Sub-Commission 4.4: Applications of Satellite and Airborne Imaging Systems

Chair: Zhenhong Li (UK)

In the past decades, satellite and airborne imaging systems, e.g. Synthetic Aperture Radar (SAR), Light Detection And Ranging (LiDAR) and Satellite Altimetry (SA), have been increasingly employed to gain insights into geophysical and engineering processes such as earthquakes, landslides, volcanoes, and structural deformation of infrastructure. The main objectives of this SC are to promote collaborative research in the development of imaging systems for geodetic applications, and to facilitate communications and exchange of data, information and research results through coordinated efforts. There are five working groups in SC4.4. Since their establishments in 2011, all the working groups have been actively recruiting new members and coordinating/participating in research and professional activities. This report attempts to summarize the major activities conducted during the period from July 2011 to May 2015.

WG 4.4.1: Quality Control Framework for InSAR Measurements.

Chair: Z. Li (UK)
Co-Chair: S. Samsonov (Canada)

Main Research Activities: A variety of advanced InSAR techniques have been developed to separate deformation signals from error sources such as atmospheric effects, orbital ramps and DEM errors:

(1) MERIS atmospheric correction model for reducing tropospheric water vapour effects on Wide Swath InSAR measurements (Li et al., 2012);
(2) Multidimensional Small BAseline Subset (MSBAS) InSAR for estimating 2D or 3D time-series of deformation (Samsonov and d'Oreye, 2012);
(3) π-RATE (Poly-Interferogram Rate And Time-series Estimator) for estimating displacement rate, time series and their associated uncertainties (Wang et al., 2012);
(4) PyAPS (Python-based Atmospheric Phase Screen) allows one to automatically download atmospheric reanalysis products (ECMWF's ERA-Interim, NCEP's NARR, and NASA's MERRA) and to produce maps of stratified tropospheric delays for InSAR correction (Jolivet et al., 2014; Lin et al., 2015);
(5) TRAIN (Toolbox for Reducing Atmospheric InSAR Noise) allows using various independent datasets, e.g. spaceborne spectrometer data (MERIS and MODIS) and weather models (ECMWF ERA-I and WRF) to reduce atmospheric effects on InSAR measurements (Bekaert et al., 2015a);
(6) An extended network orbit correction model utilises the fact that the error signals behave as a linear combination of the individual components of each of the two acquisitions that form one interferogram, and incorporates phase loops of interferogram triplets (Feng, 2014; Stockamp et al., 2015).

WG 4.4.2: InSAR Observation and Modelling of Earthquakes, Volcanoes and Tectonics

Chair: T. Wright (UK)
Co-Chair: A. Hooper (UK)

Main Research Activities: This WG has successfully responded to several recent earthquakes and volcanoes, e.g. the 2008 Wenchuan earthquake (Fielding et al., 2013), the 2010 Yushu earthquake (Li et al., 2011), the 2010 Sierra El Mayor (Mexico) earthquake (Barlow et al., 2015), the 2010-2011 Canterbury Earthquakes (Elliott et al., 2012), the 2011 Tohoku-Oki (Japan) earthquake (Wright et al., 2012), the 2011 Burma earthquake (Feng et al., 2013), the 2011 Van (Turkey) earthquake (Feng et al., 2014), the 2014 Napa (California) earthquake (Elliott et al., 2015), the Tungurahua volcano (Ecuador) (Champenois et al., 2014), the Santorini volcano (Greece) (Parks et al., 2015), and the Bárðarbunga volcano (Iceland) (Sigmundsson et al., 2015). A new algorithm has been developed to combine geodetic data with satellite gravity measurements to model the source parameters of the 2011 Tohoku-Oki (Japan) earthquake (Feng et al., 2014). The postseismic motion following the large Kokoxili event has been mapped using InSAR (Wen et al., 2012). Strain accumulation on a series of active faults has been investigated, including the Ashkabad fault (Walters et al., 2013), the central Tibetan Plateau (Garthwaite et al., 2013), the North Anatolian Fault Zone (Turkey) (Yamasaki et al., 2014), the North and East Anatolian Faults (Eastern Turkey) (Walters et al., 2014), the Dabbahu segment of the Nubia-Arabia Plate boundary (Afar, Ethiopia) (Hamling et al., 2014), and the Afar rift of Ethiopia (Pagli et al., 2014; Hammond et al., 2014).

WG 4.4.3: Landslide Monitoring and Modelling with InSAR observations

Chair: R. Tomás-Jover (Spain)
Co-Chair: R. Furuta (Japan)

Main Research Activities: The WG organized a monographic session focused on Natural Hazards in the International Workshop in Environmental Security, Geological Hazards and Management held in Tenerife, Canary Islands, Spain on 10-12 April 2013, and co-organised a session in the Wegener 2014: Measuring and Modelling our Dynamic Planet, 17th General Assembly of WEGENER on earth deformation and the study of earthquakes using geodesy and geodynamics, celebrated in Leeds, UK, on 1-4 September 2014. Members of the WG have participated as speakers and/or reviewers in a series of conferences: (i) the International Association of Geodesy Scientific Assembly 2013 held in Potsdam, Germany, 01 to 06 September 2013; (ii) the ISRM European Rock Mechanics Symposium (EUROCK 2014). Vigo, Spain, 27-29th May 2014; (iii) XII congress of the International Association for Engineering Geology and the Environment (IAEG2014). Torino, Italy, September, 15-19 2014; (iv) 15th Annual Conference of the International Association for Mathematical Geosciences (IAMG): Frontiers of Mathematical Geosciences: new approaches to understand the natural world, 2-6 September 2013, Madrid, Spain; (v) the International Symposium & 9th Asian Regional Conference of International Association of Engineering Geology (AREG2013), Beijing, China on 24th - 25th September, 2013. The chair of the WG has become an editorial member of the journal "Landslides" published by Springer. This WG have published more than twenty papers on SCI indexed journals, most of which focus on the application of DInSAR for landslide monitoring and modelling. Here is the incomplete list of landslides that have been investigated in the past four years: (i) landslides in the Betic Cordillera (S Spain) (Delgado et al., 2011), (ii) Slopes in Alicante (SE Spain) (Cano and Tomás, 2012, 2013, 2014); (iii) the Huangtupo landslide in the Three Gorges region (China)

(Tomás et al., 2014); and (iv) the Shuping landslide in the Three Gorges region (China) (Singleton et al., 2014).

WG 4.4.4: Vertical crustal motion from Satellite Altimetry

Chair: H. Lee (USA)
Co-Chair: H. Wang (China)

Main Research Activities: This WG has focused on improving retracking and surface gradient correction algorithms for satellite radar altimeter measurements over non-ocean surfaces towards estimating: (1) Topographic vertical motion over the Qinghai-Tibetan Plateau; (2) Ice mass balance over West Antarctica; (3) Glacier elevation changes over Bering Glacier, Alaska; (4) Coastal sea surface heights; (5) Water elevation changes over inland water bodies (river, lake, and wetlands) under different climate regimes (Congo, Ganges-Brahmaputra-Meghna basins, and Qinghai-Tibetan Plateau). This WG has also worked on these various types of topographic surfaces, and tested the new Ka-band measurements from recently launched SARAL/AltiKa satellite radar altimeter.

WG 4.4.5: LiDAR, Laser Scanning and Surface Generation

Chair: B. Yang (China)
Co-Chair: N. Tate (UK)

Main Research Activities: The main research activities of this WG include: (1) Integration of Laser Scanning Point Clouds and panoramic imagery for 3D reconstruction, texture mapping and classification; (2) UAV Mapping for Transportation, LBS, and GIS applications; A spatial pattern based method has been developed to match and fuse imagery, point clouds, and GIS database for 3D mapping and database updating.

Conferences:

1. Joint International Symposium on Deformation Monitoring, Hong Kong, China, 2-4 November 2011 (Jointly organised by IAG SC4.4 and FIG: http://dma.lsgi.polyu.edu.hk)
2. The International Earth Science Colloquium on the Aegean Region, Dokuz Eylül University, Izmir, Turkey, 1-5 October 2012 (one InSAR special session organised by IAG WG 4.4.1: http://web.deu.edu.tr/iesca/ocs/index.php/iesca/2012)
3. The 3rd International Workshop on Gravity, GPS and Satellite Altimetry Observations of Tibet, Xinjiang and Siberia (TibXS), Chengdu, Sichuan, China, 26-30 August 2012 (Co-organized by: IAG WG 4.4.4: http://www.sgg.whu.edu.cn/tibxs/tibxs2012/pdf/Proceedings_of_the_3rd_TibXS_workshop.pdf)
4. International Workshop in Environmental Security, Geological Hazards and Management, Tenerife, Canary Islands, Spain, 10-12 April 2013 (one landslide special session organized by IAG WG 4.4.3: http://eventos.ull.es/enviromentalsecurity2013/)
5. The EGU General Assembly 2014, Vienna, Austria, 27 Apr – 2 May 2014 (GM1.8: Land-Level Lowering of Flat Areas: Monitoring and Modelling of Natural and Human-Induced Processes and Assessment of their Impact)

6. ROYAL ASTRONOMICAL SOCIETY SPECIALIST DISCUSSION MEETING: Seismology from Space: Geodetic observations and early warning of earthquakes, Royal Astronomical Society Lecture Theatre Burlington House, Piccadilly, 9 May 2014.
7. The 17th General Assembly of WEGENER on earth deformation and the study of earthquakes using geodesy and geodynamics, Leeds, UK, 1-4 Sep 2014 (http://see.leeds.ac.uk/wegener/)

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Sub-Commission 4.5: High-Precision GNSS Algorithms and Applications

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Chair: Yang Gao (Canada)
Vice-Chair: G. Wielgosz (Poland)
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WG4.5.1 Quality Measures for Network Based GNSS Positioning

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Co-Chair: Hans-Juergen Euler (Switzerland)

WG4.5.2 Precise Point Positioning and Network-RTK

Chair: Sunil B3th (Canada)
Co-Chair: Sue Lynn Choy (Australia)

WG4.5.3 Integer Ambiguity Resolution for PPP and PPP-RTK

Chair: Xiaohong Zhang (China)
Co-Chair: Patrick Henkel (Germany)

WG4.5.4 Multi-frequency, Multi-constellation Sub-cm RTK

Chair: Bofeng Li (Australia)
Co-Chair: Yanming Feng (Australia)

Academic Activities, Conference, Workshop, Technical Session

- WC4.5.4 organized third "BeiDou/GNSS Summer School on GNSS Frontier Technology" at Tongji University, Shanghai China, 28 July-1 August 2014.
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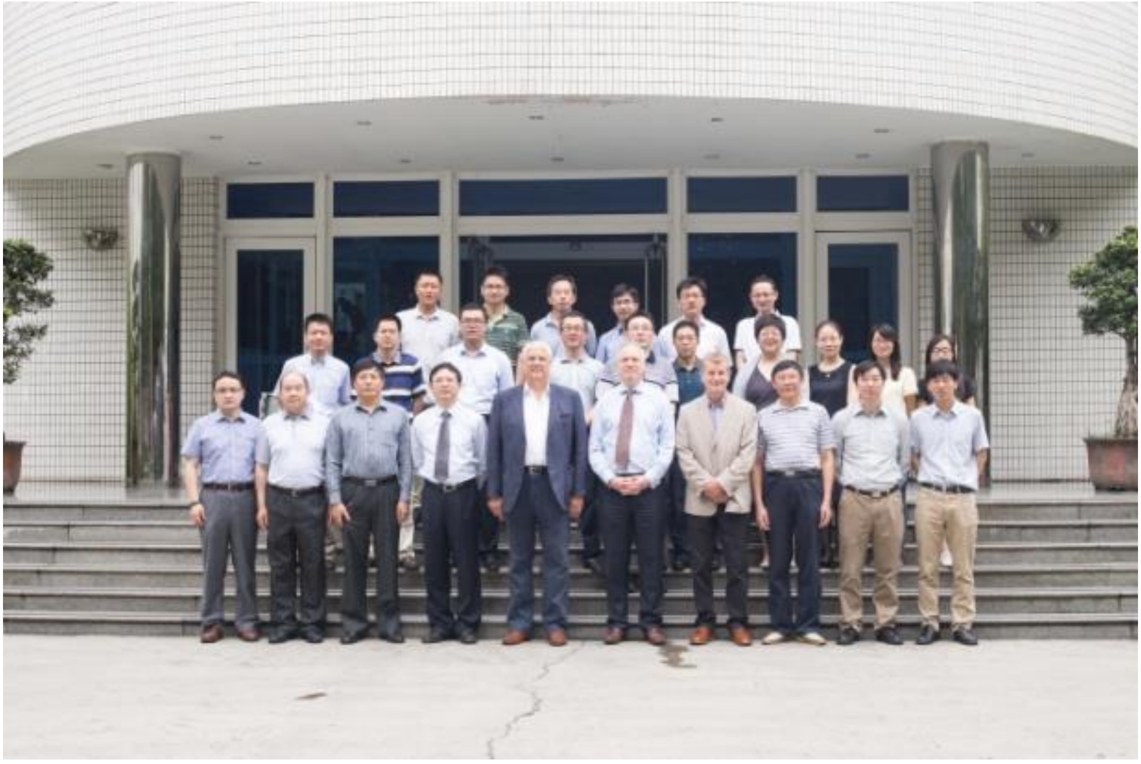
- WC4.5.1 organized a Sino-UK Workshop on Long Bridge Monitoring with Space Technologies, Tongji University, Shanghai, China, June 23, 2014.



- WC4.5.1 published special issues in Survey Review (Volume 46, Issue 339, November 2014) and Journal of Applied Geodesy in 2014.
- WG4.5.2 contributed to Inside GNSS Webinar on Precise Positioning Techniques (panellist) and ION GNSS+ 2014 (session chairs)
- SC4.5 organized Croucher Summer Course on "New GNSS Algorithms and Techniques for Earth Observations", 26-31 May 2014, Hong Kong Polytechnic University, Hong Kong.

- SC4.5 contributed to the organization of 6th CPGPS Forum, Xuzhou, China, Jan. 6-8, 2014
- SC4.5 co-organized Session G1.3 on High-Precision GNSS Algorithms and Applications in Geosciences at EGU General Assembly 2014, Vienna, Austria, 27 April – 02 May 2014.
- SC4.5 has a strong presence and contribution to the organization of the following conferences:
  - International IEEE Workshop on Asia-Pacific Satellite Navigation and Positioning, Brisbane, Australia, February 27 - March 1, 2014.
  - CSNC 2014, Nanjing, China, 21-23 May 2014.
  - 1st Congress of China Geodesy and Geophysics, Beijing, China, October 25-26, 2014.
- SC4.5 members have contributed to the organization of the following events to be held in 2015 as scientific committee members, session chairs and lecturers:
  - GNSS Summer School, Xuzhou, China, August, 2015
  - CPGPS Forum on Integrated Navigation Systems, Xuzhou, China, August, 2015
  - TransNav 2015, Gdynia, Poland, June 2015
  - CSNC 2015, Xi'An, China, May 2015.
- WG4.5.4 has contributed to the organization of the 10th international symposium on Location Based Services (LBS) November 21-22, 2013, Tongji University, Shanghai, China.

- WG4.5.1 organized a The 2nd Joint International Symposium on Deformation Monitoring (JISDM 2013), University of Nottingham, 9 - 10 September 2013. 200 people from 26 countries attended the conference.

- The Global Navigation Satellite System (GNSS) School on "New GNSS Algorithms and Techniques for Earth Observations 2012 (nGATEo 2012)" was successfully held in 14-15 May 2012, Polytechnic University (PolyU), Hong Kong. Sponsored by IAG and organized by Dr. George Liu, Secretary of SC4.5, it has more than 50 international participants from academia, industry and government agencies in Hong Kong, Mainland China, Australia, and Korea attended this GNSS School, including many in-school MSc/PhD students from mainland China. Five internationally distinguished scholars from Australia, China, Germany and USA were invited to give lectures during the two-day events.

- Beidou/GNSS Summer School on GNSS Frontier Technologies was successfully held at Beihang University, Beijing China during 25-31 August 2012. The summer school has been sponsored by IAG, CPGPS and Beihang University. The summer school has attracted 65 participants from 24 organisations in mainland China, Taiwan, Hongkong, and Pakistan. Eight internationally distinguished scholars from Australia, China, Canada, Finland, Germany and USA were invited to give lectures.

- SC4.5 contributed to the organization of the 2012 International Forum on Advanced Theory and Technologies in Geomatics (2012 IFATTG), May 19–21, 2012, Liaoning Technical University, Fuxin, China.

- SC4.5 contributed to the organization of GNSS Precise Point Positioning Workshop: Reaching Full Potential, 12-14 June 2013, Ottawa, Canada, sponsored by York University, Natural Resources Canada (NRCan), the IAG, the IGS, Natural Sciences and Engineering Research Council of Canada (NSERC). The purpose of the workshop was to bring together leading academic, government and industry researchers from across the globe to present the latest research findings and developments in GNSS PPP; to discuss issues related to advancing PPP technology; and, to contemplate the potential of PPP as the future positioning technique for high-accuracy satellite positioning, navigation and timing. The workshop attracted approximately 100 participants from 20 countries, representing over 50 different academic, government and industrial organizations. Attendees included data product producers, solution providers, technology users, and interested parties. The structure of the workshop consisted of oral sessions as well as moderated discussion sessions. Further information, including the complete post-workshop report (to be completed), the submitted presentations and posters, list of registrants, and photographs from the event can be found on the workshop website: www.yorku.ca/pppworkshop2013.

GNSS PRECISE POINT POSITIONING WORKSHOP:
REACHING FULL POTENTIAL
12-14 June 2013
Ottawa, Canada

- SC4.5 proposed and organized a session G1.3 ”High-Precision GNSS Algorithms and Applications in Geosciences”, European Geosciences Union General Assembly 2013, Vienna, Austria, 7-12 April 2013. The session has attracted 29 abstract submission with 12 oral presentations: 12 and 14 poster presentations, nearly half of them are from young scientists.
- WG4.5.1 “Quality Measures for Network Based GNSS Positioning” will organize the second Joint FIG/IAG International Symposium on Deformation Monitoring (JISDM), 9-11 September 2013, Nottingham, UK.
- WG4.5.2 “Precise Point Positioning and Network-RTK” will contribute to the organization of the 2013 International Conference on Earth Observation for Global Changes (EOGC’2013) and the 2013 Canadian Institute of Geomatics Annual Conference, 5-7 June 2013, Toronto, Canada
- WG4.5.2 “Precise Point Positioning and Network-RTK” will organize the PPP Workshop, 12-14 June 2013, Ottawa, Canada
- WG4.5.3 “Integer Ambiguity Resolution for PPP and PPP-RTK” will organize a Special Session on PPP at the 55-th International Symposium ELMAR-2013, 25-27 September 2013, Zadar, Croatia
- WG4.5.4 “Multi-frequency, Multi-constellation Sub-cm RTK” will contribute to the organization of the second GNSS Summer School, August, 2013, Beijing, China

Publications

Journal papers

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Sub-Commission 4.6: GNSS-Reflectometry and Applications

Chair: Shuanggen Jin (China)

Terms of Reference:

The Global Navigation Satellite System (GNSS) is a highly precise, continuous, all-weather and near-real-time microwave (L-band) technique, which implies more and wider applications and potentials. Recently, the versatile reflected and scattered signals of GNSS have been successfully demonstrated to sound the land surfaces (including soil moisture), ocean, and the cryosphere as a new remote sensing tool. The GNSS reflected signals from the ocean and land surface could determine the ocean height, wind speed and wind direction of ocean surface, soil moisture, ice and snow thickness, which could supplement the traditional remote sensing techniques, e.g., radar altimetry. The focus of this Sub-Commission (SC4.6) is to facilitate collaboration and communication, and to support joint researches with promising GNSS-Reflectometry (GNSS-R) technique. Specific objectives will be achieved through closely collaborating with working groups and other IAG Commissions/Sub-Commissions. Meanwhile, close collaboration with the International GNSS Service (IGS), Institute of Navigation (ION) and IEEE Geoscience and Remote Sensing Society (IGRASS) will be promoted, such as joint sponsorship of international professional workshops and conferences.

Objectives:

- To promote and extend GNSS Reflectometry/Scatterometry developments and tests as well as environment remote sensing applications;
- To improve the existing estimation algorithms, inversion theory and temporal-spatial resolution in GNSS reflectometry from the ocean and land surface and supplement the traditional remote sensors, e.g., Satellite Altimetry;
- To coordinate data from GNSS-R campaign experiments and provide environment remote sensing products through fusing with other terrestrial and satellite observations;
- To address coastal ocean topography, ocean surface roughness characteristics (wind speed/direction and wave height), ice motion, wetland monitoring and surface soil moisture and snow/ice thickness as well as the condition of sea ice, glacial melting and the freezing/thaw state of frozen ground;
- To facilitate collaboration and communication with mutual Remote Sensing related communities (Oceanography, Hydrology, Cryosphere, Geodesy...)

Program of Activities:

The Sub-commission will establish Work Groups (WGs) on relevant topics, and promote GNSS Reflectometry/Scatterometry developments and remote sensing applications. Chair/Co-Chair will work closely with members and other IAG Commissions/Sub-Commissions to obtain mutual goals. Also we will organize international workshops and symposiums to provide a platform for GNSS-R communication and collaboration and jointly sponsor special sessions at IAG Symposia and other workshop/conferences with IGARSS and ION.

Website:

http://202.127.29.4/geodesy/IAG_SC4.6/

Activities

2015

- **13-15 May 2015**, Shuanggen Jin chaired one session and gave one invited talk at Chinese Satellite Navigation Conference, Xi'an, China.
- **11-13 May 2015**, Shuanggen Jin attended Workshop on Reflectometry using GNSS and other signals (GNSS+R 2015) as member of Scientific Organizing Committee, Potsdam, Germany.

2014

- **1-11 August 2014**, Shuanggen Jin attended the 40th COSPAR Scientific Assembly as Session Chair with one invited talk, Moscow, Russia.
- **29 July-1 August 2014**, Shuanggen Jin gave a half-day lecture on GNSS Remote Sensing: Methods and Results at CPGPS Summer School on GNSS, Shanghai, China.
- **25-27 April 2014**, Shuanggen Jin attended the Editorial Board Member meeting of Acta Geodaetica et Cartography Sinica, Ningbo, Zhejiang, China.
- **17 March 2014**, The first meeting of Satellite Navigation and Remote Sensing (SNARS) was held at SHAO, Shanghai, China.
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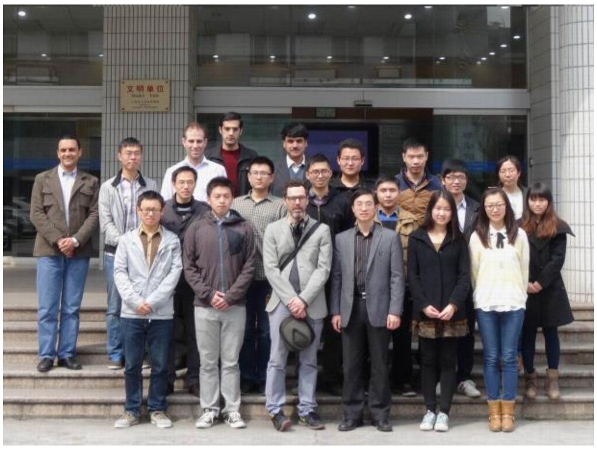

- **7-8 March 2014**, Arthur Neill (MIT, USA) and Alexander Gusev (KSU, Russia) visited and discussed with members of Satellite Navigation and Remote Sensing Group, Shanghai, China.
- **18-21 February 2014**, Shuanggen Jin was invited to give one-day lecture on GNSS at Short Training Course on Applications of Global Navigation Satellite Systems, Islamabad, Pakistan.
- **20 January 2014**, Shuanggen Jin organized Workshop on Water Cycle Observation from Space at Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China.

2013

- **9-11 December 2013**, Shuanggen Jin visited Xichang Satellite Launch Center and gave a talk on Satellite Observations and Applications, Xichang, China.
- **16-18 October 2013**, Shuanggen Jin was invited to visit the School of Environment and Spatial Informatics, China University of Mining and Technology and appointed Director of Center for Space Geodesy as well as adjunct Professor, Xuzhou, China.

- **13-16 October 2013**, Shuanggen Jin and Guiping Feng attended the 29th Annual Meeting of Chinese Geophysical Society (CGS) with receiving Liu Guangding Geophysical Youth Science and Technology Award, Kunming, 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.
- **5-7 July 2013**, Shuanggen Jin organized International Summer School on Planetary Geodesy and Remote Sensing and gave a half-day lecture on Planetary Geodesy and Science, Shanghai, China.

- **22 June 2013**, Shuanggen Jin attended the Award Ceremony of Scientific Chinese Person of the year (2012) and received Outstanding Young Scientist Award of Scientific Chinese Person of the Year (2012), Beijing, China.
- 22-26 April 2013, Shuanggen Jin attended the ION Pacific PNT 2013 and chaired one session "Ionosphere Monitoring with GNSS" Honolulu, Hawaii, USA.

2012

- **16-20 October 2012**, Shuanggen Jin attended the 28th Meeting of Chinese Geophysical Society (CGS) with receiving Fu Chengyi Award in Beijing and 56th Anniversary of SGG, Wuhan University and 80th Birthday of Academician Prof. Jinsheng Ning in Wuhan, 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
- **21-29 July 2012**, Shuanggen Jin attended the IEEE International Geoscience and Remote Sensing Symposium (IGARSS2012) with chairing one session in Munich, Germany and was invited to visit Czech Geodetic Observatory Pecny (GOP) and Deutsches Geodatisches Forschungsinstitut (DGFI) with one talk, respectively.

- **6-14 June 2012**, Shuanggen Jin attended the 34th Canadian Remote Sensing Symposium, Ottawa and visited University of Calgary and Geodetic Survey Division, Canada Centre for Remote Sensing, Natural Resources Canadian with two talks, Canada.
- **25-31 March 2012**, Shuanggen Jin was invited to give a talk at Universiti Teknologi Malaysia (UTM), Johor, Malaysia and chaired one Session with one talk at Progress In Electromagnetics Research Symposium (PIERS), Kuala Lumpur, Malaysia.

2011

- **12 December 2011**, Prof. Shuanggen Jin and Prof. Ching-Yuang Huang co-convened Cross-Strait Forum on GNSS Remote Sensing with full day talks and discussion, Shanghai, China.
- **10-18 November 2011**, Shuanggen Jin was invited to visit and gave several talks at Taiwan National Chiao Tung University, National Cheng Kung University, National Central University and Institute of Earth Sciences, Academia Sinica, Taiwan.
- **29 September 2011**, Seventeen members from ETH Zurich, Switzerland visited the SHAO and participated in a ETHZ-SHAO Forum on Space Geodesy, Shanghai, China
- **15 September 2011**, Prof. Shuanggen Jin and Prof. Valery Mironov Co-Chaired Shanghai-Siberia Workshop on Remote Sensing and discussed future cooperation in Radiowave Remote Sensing, Shanghai, China
- **20 August 2011**, Satellite Navigation and Remote Sensing Group with 14 members has travelled the ancient Fengjing Town and Jinshan Beach, Shanghai, China
- **07-09 August 2011**, Shuanggen Jin organized the International Workshop on GNSS Remote Sensing for Future Missions and Sciences as Chair of Workshop, Shanghai, China

- **08-16 August 2011**, Shuanggen Jin convened one Session at Asia Oceania Geosciences Society (AOGS 2011) with one talk, Taiwan.
- **24-29 July 2011**, Shuanggen Jin received IEEE GRSS Travel Grant Award to attend IEEE Int. Geosci. & Remote Sens. Symp (IGARSS 2011) and chaired one Session with two talks, Vancouver, Canada.

Publications

Books & Monographs

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WG 4.6.1 GNSS-R System and Development

Chair: Manuel Martin-Neira (ESA/ESTEC, The Netherlands)

Co-Chair: Fran Fabra (Institut de Ciències de l'Espai, Spain)

Within these 3 years (2011-2013) the *interferometric* technique of the Passive Reflectometry and Interferometry concept (PARIS), under study within the European Space Agency, has been well consolidated. This technique consists of the straight correlation between direct and reflected signals, without the use of any clean code replica on-board. Satellite discrimination is performed through the antenna beam, delay and Doppler diversity, particular to each satellite of each GNSS constellation. Spatial selectivity is achieved through the use of parallel high gain antenna beams, i.e. beamforming antennas in both, up- and down-looking receiving antennas. Because of the use of the maximum bandwidth of the GNSS signals, this technique is thought to provide the best altimetric performance for GNSS reflectometry.

Following a successful bridge experiment 7-8 July 2010, in 11 November 2011 the first airborne experiment of the PARIS interferometric technique was carried out. The data were processed by IEEC and the 2 cm/km slope of the geoid in the Baltic Sea area of the experiment was clearly measured, with a standard deviation of about 13 cm after 20 s. The waveforms retrieved matched well the expected ones for low wind speed, in line with the actual weather conditions during the test. The test set-up had to be restricted to one single high gain antenna beam looking up, and the same looking down. Therefore, this airborne experiment could show precise altimetry only within 15 degrees away from the aircraft track. A future experiment is being planned that will demonstrate altimetry over a wider swath of up to 35 degrees. The way this will be achieved is through making the beamformer on ground in postprocessing (on-board raw data are simply grabbed and recorded for later post-processing). The 11 November 2011 experiment is thought to be the most accurate altimetry test carried out so far in GNSS reflectometry by the European Space Agency.

Within the reporting period, ESA carried out two Phase A studies of a PARIS In-orbit Demonstration mission which showed the feasibility of a small demonstration mission dedicated to mesoscale ocean altimetry. Two additional Phase A studies will be started later in 2013 to consider a GNSS reflectometry experiment aboard the International Space Station (the GEROS experiment). The GEROS experiment is an opportunity to test the GNSS-R technology developed for the PARIS-IoD mission.

Also within 2011-2015 ESA has performed also other various studies on different applications of GNSS-R such as biomass, snow sounding, sea ice thickness and soil moisture with promising results all of them.

WG 4.6.3 GNSS Ocean Altimetry

Chair: Salvatore D'Addio (ESA/ESTEC, The Netherlands)
Co-Chair: Estel Cardellach (Institut de Ciències de l'Espai, Spain)

Activities

- On one hand, the *interferometric* technique of the Passive Reflectometry and Interferometry concept (PARIS), under study within the European Space Agency, explained in Report Subcommission WG 4.6.1, was tested for the first time under dynamic conditions. A dedicated GNSS-R interferometric receiver was developed and installed in the Finnish Skyvan aircraft, to perform, in 11 November 2011, the first airborne experiment of the PARIS interferometric technique. The data were processed by IEEC and the 2 cm/km slope of the geoid in the Baltic Sea area of the experiment was clearly measured, with a standard deviation of about 13 cm after 20 s. The waveforms retrieved matched well the expected ones for low wind speed, in line with the actual weather conditions during the test. The test set-up had to be restricted to one single high gain antenna beam looking up, and the same looking down. Therefore, this airborne experiment could show precise altimetry only within 15 degrees away from the aircraft track. A future experiment is being planned that will demonstrate altimetry over a wider swath of up to 35 degrees. The 11 November 2011 experiment is thought to be the most accurate altimetry test carried out so far in GNSS reflectometry by the European Space Agency. See references [2, 3, 8]. Conventional processing of GPS CA code signals was also carried out in the same experiment, showing an altimetry performance degradation of about a factor 2, mainly due to the reduced bandwidth of the open access CA code signal. However, the observed waveform matched very well the models also in this case.

- In 2012, two Phase A studies have been conducted by ESA, about the feasibility of a PARIS interferometric small mission for Ocean altimetric applications. See mission overview at [1].
- The proposal "GNSS REflectometry, Radio Occultation and Scatterometry onboard ISS" (GEROS-ISS), submitted to the 2011 European Space Agency Research Announcement for ISS Experiments relevant to study of Global Climate Change, was selected in September 2012, among more than 20 competing proposals. The Scientific Advisory Group is being formed (Spring 2013), to contribute defining the terms and requirements of two Phase A (feasibility) studies for such experiment.
- During 2013, a collaboration between the National Remote Sensing Center of China (NRSCC); Chinese Universities; IEEC/ICE-CSIC (Spain); and ESA has been established to conduct an experiment in the Chinese coast during the Typhoon season (July-September 2013), with the goal of capturing both scatterometric and altimetries features of the Typhoon in GNSS-R data. See [10].
- During this period, new processing techniques for Ocean altimetry have also been envisaged: in references [4, 6, 7] Ocean tide signatures were captured from 700 meter cliff using carrier-phase delays at low elevation angles of observation, with a few cm precision (data available at [5]); [9] tested a carrier-Doppler approach for altimetric applications that might work over rougher waters (less restrictive than phase-delay observations).
- The GNSS+R 2012 workshop was conducted at Purdue University (West Lafayette, IN, USA), in October 2012. Eight papers were presented related to Ocean altimetry: Yu et al.; Larson; Rius et al.; Beckheinrich et al.; Carreno-Luengo et al.; D'Addio et al.; Stienne et al.; and Semmling, Beyerle and Wickert (not listed below, please visit http://www.gnssr2012.org)

Publications

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Inter-Commission on Theory (ICCT)

http://icct.kma.zcu.cz

President: Nico Sneeuw (Germany)
Vice President: Pavel Novák (Czech Republic)

Structure

Joint Study Group 0.1:	Application of time series analysis in geodesy
Joint Study Group 0.2:	Gravity field modelling in support of height system realization
Joint Study Group 0.3:	Comparison of current methodologies in regional gravity field modelling
Joint Study Group 0.4:	Coordinate systems in numerical weather models
Joint Study Group 0.5:	Multi-sensor combination for the separation of integral geodetic signals
Joint Study Group 0.6:	Applicability of current GRACE solution strategies to the next generation of inter-satellite range observations
Joint Study Group 0.7:	Computational methods for high-resolution gravity field modelling and nonlinear diffusion filtering
Joint Study Group 0.8:	Earth system interaction from space geodesy
Joint Study Group 0.9:	Future developments of ITRF models and their geophysical interpretation

Overview

Terms of reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities.

The main objectives of the ICCT are:

- to be the international focal point of theoretical geodesy,
- to encourage and initiate activities to further geodetic theory,
- to monitor research developments in geodetic modelling.

The structure of the ICCT is specified in the IAG by-laws. The ICCT Steering Committee consists of the President, the Vice-President and representatives from all IAG Commissions:

President: Nico Sneeuw (Germany)
Vice-President: Pavel Novák (Czech Republic)
Representatives:
Commission 1: Tonie van Dam (Luxembourg)
Commission 2: Urs Marti (Switzerland)
Commission 3: Richard Gross (USA)
Commission 4: Dorota Brzezinska (USA)
GGOS: Hans-Jörg Kutterer (Germany)

Website

Since 2007, the ICCT website is hosted at http://icct.kma.zcu.cz by the web server of the Department of Mathematics, University of West Bohemia in Pilsen, and is powered by the MediaWiki Engine (similar to that used for the Wikipedia, a free, web-based multilingual encyclopaedia project). Due to this setup, the content of the ICCT Website can easily be edited by any authorized personnel (members of the ICCT Steering Committee and Chairs of the Study Groups). Thus, the website can be used by for fast and easy communication of ideas among the members of the Study Groups. During 2008 the latest Study Group was established (IC-SG9), i.e., there are currently nine active Study Groups within the ICCT.

VIII Hotine-Marussi Symposium

The main highlight of ICCT is the organization of the VIII Hotine-Marussi Symposium in Rome. Since the inception of ICCT, the already existing series of Hotine-Marussi Symposia falls under the responsibility of ICCT. Earlier ICCT-organized Symposia were the numbers VI (2006, Wuhan) and VII (2009, Rome). June 17–21, 2013, the VIII Hotine-Marussi Symposium took place in Rome. The venue was the same as 2009, namely at the Faculty of Engineering of the Sapienza University of Rome. Also the local organization was in the hands of Prof. Mattia Crespi again. From a total attendance of about 100 participants about 70 oral presentations and 15 posters were contributed to the following sessions:

1. Geodetic Data Analysis (W. Kosek, R. Gross, C. Kreemer)
2. Theoretical aspects of reference frames (A. Dermanis, T. Van Dam)
3. Digital Terrain Modeling, Synthetic Aperture Radar and new sensors: theory and methods (M. Crespi, E. Pottier)
4. Geopotential modeling, boundary value problems and height systems (P. Novák, M. Schmidt, C. Gerlach)
5. Atmospheric modeling in geodesy (T. Hobiger, M. Schindelegger)
6. Gravity field mapping methodology from GRACE and future gravity missions (M. Weigelt, A. Jäggi)
7. Inverse modeling, estimation theory (P. Xu)
8. Computational geodesy (R. Čunderlík, K. Mikula)
9. Special Session at Accademia Nazionale dei Lincei (F. Sansò, R. Barzaghi, N. Sneeuw)

The session topics follow roughly the study group structure of ICCT. Conveners (in brackets) were recruited (mostly) from the study group chairs and members.

True to the InterCommission nature of ICCT, the sessions dealt with the full width of topics in theoretical geodesy. During the special session at the Accademia Nazionale dei Lincei Fernando Sansò was honoured for his long-term involvement in the organization of the series of Hotine-Marussi Symposium, after taking over the baton from Antonio Marussi in 1985. It was decided to rename the VIII Hotine-Marussi Symposium by adding "*in honour of Fernando Sansò*" to its title.

This report

The activities of the ICCT are related namely to the research carried out by members of its Joint Study Groups. Their final reports specify the areas investigated by the members of the Joint Study Groups, achieved results (publications and presentations). Based on the content of the reports, it can be concluded that the Joint Study Groups are active, although the level of mutual co-operation and/or interaction between its members is not necessarily the same for all the Joint Study Groups.

Joint Study Group 0.1: Application of Time Series Analysis in Geodesy

Chair: Wieslaw Kosek (Poland)

In October 2010 the US Naval Observatory (USNO 2013) together with the Space Research Centre (SRC 2013) in Warsaw initiated the IERS Earth Orientation Parameters Combination of Prediction Pilot Project (EOPCPPP). The goal of this project is to determine the feasibility of combining Earth Orientation Parameters (EOP) predictions on an operational basis. The pole coordinate data predictions from different prediction contributors and ensemble predictions computed by the USNO were studied to determine the statistical properties of polar motion forecasts (Kosek et al. 2012). Short term prediction errors of pole coordinates data are caused by wideband short period oscillations in joint atmospheric-ocean excitation functions and their increase can be also caused by the change of phase of the annual oscillation in this function (Kosek 2012). The combination of the least-squares and multivariate autoregressive prediction using the axial component of the atmospheric angular momentum excitation function method was applied to predict UT1−UTC data which improved their prediction accuracy in relation to the combination of the least-squares and the autoregressive prediction of the univariate time series (Niedzielski and Kosek 2012).

Higher order semblance function reveals that addition of hydrology angular momentum to the sum of atmospheric and oceanic excitation functions of polar motion improves the phase agreement between the geodetic and fluid excitation functions in the annual frequency band. The common oscillations in the geodetic and fluid excitation functions of polar motion can be detected using wavelet based semblance filtering (Kosek et al., 2011).

At the University of Wroclaw in Poland the real time system and service for sea level prediction called PROGNOCEAN has been built (Niedzielski and Mizinski 2013). The aim of this system is computation of alitmeter-derived sea level anomelies data prediction for 1 day, 1 week and 2 weeks in the future, together with the maps of the mean prediction errors. The predictions are computed in real time, so the users are available to evaluate the performance of the system and service. The forecasting strategies are based on a few time series methods: (1) extrapolation of the polynomial-harmonic model, (2) extrapolation of the polynomial-harmonic model with autoregressive prediction, (3) extrapolation of the polynomial-harmonic model with self-exciting threshold autoregressive model, (4) extrapolation of the polynomial-harmonic model with autocovariance prediction, (5) extrapolation of the polynomial-harmonic model with vector autoregressive prediction, (6) extrapolation of the polynomial-harmonic model with generalized space-time autoregressive model (Prognocean 2013).

A software package TSoft for the analysis of Time Series and Earth Tides has been created by by Paul Vauterin in the Royal Observatory of Belgium. It allows the user to process the data in a fully interactive and graphical way and has a number of important advantages, particularly in the field of error correction of (strongly perturbed) data, and the detection and processing of special events (e.g. free oscillations after Earthquakes (ROB 2013).

The influence of the hydrological noise on repeated gravity measurements has been investigated on the basis of the time series of 18 superconducting gravimeters (SGs) and on predictions inferred from the Land Dynamics (LaD) world Gascoyne land water energy balances model. It is shown that the PSDs of the hydrological effects flattens at low frequency and is characterized by a generalized Gauss Markov structure (Van Camp et al. 2010).

The new method of data processing was used for the absolute gravimeters (AGs) observations during intercomparison campaigns since 1980. A new criterion, based on the minimization of the L1 norm of the offsets, for fixing the constant of the ill-conditioned problem, was found to be statistically more precise than the one classically used (de Viron et al. 2011). Based on synthetic data representative of signals observed by superconducting gravimeters (SG) at various station locations, it was found that the addition of SG information mitigates the error in the estimation of gravity rates of change caused by the presence of long period, interannual, and annual signals in the AGs data. These results were discussed as a function of the sampling rate of the absolute gravity measurements, the duration of the observations, and the uncertainties of the AGs (Van Camp et al. 2013).

It was shown that 25 different climate indices associated with a great variety of climatic fields and geographic regions share a very substantial fraction of their variability. This common fraction can be captured and described by using no more than four leading modes of variability correlated with the sea surface temperature field. The preferred periodicities apparent in these modes reflect mainly the quasi-biennial and quasiquadrennial periodicities of El Nino Southern Oscillation (de Viron et al. 2013).

Meetings

Since 2011 at each European Geosciences Union General Assembly the sessions G1.2 "Mathematical methods in the analysis and interpretation of potential field data and other geodetic time series" were organized, by two members of the JSG 0.1 study group (EGU 2011, 2012, 2013).

Publications

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SRC 2013, http://www.cbk.waw.pl/eopcppp/cfp.html

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Van Camp, M., L. Métivier, O. de Viron, B. Meurers, and S. D. P. Williams, 2010, Characterizing long-time scale hydrological effects on gravity for improved distinction of tectonic signals. Journal of Geophysical Research, VOL. 115, B07407, doi:10.1029/2009JB006615, 2010

Van Camp M., O. de Viron, R.J. Warburton, Improving the determination of the gravity rate of change by combining superconducting with absolute gravimeter data, Computers & Geosciences 51 (2013) 49–55

de Viron O., M Van Camp, and O Francis, 2011, Revisiting absolute gravimeter intercomparisons, Metrologia 48 (2011) 290–298 doi:10.1088/0026-1394/48/5/008.

de Viron O., J. O. Dickey, and M. Ghil, 2013, Global modes of climate variability, Geophysical Research Letters, VOL. 40, 1–6, doi:10.1002/grl.50386, 2013

Joint Study Group 0.2: Gravity Field Modelling in Support of Height System Realization

Chair: Pavel Novák (Czech Republic)

1. Introduction and objectives

This report describes activities and scientific outputs of the ICCT's Joint Study Group 0.2 for the period of 2011-15. In its terms of reference, the group members investigated several research topics of a theoretical nature that were closely related to gravity field modelling at all scales in service of establishing a world height system (WHS). Namely geometric properties of the Earth's gravity field are very significant in this respect as one of its equipotential surfaces serves as a global vertical datum in geodesy.

Theoretical issues investigated by JSG0.2 have included the following topics:

- Combining heterogeneous gravity field observables by using spatial inversion, spherical radial functions, collocation and wavelets, etc. and by taking into account their sampling in time and space, spectral and stochastic properties.
- Studying stable, accurate and numerically efficient methods for continuation of gravity field parameters including satellite observables of type GRACE and GOCE.
- Advancing methods for gravity potential estimation based on its measured directional derivatives (gravity and gravity gradients) by exploiting advantages of simultaneous continuation and inversion of observations.
- Investigating gravity data specifications (stochastic properties, spatial and temporal sampling and spectral content) required by specific geodetic applications.
- Studying available Earth's gravitational models (EGM) in terms of their available resolution and accuracy for the purpose of WHS realization.
- Defining relations between an adopted conventional EGM and parameters of a geocentric reference ellipsoid of revolution approximating a time invariant equipotential surface of the adopted EGM aligned to reduced observables of mean sea level.

This study group (SG) is affiliated to IAG Commissions 1 (*Reference Frames*) and 2 (*Gravity Field*); co-operation with the GGOS Theme 1 *Unified Global Height System* was undertaken.

2. Report on published/presented results of the study group

Main scientific outcomes of JSG0.2 include journal publications, oral and poster presentations at international conferences and meetings, as well as progress and final reports delivered to various scientific authorities. Major meetings organized within 2011-15 (such as GGHS 2012, IAG Scientific Meeting 2013, Hotine-Marussi 2013, ESA Living Planet 2013, IGFS 2014, IUGG 2015 as well as annual meetings of EGU, CGU and AGU) included sessions on global geopotential models, vertical datum unification and local gravity field modelling. The following overview provides merely selected publications and presentations.

2.1. Selected publications

Čunderlík R, Mikula K, Špir R (2012) An oblique derivative in the direct BEM formulation of the fixed gravimetric BVP. In: *7th Hotine-Marussi Symposium on Mathematical Geodesy*. International Association of Geodesy Symposia 137, DOI: 10.1007/978-3-642-22078-4_34.

Čunderlík R, Fašková Z, Mikula K (2012) Fixed gravimetric BVP for the vertical datum problem. In: *Geodesy for Planet Earth. International Association of Geodesy Symposia* 136, DOI: 10.1007/978-3-642-20338-1_40.

Čunderlík R, Minarechová Z, Mikula K (2014) Realization of WHS based on the static gravity field observed by GOCE. *International Association of Geodesy Symposia* 141: 211-220.

Featherstone WE (2013) Deterministic, stochastic, hybrid and band-limited modifications of Hotine's integral. *Journal of Geodesy* 87(5): 487-500, DOI: 10.1007/s00190-013-0612-9.

Filmer MS, Hirt C, Featherstone WE (2013) Error sources and data limitations for the prediction of surface gravity: a case study using benchmarks. *Studia Geophysica et Geodaetica* 57(1): 47-66, DOI: 10.1007/s11200-012-1114-6.

Featherstone WE, Filmer MS (2012) The north-south tilt in the Australian Height Datum is explained by the ocean's mean dynamic topography. *Journal of Geophysical Research –Oceans* 117: C08035, DOI: 10.1029/2012JC007974.

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

Heck B (2011) A Brovar-type solution of the fixed geodetic boundary-value problem. *Studia Geophysica et Geodaetica* 55(3): 441-454, DOI: 10.1007/s11200-011-0025-2.

Gerlach C, Rummel R (2014) Global height system unification with GOCE: a simulation study on the indirect bias term in the GBVP approach. *Journal of Geodesy* 87(1): 57-67.

Gruber C, Novák P, Sebera J (2011) FFT-based high-performance spherical harmonic transformation. *Studia Geophysica et Geodaetica* 55(3): 489-500.

Gruber T, Gerlach C, Haagmans R (2013) Intercontinental height datum connection with GOCE and GPS-levelling data. *Journal of Geodetic Science* 2(4): 270–280.

Kotsakis C (2013) A conventional approach for comparing vertical reference frames. *Journal of Geodetic Science* 2(4): 319-324.

Novák P, Tenzer R (2013) Gravitational gradients at satellite altitudes in global geophysical studies. *Surveys in Geophysics* 34(5): 653-673.

Rummel R (2013) Height unification using GOCE. *Journal of Geodetic Science* 2(4): 355-362.

Rummel R, Gruber T, Ihde J, Liebsch G, Rülke A, Schäfer U, Sideris MG, Rangelova E, Woodworth P, Hughes C (2014) Height system unification with GOCE. Final report of the ESA project STSE – GOCE+, GO-HSU-RP-0021.

Sjoeberg LE, Eshagh M (2012) A theory on geoid modelling by spectral combination of data from satellite gravity gradiometry, terrestrial gravity and an Earth gravitational model. *Studia Geophysica et Geodaetica* 47(1): 13-28, DOI: 10.1556/AGeod.47.2012.1.2.

Sjoeberg LE (2011) Geoid determination by spectral combination of an Earth gravitational model with airborne and terrestrial gravimetry – a theoretical study. *Studia Geophysica et Geodaetica* 5(4): 579-588, DOI: 10.1007/s11200-010-0069-8.

Sideris MG, Rangelova E, Amjadiparvar B (2014) First results on height system unification in North America using GOCE. *International Association of Geodesy Symposia* 141: 221-227.

Sebera J, Šprlák, Novák P, Bezděk A, Val'ko M (2014) Iterative spherical downward continuation applied to magnetic and gravitational satellite data. *Surveys in Geophysics* 35(4): 941-958.

Sebera J, Pitoňák M, Hamáčková E, Novák P (2015). Comparative study of the spherical downward continuation. *Surveys in Geophysics* 36(2): 253-267.

Šprlák M, Sebera J, Val'ko M, Novák P (2014) Spherical integral formulas for upward & downward continuation of gravitational gradients onto gravitational gradients. *Journal of Geodesy* 88(2): 179–197.

Šprlák M, Novák P (2014) Integral transformations of gradiometric data onto GRACE type of observable. *Journal of Geodesy* 88(4): 377-390.

Šprlák M, Novák P (2014) Integral transformations of deflections of the vertical onto satellite-to-satellite tracking and gradiometric data. *Journal of Geodesy* 88(7): 643-657.

Šprlák M, Novák P (2015) Integral formulas for computing a third-order gravitational tensor from volumetric mass density, disturbing gravitational potential, gravity anomaly and gravity disturbance. *Journal of Geodesy* 89: 141-157.

Tenzer R, Hamayan, Novák P, Gladkikh V, Vajda P (2012) Global crust-mantle density contrast estimated from EGM2008, DTM2008, CRUST2.0 and ICE-5G. *Pure and Applied Geophysics* 169(9): 1663-1678.

Tenzer R, Novák P, Gladkikh V (2012) The bathymetric stripping corrections to gravity field quantities for a depth-dependent model of seawater density. *Marine Geodesy* 35: 1-23.

Tenzer R, Novák P (2013) Effect of crustal density structures on GOCE gravity gradient observables. *Terrestrial, Atmospheric and Oceanic Sciences* 24(5): 793-807.

Tenzer R, Chen W, Tsoulis D, Bagherbandi M, Sjoeberg LE, Novák P, Jin S (2015). Analysis of the refined CRUST1.0 crustal model and its gravity field. *Surveys in Geophysics* 36(1): 139-165.

Woodworth PL, Hughes CW, Bingham RJ, Gruber T (2013) Towards worldwide height system unification using ocean information. *Journal of Geodetic Science* 2(4): 302–318.

2.2. Selected oral and poster presentations

Abd-Elmotaal H, Kuehtreiber N (2012) Comparison between astro-gravimetric and astro-geodetic geoids for Austria. EGU2012-223.

Amjadiparvar B, Rangelova E, Sideris MG, Hayden TS (2013) The role of local gravity information in the unification of the North American vertical datums. EGU2013-6480.

Čunderlík R, Mikula K (2012) Realization of WHS based on the static gravity field observed by GOCE. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-179).

Elhabiby MM, Sideris MG, Keller W (2011) A combined multi-resolution multi-dimensional wavelet approach for the inversion of geodetic integrals. EGU2011-13775.

Fašková Z, Macák M, Čunderlík R, Mikula K (2012) Finite volume numerical scheme for high-resolution gravity field modelling and its parallel implementation. EGU2012-8827.

Gruber C, Novák P, Barthelmes F (2011) Derivation of topographic potential from global DEM models. EGU2011-10170.

Gruber C, Moon YJ, Flechtner F, Novák P, Daras I (2011) Submonthly GRACE solutions from localising integral equations and Kalman filtering. 25th General Assembly of IUGG, Melbourne, July 2011.

Gruber T, Rummel R, Sideris MG, Rangelova E, Woodworth P, Hughes C, Ihde J, Liebsch G, Schäfer U, Rülke A, Gerlach C, Haagmans R (2013) Height system unification with GOCE: overview and selected results. ESA Living Planet Symposium, Edinburgh, September 2013.

Gruber T, Rummel R, Sideris MG, Rangelova E, Woodworth P, Hughes C, Ihde J, Liebsch G, Schäfer U, Rülke A, Gerlach C, Haagmans R (2014) Scientific Roadmap towards Height System Unification with GOCE. 3rd International Gravity Field Service Meeting, Shanghai, July 2014.

Heck B, Müßle M, Seitz K, Grombein T (2013) On the effect of planar approximation in the geodetic boundary value problem. EGU2013-8963.

Huang J, Véronneau M (2013) Contribution of the GRACE and GOCE models to a geopotential-based geodetic vertical datum in Canada. EGU2013-10164.

Novák P, Sebera J, Val'ko M (2012) On the downward continuation of gravitational gradients. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S2-201).

Roman D, Véronneau M, Avalos D, Li X, Holmes S, Huang J (2012) Integration of gravity data into a seamless transnational height model for North America. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-075).

Rummel R, Gruber T, Gerlach C, Hughes C, Ihde J, Liebsch G, Rangelova E, Sideris MG, Woodworth P (2011) GOCE's impact on World Height System unification. AGU Fall Meeting, San Francisco, December 2011.

Sideris MG, Rangelova E (2012) First results on height systems unification in North America using GOCE. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-092).

Sideris MG, Rangelova E (2012) Global Height System Unification by means of the GOCE geoid. International Jubilee Conference UACEG2012, Calgary, November 2012.

Sebera J, Novák P, Vaľko M, Šprlák M, Bezděk A, Bouman J, Fuchs M (2013) Downward continuation of gridded and reprocessed GOCE gravitational gradients. EGU2013-8265.

Sebera J, Novák P, Val'ko M, Šprlák M, Bouman J, Fuchs M, Haagmans R (2014) Grids of GOCE-only gravitational gradients for geophysical applications. 11th EGU General Assembly, Vienna, April-May 2014.

Šprlák M, Novák P, Val'ko M, Sebera J (2013) Spherical integral formulas for upward/downward continuation of gravitational gradients onto gravitational gradients. 8th Hotine-Marussi Symposium, Rome, June 2013.

Šprlák M, Novák P, Val'ko M, Sebera J (2013) Comparison of three methods for the downward continuation of the gravitational gradients. ESA Living Planet Symposium, Edinburgh, September 2013.

Šprlák M, Novák P, Hamáčková E, Sebera J (2014) Integral transformations of disturbing potential onto gradiometric data. 11th EGU General Assembly, Vienna, April-May 2014.

Šprlák M, Hamáčková E, Novák P (2014) Validation of GOCE gravitational gradients by satellite altimetry. AGU Fall Meeting, San Francisco, December 2014.

Vergos GS, Andritsanos VD, Grigoriadis VN, Pagounis V, Tziavos IN (2014) Evaluation of GOCE/GRACE GGMs over Attika and Thessaloniki, Greece, and W0 determination for height system unification. 3rd International Gravity Field Service Meeting, Shanghai, July 2014.

Wang YM, Li X, Holmes S, Roman D, Smith D (2013) Investigation of the use of deflections of vertical measured by DIADEM camera in the GSVS11 survey. EGU2013-12779.

2.3. Study group web page

The webpage of the Joint Study Group 0.2 was http://icct.kma.zcu.cz/index.php/IC_SG2.

3. Report on activities of the study group

During the 2011-15 period, there were no specific sessions organized during regular geodetic conferences but one at the Hotine-Marussi Symposium 2013 in Rome. At this symposium organized by ICCT a session on geopotential modelling, boundary-value problems and height systems co-convened by the chairmen of JSG0.2 and JSG0.3 has been organized with total 11 oral and 2 poster presentations. However, other contributions of the JSG0.2's members can be found in programs of many geodetic and geophysical conferences and meetings (such as ESA's Living Planet 2013, annual meetings of AGU, CGU and EGU, GGHS 2012, IAG SM 2013, IGFS 2014 or IUGG 2015) organized within the period starting after the IUGG General Assembly in Melbourne and ending by the IUGG Assembly in Prague. Activities within the scope of the JSG partially overlapped with R&D project activities of its members including two projects funded through the ESA's Support to Science Element (STSE) program (GOCE data in support of WHS realization and GOCE data for geophysical exploration). These international projects represented a major platform for international scientific co-operation of scientists – members of JSG – including their regular meetings and mutual visits.

4. Outlook and plans

As IAG's efforts to establish a unified world height system are still ongoing, there will be further requirements for advancing theoretical foundations and investigations in the area of defining and establishing a global vertical datum that could be used for merging and unifying local and regional height systems and vertical datums used by different countries. Activities advanced within the 2011-15 period by this JSG shall continue in the 4 year period starting after the IUGG General Assembly 2015 with more stress on closer cooperation with IAG's commissions and namely with GGOS. Due to strong links and some overlaps with JSG0.3 their activities could possibly be merged under the umbrella of one JSG for the period of 2015-19 reflecting demands and requirements reflecting recent work progress on the WHS realization.

Joint Study Group 0.3: Comparison of Current Methodologies in Regional Gravity Field Modelling

Chairs: Michael Schmidt, Christian Gerlach (Germany)

Introduction

The main objectives of JSG0.3 are:

- to collect information of available methodologies and strategies for regional modelling,
- to analyze the collected information in order to find specific properties of the different approaches and to find, why certain strategies have been chosen,
- to create a benchmark data set for comparative numerical studies,
- to carry out numerical comparisons between different solution strategies for estimating the model parameters and to validate the results with other approaches (spherical harmonic models, least-squares collocation, etc.),
- to quantify and interpret the differences of the comparisons with a focus on detection, explanation and treatment of inconsistencies and possible instabilities of the different approaches,
- to create guidelines for generating regional gravity solutions,
- to outline standards and conventions for future regional gravity products.

Since the focus is on the methodological foundations it is straightforward to compare different methodologies in regional gravity field modelling based on synthetic data.

A first initiative to motivate active contribution to this study was a workshop on regional potential field modelling (see next section). On the workshop it was agreed to prepare a set of simulated gravity field data which should be used for computing regional gravity field models by different groups employing different methodologies. This should facilitate a numerical comparison of the different approaches.

Workshop

On February 23-24, 2012, an international "Workshop on Regional Gravity and Geomagnetic Field Modelling" was held at the Bavarian Academy of Sciences and Humanities (BAdW) in Munich, Germany. The workshop was jointly organized by the German Geodetic Research Institute (DGFI, Michael Schmidt), the Commission for Geodesy and Glaciology of BAdW (KEG, Christian Gerlach) and the Institute for Geodesy and Geoinformatics of the University of Bonn (IGG, Jürgen Kusche).

The active participants were asked to present their modelling approach with regard to their

- field of application (gravity field, geomagnetic field, static or time-variable, etc.),
- the type of input data used (terrestrial, airborne, satellite data or a combination of those),
- the type of modelling approach used including choice of base functions and point grids, properties of the mathematical and stochastic models and details on the mathematical solution and regularization techniques which are employed.
- In addition, open question and specific problem areas were presented.

After a general introduction by Michael Schmidt on general aspects of regional modelling and the scope of the workshop several modelling approaches were presented by several groups.

Fehler! Verweisquelle konnte nicht gefunden werden. gives an overview of the modelling approaches presented during the two workshop days. Altogether there were 31 participants from 11 different countries. The participation was not limited to the original members of JSG 0.3 which reflects the study groups open policy that interested research groups can join at any time.

Table 1: Overview of modelling approaches presented at the "Workshop on Regional Gravity and Geomagnetic Field Modelling"

Functional model (base function)	Field of Application	Research Group
Spherical splines	Static and time-variable gravity field from satellite data	IGG, Bonn (Eicker, Schall, Kusche)
Spherical radial basis functions	Time-variable gravity field from satellite data	University of Life Sciences Ås, Norway (Bentel, Gerlach)
Spherical radial basis functions	Multi resolution representation of static and time-variable gravity field and combination of all data types	DGFI, Munich (Lieb, Schmidt)
Poisson multipole wavelets	Regional static gravity field refinement by combination of satellite and terrestrial data	IGN / IPGP Paris (Panet)
Spherical radial basis functions	Regional static and time-variable gravity field from satellite data	University Hannover (Naemi)
Spherical radial basis functions	Regional gravity field modelling from satellite data	University Stuttgart (Antoni)
Slepian functions	Spatiospectral locatlization on the sphere	Princeton University (Harig, Simons)
Global directional wavelets	Sensitivity of satellite formations and geomagnetic data analysis	Danish National Space Institute (Einarsson)
Regional empirical orthonormal functions	Geomagnetic field modeling	GFZ Potsdam (Schachtschneider)
Poisson multipole wavelets	Time variable gravity field from satellite data	University Potsdam (Fuhrmann)
Harmonic splines	Regional geomagnetic field	GFZ Potsdam (Lesur)
Least-squares collocation	Regional static gravity field from combination of all various data sources	Technical University Munich (Pail)
Greens function	Regional time-variable gravity field from satellite data	GFZ Potsdam (Fagioligni, Gruber)
Isoparametric boundary elements	Regional gravity field from satellite data	University Stuttgart (Weigelt)
Point mass modelling	Regional gravity field and geoid models from all available data	BKG Frankfurt (Schäfer)

Simulation Data

On the workshop it was agreed within the final discussion to generate a simulation data set to be used by all different groups in order to facilitate numerical comparison between the different methodologies. The data set was jointly prepared by DGFI and IGG Bonn; it is available from the web site of JGS 0.3 at http://jsg03.dgfi.badw.de. The data set is publicly available and all groups interested in testing their approach are invited to use the data set and share the results. First results of individual groups were presented during the VIII Hotine-Marussi Symposium in Rome, June 17-21, 2013. Comprehensive comparisons and

evaluations of the individual results are planned for the beginning of 2014 and will be presented at the EGU General Assembly 2014 in Vienna at the end of April, so far results from the actively contributing groups are made available to JGS 0.3 by the end of 2013.
The data sets comprise terrestrial data on regular geographic coordinate grids, airborne data on synthetic flight tracks and satellite data along real orbits of GRACE and GOCE. They are provided for two test areas, namely in Europe and South America, both having an extension of 20° × 30°. The data is provided error-free along with time series of white noise errors.

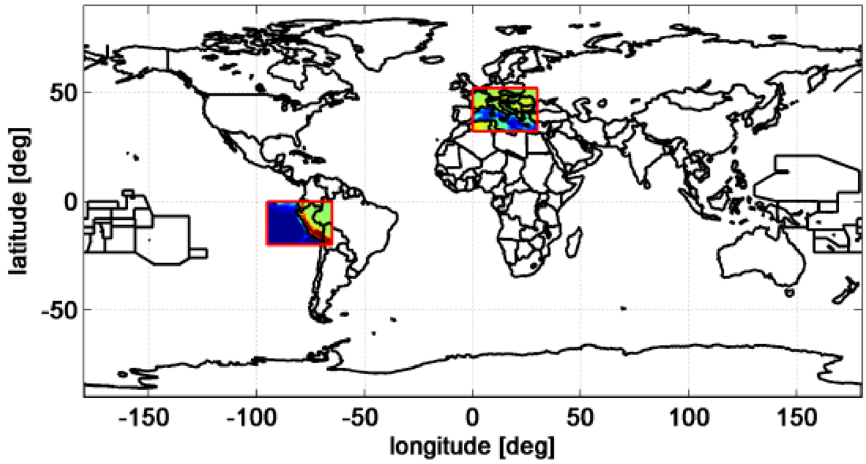

Figure 1: Global map with red boxes marking the test regions.

For validation of the computations from the data sets an additional data also on regular geographic surface grids is provided. In order to allow validation of gravity field approximation at independent locations, the validation grids are shifted with respect to the observation data grids.

Comparisons of regional models

At the EGU General Assembly 2014 several group members presented their regional gravity field approaches within the Session G1.2: "Mathematical methods for the analysis of potential field data and geodetic time series", which was partly dedicated to the topics of the JSG 0.3. To be more specific, the regional approaches were applied either to single data sets such as GOCE gravity gradients or terrestrial data, but also to the combination of different observation types. Because the full gravity signal can only be derived from global sets of observational data, all of the regional solutions were derived in the classical remove-compute-restore procedure. Thereby, a global gravity field model is used to reduce the long wavelength part from the observations. After regional modeling of the residual field in the investigation area, the long wavelength part is restored again. The global background model and its resolution differ for the various simulation scenarios.

The following approaches have been employed in detail in these studies:

1. Spherical scaling functions on a Reuter grid (employing the Shannon function in the analysis step and the Blackman function for the synthesis step); solution by variance component estimation (VCE); *(DGFI, Munich: Lieb, Schmidt)*
2. Spherical wavelets on a Reuter grid (employing the cubic polynomial scaling function for analysis and synthesis); solution by VCE *(University of Life Sciences Ås, Norway; Jet Propulsion Laboratory, Pasadena: Bentel, Gerlach)*
3. Spherical spline functions on a triangular grid (employing Kaula's degree variance model as shaping function); solution by VCE, *(IGG, Bonn: Eicker, Schall, Kusche)*

4. Reduced point masses (basis functions are disturbing potential values obtained from point masses located on a regular grid on the Bjerhammer sphere with a $0.25° \times 0.5°$ spacing and a depth of 20 km), (*University of Copenhagen, Denmark: Tscherning, Herceg),*
5. Least-squares collocation (all admissible data are used), (*University of Copenhagen, Denmark: Tscherning, Herceg).*

Besides the solutions of these methods, calculations stemming from other regional modeling approaches such as expansions in Slepian basis functions have been presented. All the results have been rated as extremely valuable for reaching the goals of the Study Group.

To put the obtained numerical results of the regional solutions in perspective to what is expected from global spherical harmonic (SH) modelling a global data set of GOCE gravity gradients T_{rr} along the real GOCE orbits was generated from EGM2008 up to degree and order 250. As in case of the simulated regional data sets the gravity gradients are provided error-free along with a time series of white noise errors. Equivalently to the regional data sets also a global validation data set was performed.

Comparisons of regional models with a global spherical harmonic solution

At the EGU General Assembly 2015, again in the Session G1.2: "Mathematical methods for the analysis of potential field data and geodetic time series", several closed-loop scenarios were presented related to the comparison of the global SH solution - calculated from the global simulated GOCE gravity gradient T_{rr} data mentioned before - with corresponding regional solutions following the strategies (1) and (3) of the aforementioned list. The comparisons with the validation data from EGM2008 for the two test areas in Europe and in South America demonstrated that all solutions are of similar accuracy. Thus, it was concluded that the two RBF approaches using only regional input data, are at least of the same quality as global spherical harmonic models. However, it has to be pointed out that the chosen input data generated from EGM2008 cannot be used to show that a regional approach could be even "better" than the global approach. For such an investigation input data has to be chosen which is not stemming from a spherical harmonic model.

Other mentionable remarks

As an additional outcome of the investigations of the Study Group the two doctoral theses of Majid Naeimi: "Inversion of satellite gravity data using spherical radial base functions" and Katrin Bentel: "Regional Gravity Modeling in Spherical Radial Basis Functions - On the Role of the Basis Function and the Combination of Different Observation Types" have been completed successfully at the Institute of Geodesy of the Leibniz University Hannover at August 23, 2013 and at the Department of Mathematical Sciences and Technology of the University of Life Sciences Ås in Norway at November 13, 2013, respectively. Some other Study Group members are currently working on their PhD thesis also directly related to the topics of and the studies within the JSG 0.3.

At the 24th of October 2014 our Study Group member Carl Christian Tscherning passed away unexpectedly. We want to express our deep sorrow about the loss of one of the most famous geodesists of the last decades. We miss him and with him the discussions about the pros and cons of different regional gravity field strategies.

Final remarks

Finally, we can state that from the range of results after many years of research and the four years lifetime of the JSG 0.3 a lot of information and progress was gained from systematic tuning of regional methods in combination with simulated gravity field data. Since all the work done in the last years within the JSG 0.3 is related to static regional gravity field modelling, a logical extension for the next 4 year period is the integration of the time dependency. Since regional approaches are in particular important for studying time evolving processes such as hydrology variations, the inclusion of a time-dependent model part is indispensable. Other issues, such as the multi-scale-analysis or the combination of point observations with area measurements are still unsolved.

Joint Study Group 0.4: Coordinate Systems in Numerical Weather Models

Chair: Thomas Hobiger (Sweden)

Numerical weather models (NWM's) contain valuable information relevant for removing the environmental signal from geodetic data. Currently no clear documentation exists regarding how to deal with the height systems when carrying out the calculations in a geodetic reference frame. A "conventional" transformation model (available also as source code) would enable geodesists to handle such data easily and allow them to use data from different meteorologic datasets. In addition, geodetic products such as GNSS-derived zenith total delays are being assimilated into NWMs. Thus, the transformations that convert the meteorological data into a geodetic reference frame should also support the use of geodetic data in meteorological models. This study group was set up to 1) deal with the differences between geodetic and meteorologic reference systems and 2) provide consistent models for transforming between the two systems.

Vertical transformation

In order to decide on a consistent transformation to/from numerical weather models the study group investigated vertical transformation first, before making a decision on how to deal with horizontal coordinates.

Ellipsoidal heights ↔ geopotential heights

Ellipsoidal heights (h) can be obtained from orthometric heights (H) when the geoid height (N) is known.

$$h = H + N \quad (1)$$

Furthermore, orthometric heights relate to geopotential heights (Z) by

$$H = Z\, g_n / g_0 \quad (2)$$

where g_n denotes the conventional gravity constant used throughout the numerical weather model. g_0 is the mean gravity, defined as

$$g_0 = 1/\zeta \int g \, dz \quad (3)$$

where the (vertical) integration is performed from the geoid surface to height ζ.

Error sources

Although the transformation between numerical weather model heights and geodetic (ellipsoidal) heights can be described in a mathematically unique sense (equations 1-3) the choice of geophysical models, the selection of constants, or the definition of the origin can lead to uncertainties of the transformation which can reach several meters. Thus, in the next sections the following effects on ellipsoidal heights are studied:

- Impact of the gravity model and the way in which the mean gravity (g_0) is calculated
- Impact of using the vertical direction w.r.t. the ellipsoid instead of the vertical w.r.t. a sphere (as used for numerical weather models)
- Uncertainty of the geoid (height)
- Using a different value for the gravity constant.

In order to choose the mean gravity for the height transformation the study group has investigated how and to what extent the choice of the gravity model changes the obtained ellipsoidal height. In doing so, geopotential heights from a numerical weather model (gn=9.80665 m/s^2) [Taylor and Thompson] had to be transformed to ellipsoidal heights (assuming a constant geoid height of N=20 m). Calculations were performed on global 1°x1° grids, and it was assumed that geodetic latitude/longitude is identical to the one used in the numerical weather models. In total eight contributions (from GFZ/Germany, GRGS/France, NICT/Japan, UNB/Canada(5 solutions) and TU Wien/Austria) were submitted. Fitting a linear function over all results allows the derivation of a simple estimate for the uncertainty due to the choice of the mean gravity (see figure 0.4).

When the normal to the sphere is used instead of the normal to the ellipsoid, transformed heights are expected to change slightly as well. In a similar study about the mean gravity model, GRGS evaluated data at various heights and grid points and computed the difference between two transformations, one using the normal to the ellipsoid and one using the normal w.r.t. a mean sphere.

Geoid heights N must be obtained from regional or global geoid models and applied to all grid points of the numerical weather model before obtaining ellipsoidal heights from orthometric heights (Equation 1). Thus, any error in these models directly propagates into the calculated ellipsoidal heights. Although regional geoid solutions can provide mm-accuracy, such models do not cover the whole area of the numerical weather model. Thus, an error of 1 cm is taken as a (conservative) value for the uncertainty of geoid heights on a global scale.

In case the gravity constant is inaccurate and not properly considered for the transformation, an additional error source for obtaining ellipsoidal heights results. However, most of the NWMs rely on a value of g_n=9.80665 m/s^2 or explicitly document the usage of another value. Thus, the impact from this error source can be assumed to be zero.

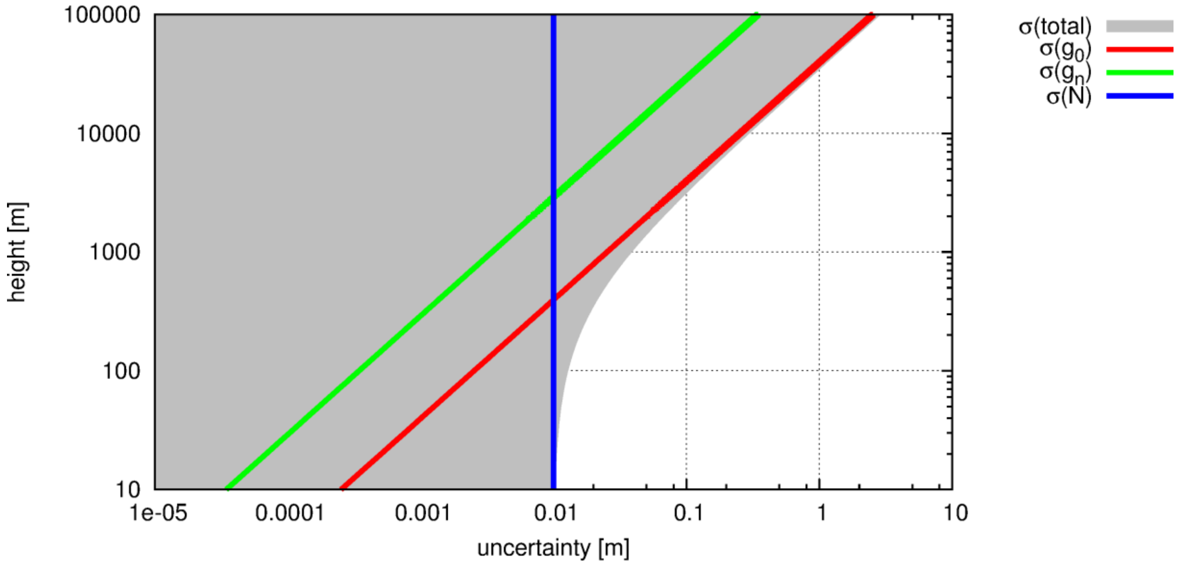

Figure 1: Uncertainties of $\sigma(g_0)$, σ(norm) , σ(N) and the total error budget of the height transformation[Hobiger et al., 2012].

As shown in figure 0.4, the uncertainty of the geoid model, which results mostly from the geoid height (N), dominates the overall error budget in the lower height domains, i.e. <500 m. Above that height the choice of the gravity model and the way in which the mean gravity acceleration is computed becomes more important, and this error source starts to reduce the accuracy of the transformation. Thus, for a consistent and conventional height transformation between geopotential heights from a numerical weather model and ellipsoidal heights it is important that

- geoid heights are known with mm-accuracy on a global scale
- the gravity model provides both geoid heights and gravity acceleration at a given location
- the proper direction of the normal w.r.t. the reference figure is properly considered.

Fortunately, most of the atmospheric parameters relevant for geodesy (mainly pressure) decrease exponentially with height, which reduces the impact of an imperfect height transformation when performing an integration or summation in the vertical direction.

The study group agreed that a conventional vertical transformation be made available for users online, and we recommend it be provided in three programming languages (FORTRAN, C/C++ and Matlab). Depending on the accuracy requirement and computational efforts, three different versions of the transformation should be provided.

1. A “conventional algorithm” based on EGM96 which transforms between the two systems. The model is expected to provide mean gravity as well as geoid height.
2. A “reduced algorithm” similar to (1) which uses a sub-set of the spherical harmonic coefficients. Source code should be available in the three programming languages and should aim at high performance for reduced accuracy applications.
3. A “simple algorithm” which is also available in the three programming languages. This algorithm is based on a (semi-) analytical expression for the gravity calculations and requires the user to input geoid heights manually.

Routines should be made available after the output from different programming languages has been checked for consistency, especially for model (1), which deals with high degree and order spherical harmonics.

Horizontal transformation

Based on various discussions it appears that horizontal coordinates in numerical weather models are equivalent to geodetic (WGS84 based) latitude/longitude pairs. Meteorologists deal with geodetic coordinates directly, i.e. they apply them on the sphere without any transformation. Although this method is straightforward for operational use, it might lead to some inconsistencies since the total volume of the atmosphere is changed. Thus, the study group drafted a document that lists questions concerning horizontal coordinates which need to be addressed to (by?) weather agencies. A draft version can be found in the appendix of this report for future reference.

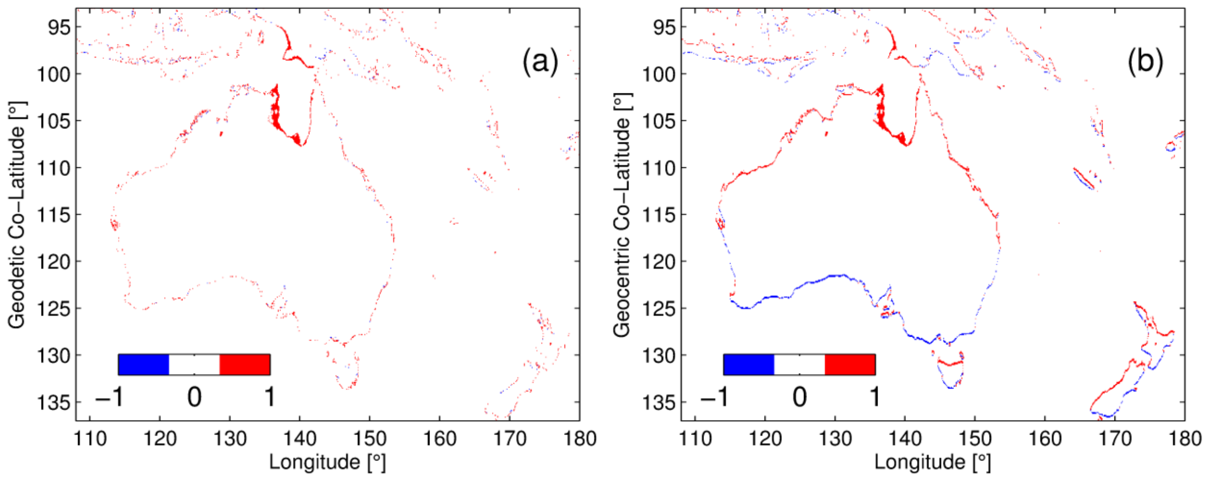

Figure 2: Land-sea-mask (LSM) differences between ETOPO2 and the operational ECMWF model as of April 2012 at a resolution of 6'. The ETOPO2 LSM was resampled from 2' to 6' using coordinate grids referred to (a) geodetic latitude and (b) geocentric latitude. Differences are shown in the sense 'ETOPO2 minus ECMWF'.

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Appendix:

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Questionnaire

IAG ICCT SSG member name:
Weather model:
Contact person(s) related to this model:


Brief description of the model:
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Questions:
==========

(1) Vertical coordinate system
------------------------------
(1.1) What is the vertical coordinate system used by the model, and how
does it relate to geometric height, pressure, or other parameters ?

(1.2) Are you using the standard value for gravity acceleration (9.80665
m/s^2)?

(1.3) What is the reference figure of your model? What is zero height? What
is your understanding of the geoid?

(1.4) How do you geo-reference ground based measurements, balloon launches,
etc? In particular how do you transform between ellipsoidal heights and
model heights?

(1.5) Do you consider the Earth's oblateness?

(2) Horizontal coordinate system
--------------------------------
(2.1) What is the horizontal coordinate system used by the model, and how
does it relate to latitude and longitude?

(2.2) How is orography (topography dealt with)? In particular what is your
understanding of latitudes (geocentric vs. geodetic)?

(2.3) How does this effect the inclusion of in-situ (ground based,
balloons, etc.) data? How do you geo-reference a site/location properly?
How do you geo-reference satellite data?

(2.4) If you use map projections, how is orography generated in your model
and how can it be geo-referenced in a geodetic reference system?

(3) Miscellaneous
-----------------
(3.1) Would you use a "conventional transformation" from/to geodetic
reference systems if it is available?

(3.2) What are you accuracy requirements on such a transformation?

(3.3) Do you have any other requirements concerning the inclusion of data
which has been geo-referenced in a geodetic coordinate system

(4) Other points discussed:
---------------------------
Please fill in here if you discussed something beyond (1) - (3)
```

Joint Study Group 0.5: Multi-Sensor Combination for the Separation of Integral Geodetic Signals

Chair: Florian Seitz (Germany)

1. Introduction and Objectives

This document presents the report of the work undertaken in the framework of the ICCT Joint Study Group JSG0.5 since its creation in 2011. Activities of the study group were focussed on the analysis and interpretation of observations from modern space-borne methods of Earth observation. A large part of the parameters derived from space geodetic observation techniques are integral quantities of the Earth system. Among the most prominent ones are parameters related to Earth rotation and the gravity field, whose variations reflect the superposed effect of a multitude of dynamic processes and interactions in various subsystems of the Earth. The integral geodetic quantities provide fundamental and unique information on different balances in the Earth system, in particular on the balances of mass and angular momentum that are directly related to (variations of) the gravity field and Earth rotation.

In respective balance equations, the geodetic parameters reflect the integrative effect of all mass- and angular momentum-related processes in the Earth system. For studies of suchlike processes, geodesy provides important input in the form of highly accurate parameter time series along with uncertainty information covering many decades. Variations of Earth rotation have even been determined for more than one and a half century using continuously improved astrometric and space geodetic observation techniques. Thus geodesy provides an excellent data base for the analysis of long term changes in the Earth system and contributes fundamentally to an improved understanding of large-scale processes.

However, in general the integral parameter time series cannot be separated into contributions of specific processes without further information. Their separation and therewith their geophysical interpretation requires complementary data from observation techniques that are unequally sensitive for individual effects and/or from numerical models. Activities of the study group were focussed on the development of strategies for the separation of the integral geodetic signals on the basis of modern space-based Earth observation systems. A multitude of simultaneously operating satellite systems with different objectives is available today. They offer a broad spectrum of information on global and regional-scale processes at different temporal resolutions. Research within the study group dealt with the question in which way the combination of heterogeneous data sets allows for the quantification of individual contributors to the balances of mass and angular momentum. The activities are coordinated between the participating scientists and conducted in interdisciplinary collaboration. The study group is primarily affiliated with IAG Commissions 2 (Gravity field) and 3 (Earth rotation and geodynamics).

2. Members

Chair: Florian Seitz (Technische Universität München, Germany)

Full members:
Sarah Abelen (Germany)
Rodrigo Abarca del Rio (Chile)
Andreas Güntner (Germany)
Karin Hedman (Germany)
Franz Meyer (USA
Michael Schmidt (Germany)
Manuela Seitz (Germany)
Alka Singh (India)

3. Report of Activities of the Study Group

The main results are related to the analysis and separation of Earth rotation and gravity field time series. The contributions of individual Earth system components (e.g., atmosphere, ocean, land hydrology) or even of particular dynamic processes (e.g., wind, ocean currents) were quantified and separated from the integral observed signals by means of specific data analysis methods (such as principle component analysis) or by the integration of complementary observation techniques and model data. The results have been presented in 12 joint reviewed journal publications and various conference contributions (talks and posters). Dedicated sessions at conferences were initiated and chaired by members of the study group. Among the most important and successful efforts were the joint application of two third-party funded projects in which five PhD students are working on topics related to the goals of the study group. They form a network with further PhD students and scientists at the participating institutions. Both projects are conducted in the frame of the International Graduate School of Science and Engineering (IGSSE) of the Technische Universität München (TUM).

The project CLIVAR-Hydro (*Signals of Climate Variability in Continental Hydrology from Multi-Sensor Space and In-situ Observations and Hydrological Modeling*) has been initiated in 2010 (http://www.dgfi.tum.de/en/projects/clivar-hydro/) and provides funds for three PhD students. CLIVAR-Hydro aims to perform a multi-sensor approach in order to detect, separate and balance individual contributions to continental water storage variations for selected large river basins. A specific focus of the study is on the analysis of climate signals. The project exploits the synergies of various observation systems and combines their output with hydrological simulation models. The project is carried out within a largely interdisciplinary group of networking scientists and PhD students from space engineering, geodesy, hydrology and climate research. It provides new and valuable insights into hydrological processes and the impacts of climate change on the global water cycle.

A follow-up project for two additional PhD positions has been developed in collaboration between members of JSG0.5. The project REWAP (*Monitoring and Prediction of Regional Water Availability for Agricultural Production under the Influence of Climate Anomalies and Weather Extremes*) started in 2014 (http://www.dgfi.tum.de/en/projects/rewap/). It addresses one of the most important issues facing humanity during this century, i.e., the threat posed by hydrological impacts on agricultural production under climate change. The principal task of the project is to investigate, in which way and with which consequences time-variable hydrological conditions are linked to regional water availability. Of particular interest is the question, in which way changes in regional conditions occur in response to large-scale phenomena in the global climate system. Using up-to-date satellite technology, in particular the twin-satellite gravity field mission GRACE, the project aims at monitoring suchlike large-scale phenomena and – in combination with ground and model data – forecasting their impact to regional-scale hydrological and agricultural conditions.

Members of the JSG0.5 performed mutual research visits at the institutions involved, where they worked together for several months in the frame of the common projects. The exchange of personnel between the institutions was financed through project funds. From March until November 2013 a PhD student of the Universidad de Conceptión worked at DGFI/TUM in the field of GRACE data analysis. From January to February 2014 Sarah Abelen joined the group in Chile and worked towards the separation of the soil moisture component in GRACE observations. Rodrigo Abarca del Rio (Chile) joined DGFI/TUM in October 2014 for discussions about the interpretation of variations of Earth rotation and the gravity field. This mobility contributed significantly to the cross-linked collaboration within JSG0.5.

3.1. Publications of SG Members

Abelen, S., F. Seitz, R. Abarca del Rio, A. Güntner: Droughts and floods in the La Plata basin in soil moisture data and GRACE. Remote Sensing, in press.

Göttl, F., M. Schmidt, F. Seitz, M. Bloßfeld: Separation of atmospheric, oceanic and hydrological polar motion excitation mechanisms based on a combination of geometric and gravimetric space observations. J. Geodesy, 89, 377-390, 2015.

Seitz, F., Hedman, K., Meyer, F., Lee, H.: Multi-sensor space observation of heavy flood and drought conditions in the Amazon region. In: Rizos, C., Willis, P. (eds.) Earth on the Edge: Science for a Sustainable Planet, IAG Symposia, Vol. 139, 311-318, Springer, 2014.

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3.2. Selected Conference Contributions of SG Members

Ressler, G., Eicker, A., Lieb, V., Schmidt, M., Seitz, F., Shang, K., Shum, C.K.: Water storage variations extracted from GRACE data by combination of multi-resolution representation (MRR) and principal component analysis (PCA). EGU GA, Vienna, Austria, 16.4.2015.

Baumann, S., Menzel, A., Seitz, F., Güntner, A., Abelen, S.: Comparison of measured glacier mass balance data in the Tian Shan and Pamir Mountains, Central Asia, with GRACE satellite gravimetry. International Symposium on Glaciology in High-Mountain Asia, Kathmandu, Nepal, 2.-6.3.2015.

Abelen, S., Schnitzer, S., Singh, A., Seitz, F., Abarca del Rio, R., Güntner, A.: How heavy are extreme weather events? WCRP-ICTP Summer School on Attribution and Prediction of Extreme Events, Trieste, Italy, 21.7.2014.

Göttl, F., Schmidt, M., Seitz, F., Bloßfeld, M.: Separation of atmospheric, oceanic and hydrological polar motion excitation by a combination of geometric and gravimetric space observations. EGU GA, Vienna, Austria, 29.4.2014.

Abelen, S.; Seitz, F.: Relating global soil moisture data to total continental water storage; Satellite Soil Moisture Validation and Application Workshop, Frascati, ESA ESRIN, 02.07.2013

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Seitz, F., Kirschner, S., Neubersch, D.: Polar motion as boundary condition in an adaptive Kalman Filter approach for the determination of period and damping of the Chandler oscillation. AGU 2012 Fall Meeting, San Francisco, USA, 07.12.2012 (invited).

Seitz, F., Hedman, K.: Towards the Separation of Integral GRACE Signals of Continental Water Storage Using Multi-Sensor Space and In-situ Observations. AGU 2012 Fall Meeting, San Francisco, USA, 06.12.2012.

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Singh, A., Seitz, F., Schwatke, C., Bosch, W.: Application of the Satellite Altimetry over Terrestrial Water Body: A Case Study on Aral Sea. 20 Years of Progress in Radar Altimetry, Venice, Italy, 25.09.2012.

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Singh, A., Seitz, F.: Water storage variations in the Aral Sea from multi-sensor satellite data in comparison with results from GRACE gravimetry. IGARSS, Munich, 25.07.2012.

Singh, A., Seitz, F., Schwatke, C.: Observations of Water Storage Variations in the Aral Sea from Multi-sensor Satellite data. 2nd IAHR Europe Congress, Munich, 28.06.2012.

Seitz, F., Göttl F., Heiker A., Kirschner S., Kutterer H., Schmidt M.: Combination of geodetic observations and geophysical models for estimating consistent Earth rotation and gravity field parameters, individual excitation mechanisms and physical Earth parameters. EGU GA, Vienna, Austria, 22.-27.4.2012.

Singh, A., Seitz, F., Schwatke, C., Güntner, A.: Geometrical and gravimetrical observations of the Aral Sea and its tributaries along with hydrological models. EGU GA, Vienna, Austria, 23.4.2012.

Spiridonova, S., Seitz, F., Hedman, K., Meyer, F.: Water mass change in the Amazon basin estimated by multi-temporal SAR data, GRACE gravimetry and water level observations. EGU GA, Vienna, Austria, 22.-27.4.2012.

Abelen, S., Seitz, F., Güntner, A.: Global comparison of soil moisture variations as derived from remote sensing, satellite gravimetry, and hydrological modeling. EGU GA, Vienna, 25.04.2012.

Seitz, F., Kirschner, S.: Simulation, prediction and analysis of polar motion with a dynamic Earth system model. EGU GA, Vienna, 23.04.2012.

Seitz, F., Abelen, S., Singh, A., Schnitzer, S.: Compartmental water storage changes from multi-sensor data and their signatures in GRACE observations. SPP 1257 Workshop on GRACE-Hydrology, Bonn, 13.02.2012.

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Rinner, C., Seitz, F., Abelen, S.: Comparison of soil moisture products of the sensors AMSR-E and MIRAS. German Geodetic Week 2011, Nuremberg, 28.09.2011.

Seitz, F.: Simulation, prediction and analysis of Earth rotation parameters with a dynamic Earth system model. Journées "Systèmes de référence spatio-temporels", Vienna, 20.09.2011.

Abelen, S., Seitz, F., Güntner, A., Schmidt, M.: Analysis of regional variations in soil moisture by means of remote sensing, satellite gravimetry and hydrological modeling. IUGG XXV GA, Melbourne, 05.07.2011.

Seitz, F., Schmidt, M., Shum, C.K., Hedman, K., Lee, H., Meyer, F.: Multi-sensor space and in-situ monitoring of extreme hydrological conditions in the Amazon region. IUGG XXV GA, Melbourne, 03.07.2011.

Abelen, S., Seitz, F., Güntner, A., Schmidt, M.: Signals of soil moisture variations in remote sensing and gravity field observations. IUGG XXV GA, Melbourne, 02.07.2011.

Seitz, F.: Multi-sensor space and in-situ observations for the separation of integral GRACE signals of continental water storage. EGU GA, Vienna, Austria, 7.4.2011.

Seitz, F., Kutterer H., Schmidt M., Kirschner, S., Heiker A., Göttl F.: Estimation of Earth rotation and gravity field parameters, separated excitation mechanisms and physical Earth parameters from geometric and gravimetric space observations. EGU GA, Vienna, Austria, 6.4.2011.

3.3. Study group web page

The webpage of the group is http://icct.kma.zcu.cz/index.php/IC_SG5

3.4. Conference Sessions

EGU General Assembly, Vienna:

- 2012, April 23: Session G5.1, Observing and understanding Earth rotation variability and its geophysical excitation (Convenor: F. Seitz): 12 oral presentations, 18 posters.
- 2013, April 8: Session G3.3, Observing and understanding Earth rotation variability and its geophysical excitation (Convenor: F. Seitz): 6 oral presentations, 10 posters.
- 2014, April 29/30: Session G3.3, Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation (Convenor: F. Seitz): 6 oral presentations, 16 posters.
- 2015, April 15: Session G3.4, Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation (Co-Convenor: F. Seitz): 6 oral presentations, 12 posters.

IAU General Assembly, Beijing:

- 2012, August 29/30: Science Meeting of IAU Commission 19 – Rotation of the Earth (Convenor: F. Seitz): 10 oral presentations.

INTERGEO/German Geodetic Week:

- 2011, September 28, Nuremberg: Session 5: GGOS – Global Geodetic Observing System (Convenor: F. Seitz): 6 oral presentations.
- 2012, October 11, Hanover: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 5 oral presentations.
- 2013, October 9/10, Essen: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 9 oral presentations.
- 2014, October 7, Berlin: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 7 oral presentations.

Joint Study Group 0.6: Applicability of Current GRACE Solution Strategies to the Next Generation of Inter-Satellite Range Observations

Chairs: Matthias Weigelt (Germany), Adrian Jäggi (Switzerland)

The main objective of this study group is the preparation and testing of existing solution strategies for their applicability to the upcoming GRACE-Follow On and future satellite missions. These missions will be equipped with improved instruments such as the laser interferometer (LRI). Since existing solution strategies make use of linearization and/or depend on augmentation with other observed quantities, e.g. GPS, it needs to be tested if existing solution strategies are suitable to take full advantage of the offered precision.

Simulation of observations:

The creation of simulated data sets, which are applicable to theoretical questions but offer also a great deal of realism at the same time, is the first and a very demanding task. The group opted for two data sets: (1) for theoretical questions use was made of the SC7 data set, which has been developed by a team led by the University of Bonn in 2003, and (2) a second data set was prepared by Jean-Claude Raimondo and colleagues at the German Research Centre for Geoscience in Potsdam and is based on orbit integration of the static gravity field EIGEN-GL04C up to degree and order 90 but includes also solid Earth and ocean tides, geophysical effects inducing a time variable gravity signal or non-gravitational forces. Details are listed in table 1.

Table 1: Models included in the preparation of the simulated data set with a high degree of realism

Source	**Implementation**
Static gravity field	EIGEN-GL04C up to 90x90
Planetary Ephemerides	JPL DE405 - only Sun and Moon
Ocean tides	EOT08a up to 50x50 only 8 waves: Q1, O1, P1, K1, N2, M2, S2, K2
Time variable gravity field	AOHIS ESA model up to 90x90
Non-gravitational accelerations	atmospheric drag, solar radiation pressure, Earth albedo and infra-red radiation (also provided separately)

Both data set are prepared for 30 days and with a five second sampling. Satellite-specific as well as inter-satellite quantities are provided including attitude information for both satellites.

The second important step is the preparation of realistic noise time series for the various simulated sensors, e.g. the inter-satellite K-Band and LRI observations. These noise time series are only prepared for the second data set at the moment. One types of noise data set has been prepared in the framework of the “BMBF-Geotechnologien” program "Zukunftskonzepte für Schwerefeldmissionen” and is kindly made available to members of this study group (thanks to Phillip Brieden).

Investigations on the acceleration approach for the llSST-case

Theoretical investigations focused primarily on the acceleration approach being one that incorporates GPS-observations in the mathematical model. Using the observations as is results in a mixture of the poorer precision of GPS-observations with the K-Band information. One common way to reach a solution has been to reduce the observations to residual quantities using *a priori* information and subsequently solving for corrections to the used *a priori* gravity field model neglecting the GPS-related term (a.k.a. crosstrack or radial term). Investigations showed that this approximation is even for the current GRACE K-Band solutions insufficient. The approach therefore needs to be refined by considering the residual radial term which requires the solution of the variational equations. Due to the distinct spectral behaviour the development for this second term can be limited to a very low degree (10), i.e. the computational burden can be significantly reduced. The relation between the relative gravity gradient projected on the line of sight and the range-observations cannot be considered as an in-situ approach anymore but solutions are on the same level of precision as existing GRACE solutions of the processing centres.

As it was the idea of the acceleration approach to be an in-situ approach, alternatives have been investigated and one possibility has been found by developing the radial term in terms of rotational quantities. This has been successfully achieved and the new formulation allows for considerable insight into the nature of the satellite observation system, e.g. an analytical explanation for the poor East-West observability of GRACE is at hand now. Investigations on the provided precision of the star cameras showed that they currently insufficient but the upcoming LRI will provide a new technology called differential wavefront sensing which may allow the exploitation of the approach.

Activities related to the Gravity Recovery And Interior Laboratory (GRAIL) mission

The Gravity Recovery And Interior Laboratory (GRAIL) mission orbiting the Moon and the Gravity Recovery And Climate Experiment (GRACE) mission orbiting the Earth share many conceptual commonalities. Major differences reside, however, in the absolute positioning of the spacecraft, which is accomplished by Doppler tracking from NASA's Deep Space Network (DSN) for GRAIL and by the Global Positioning System (GPS) for GRACE. Data from GRACE and from the Gravity and steady-state Ocean Circulation Explorer (GOCE) has been used to investigate the role of position information. Artificially degrading either the geographical coverage or the accuracy of kinematic positions serving as input data together with continuously available K-Band inter-satellite data is found not to be a limiting factor for gravity field recovery using the Celestial Mechanics Approach (CMA). Eventually, the CMA has been applied to Level-1B data of the GRAIL mission deriving first Bernese lunar gravity field solutions.

Organisational and other achievements

Besides the technical progress also other activities have been successfully accomplished. The members of the group assigned themselves to various workgroups allowing for a structured approach to the various objectives of the study group. The exchange of information and knowledge has been fostered, e.g. a literature list with the most important and relevant publications for the investigated approaches has been compiled and made available to the members of the group. Group members are updated about the developments within the group by means of the internal newsletter "JSG0.6 Circular". Most importantly, one of the largest sessions at the VIII Hotine-Marussi Symposium in Rome in June 2013 has been successfully organized whereas eleven presentations were related to JSG0.6 activities. Gerhard Beutler and Christoph Dahle gratefully agreed to give invited presentations. A number of publications stemming from these presentations were also submitted to the upcoming proceedings of the meeting.

Experiences

As requested by ICCT a short feedback on the management and experiences throughout the last four years is given. The chairs are very grateful to the commitment of the group members and quite some work has been achieved.

The primary concern is that this commitment is based on voluntary contributions, which means that these activities will always have a lower priority than ongoing project- or thesis-work. Delays and slow progress are the natural consequence. It is emphasized that it is not due to a lack of willingness or commitment by group members but rather a question of priority. ICCT and IAG needs to consider how to support the activities under their umbrella and how to stimulate advancement. This could for example be achieved by financial support or waivers for publications fees which in turn will allow members of the JSG to assign a higher priority to the activity. After all, activities often need to be justified to supervisors and/or other authorities. Furthermore a more active role of ICCT and IAG in these activities should be considered. Contrary to the activity itself, the benefit to do the work within the umbrella of ICCT and IAG is not obvious to members on the one hand and outsiders on the other hand. IAG and ICCT should therefore consider to develop and evolve their framework of support.

Another major point of concern is the again long delay in the publication of the Hotine-Marussi proceedings. Already for the VII Hotine-Marussi proceedings it took more than three years and the current one is still not published although nearly two years have been passed since the meeting. It will be increasingly difficult to motivate people to contribute to the meeting and the proceedings if delays continue to exist.

Joint Study Group 0.7: Computational Methods for High-Resolution Gravity Field Modelling and Nonlinear Diffusion Filtering

Chairs: Róbert Čunderlik, Karol Mikula (Slovakia)

Activities of the JSG-0.7 have been mainly focused on development of new approaches for high-resolution gravity field modelling and nonlinear diffusion filtering using efficient numerical methods, namely the boundary element method (BEM), finite volume method (FVM), method of fundamental solution (MFS) or singular boundary method (SBM). Most of the achieved results were presented mainly in geodetic conferences, e.g. the GGHS-2012 symposium in Venice (October 2012), EGU-2013, EGU-2014 and EGU2015 in Wien, IAG-2013 in Potsdam (September 2013) or IGFS-2014 in Shanghai (July 2014). In addition, our JSG was organizing the session "Computational geodesy" within the VIII Hotine-Marussi Symposium in Roma (June 2013) that included 5 oral presentations and 3 posters. The results achieved by our JSG have been also published in the journal papers or proceedings from the IAG Symposia. Below is a more detail description of our activities.

High-resolution gravity field modelling

Boundary element method

In case of the developed parallel approach by BEM, which considers real topography of the Earth's surface, the problem of oblique derivative has been investigated. There have been proposed and tested algorithms where the oblique derivative is decomposed to normal and tangential components. The numerical experiments have been applied for high-resolution global gravity field modelling as well as for precise local modelling using discrete terrestrial gravimetric measurements, e.g. in Slovakia and New Zealand.

Finite volume method

There have been proposed and developed new approaches by FVM for global and local modelling. The parallel implementation using the MPI procedures and large-scale parallel computations on clusters with distributed memory has resulted in the global FVM solutions with the horizontal resolution corresponding to the spherical harmonics (SH) up to degree 2160 (like EGM2008). The FVM approach has been successfully applied for local modelling as well. Later the problem of oblique derivative has been incorporated in the proposed numerical schemes. The FVM numerical scheme for the nonlinear geodetic BVP has been derived as well. The FVM approach has been also applied to solve the altimetry-gravimtery BVP. It has resulted in high-resolution modelling of the altimetry-derived gravity data over oceans.

Method of fundamental solutions and singular boundary method

There has been developed new approach by MFS for global gravity field modelling. This approach based on the point masses modelling has been proposed to process the GOCE gravity gradients. The developed algorithm has been designed to derive the disturbing potential or its derivatives from the T_{rr} radial components available from the SGG_TRF_2 product. The numerical experiments have studied how a depth of the fictitious boundary, where the source points are located, influences accuracy of the achieved results. Ideas of SBM have been applied in case that the source points are located directly on the Earth’s surface. Such ideas are based on appropriate regularization techniques that isolate singularities of the fundamental solution or its derivatives. A parallel implementation of algorithms, iterative elimination of far zones’ interactions and large-scale computations has yielded an efficient tool for gravity field modelling from the GOCE observations while solving the problem in a space domain. Processing of all available GOCE data has resulted in the static GOCE-based global gravity field model. It has been used to evaluate the geopotential on the mean sea surface models leading to the W_0 estimates that are independent from ones obtained by the SH-based methods.

Nonlinear diffusion filtering

There have been proposed and developed new approaches for linear and nonlinear diffusion filtering on a closed surface like a sphere, ellipsoid or the triangulated approximation of the real Earth’s surface. The surface FVM have been used to derive an implicit numerical scheme for the linear diffusion and semi-implicit numerical schemes for the nonlinear diffusion equations on such closed surfaces. Two nonlinear models have been considered. In case of the Perona-Malik model, which is suitable for reducing an additive noise, the developed method has been applied for filtering various data, e.g., the satellite-only mean dynamic topography or the direct GOCE measurements. This model as well as numerical experiments has been published in Journal of Geodesy (2013, Vol. 87). Another nonlinear filtering model based on the geodesic mean curvature flow, which is suitable for reducing noise of the type “salt & papper”, has been recently proposed and developed. It will be presented during the IUGG-2015 General Assembly in Prague.

Publications

Journal Papers

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Others

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Joint Study Group 0.8: Earth System Interaction from Space Geodesy

Chair: Shuanggen Jin (China)

Introduction

The gravity field and geodetic mass loading reflect mass redistribution and transport in the Earth's fluid envelope, and in particular interactions between atmosphere, hydrosphere, cryosphere, land surface and the solid Earth due to climate change and tectonics activities, e.g., dynamic and kinematic processes and co-/post-seismic deformation. However, the traditional ground techniques are very difficult to obtain high temporal-spatial resolution information and processes, particularly in Tibet. With the launch of the Gravity Recovery and Climate Experiment (GRACE) mission since 2002, it was very successful to monitor the Earth's time-variable gravity field by determining very accurately the relative position of a pair of Low Earth Orbit (LEO) satellites. Therefore, the new generation of the gravity field derived from terrestrial and space gravimetry, provides a unique opportunity to investigate gravity-solid earth coupling, physics and dynamics of the Earth's interior, and mass flux interaction within the Earth system, together with GPS/InSAR.

Objectives

- To quantify mass transport within the Earth's fluid envelope and their interaction in the Earth system.
- To monitor tectonic motions using gravimetry/GPS, including India-Tibet collision, post-glacial uplift and the deformation associated with active tectonic events, such as earthquakes and volcanoes.
- To develop inversion algorithm and theories in a Spherical Earth on gravity field related deformation and gravity-solid Earth coupling, e.g. crust thickness, isostatic Moho undulations, mass loadings and geodynamics.
- To develop methods to extract a geodynamic signals related to Solid-Earth mantle and/or core and to understand the physical properties of the Earth interior and its dynamics from the joint use of gravity data and other geophysical measurements.
- To analyze and model geodynamic processes from isostatic modelling of gravity and topography data as well as density structure of the Earth's deep interior.
- To address mantle viscosity from analyzing post-seismic deformations of large earthquakes and postglacial rebound (PGR) and to explain the physical relationships between deformation, seismicity, mantle dynamics, lithospheric rheology, isostatic response, etc.
- To achieve these objectives, the IC SG interacts and collaborates with the ICCT and all IAG Commissions.

Activities

2015

- **12-17 April 2015**, Shuanggen Jin was Session Co-Convener, European Geosciences Union (EGU) General Assembly, Vienna, Austria.

2014

- **15-18 December 2014**, Shuanggen Jin was Session Co-Convener, AGU Fall Meeting, San Francisco, USA.

- **1-11 August 2014**, Shuanggen Jin attended the 40th COSPAR Scientific Assembly as Session Chair with one invited talk, Moscow, Russia.
- **22-26 July 2014**, Shuanggen Jin was Member of Scientific Organizing Committee and Session Chair at International Symposium on Geodesy for Earthquake & Natural Hazards, Miyagi, Japan.
- **20 January 2014**, Shuanggen Jin organized Workshop on Water Cycle Observation from Space at Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China.

2013

- **13-16 October 2013**, Shuanggen Jin attended the 29th Annual Meeting of Chinese Geophysical Society (CGS) with receiving Liu Guangding Geophysical Youth Science and Technology Award, Kunming, 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.

2012

- **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, Shanghai, China

2011

- **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 Univesity and Institute of Earth Sciences, Academia Sinica, Taiwan.

Selected Publications

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Joint Study Group 0.9: Future Developments of ITRF Models and their Geophysical Interpretation

No report available

Communication and Outreach Branch (COB)

http://www.iag-aig.org

President: József Ádám (Hungary)
Secretary: Szabolcs Rózsa (Hungary)
IAG Newsletter Editor: Gyula Tóth (Hungary)

Activity Report

1. Introduction

The period of 2011-2015 is the third term in the operation of the Communication and Outreach Branch (COB) hosted at the Department of Geodesy and Surveying of the Budapest University of Technology and Economics (BME).

The Communication and Outreach Branch is one of the components of the Association.

According to the new Statues (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members.

The Terms of Reference and program of activities of the COB, and a short report on the IAG website ("IAG on the Internet"), were published in The Geodesist's Handbook 2012 (Ádám and Rózsa, 2012; Rózsa, 2012), respectively.

In the past period of the third term (since the 2011 IUGG General Assembly in Melbourne till June, 2015 in Prague IUGG GA) the COB's President attended the Executive Committee (EC) meeting in four cases (Singapore, August 15, 2012; Vienna, April 7, 2013; Potsdam, September 1, 2013 and Vienna, April 26, 2014), while COB's Secretary represented COB on the EC meeting in San Francisco, December 5, 2011. A joint meeting of the IAG Office (H. Drewes and H. Hornik) and the COB (J. Ádám, Sz. Rózsa and Gy. Tóth) was organized in Budapest in November 22-23, 2012, where the following topics were discussed:

- the structure and operation of the website;
- IAG gifts/merchandising during the 150th anniversary year at the SA in Potsdam.

An other joint meeting of the IAG Office (H. Drewes and H. Hornik) and the COB (J. Ádám and Sz. Rózsa) was organized in Melk, Austria in August 21, 2013 just before of the IAG Scientific Assembly (SA) in Potsdam, Germany, September 2-6, 2013. At this steering committee meeting the above two topics were again discussed and improved.

Note that the COB (J. Ádám, Sz. Rózsa and Gy. Tóth) organized a special meeting with Professor Ivan I. Mueller, Past President of the IAG in June 12, 2012 at the Budapest University of Technology and Economics, Hungary. During this discussion we outlined the possibilities how to improve the COB activities and the celebration of the 150th anniversary of IAG in Potsdam IAG SA meeting in 2013.

2. The IAG Website

The Communication and Outreach Branch maintained the IAG Website. The website has been operational, no significant downtime has been experienced in the service. A regular update of the content has been carried out using the material provided by Association and Commission leaders, conference organizers and other members of the Association. The website has been redesigned in 2012/2013 introducing some new features like the section of the „hot topics", a slide-show introducing the most important information on the IAG website, according to the decision of the joint meetings of the IAG Office and COB. In the new section of „Hot topics" the actual topics in Geodesy can be highlighted. Moreover a separate section is devoted to the history of the association celebrating the 150 years anniversary of IAG. The updated website was available for the SA in Potsdam.

Since the submission of the last quadrennial report the following features have been also added to the website:

- Facebook integration: all the pages of the website can be 'liked' on FB.
- Regenerating forgotten passwords automatically for the IAG Forum and the Members' Area.

Fig. 1. Monthly visitors from May 2011 to April 2015

Note that the number of visitors of the IAG Homepage is about 1500 visitors/month (in daily average approx. 50 visitors) during the past four years (see *Fig. 1*).

3. The IAG Newsletters

Altogether 48 IAG Newsletters have been published from June 2011 till June 2015 and can be accessed on the IAG website in HTML, HTML print version and in PDF formats. Each issue of the IAG Newsletter in 2012, 2013 and 2014 contains a special IAG logo designed for the 150th anniversary of the IAG. We strive to publish only relevant information by keeping the Newsletter updated on a per-monthly basis. The IAG Officers, Individual Members, IUGG and JB GIS Presidents and Secretaries as well as interested persons mainly in developing countries (altogether about 900 addresses) received it each month in PDF and/or text attachments, with a link in the e-mail message to access the actual HTML Newsletter on the IAG website. Selected content of the electronic Newsletters were compiled and have been sent regularly to Springer for publication for 46 issues of the Journal of Geodesy (Vol 85/9 – 89/8). Starting from the double issue 82/11-12 the volume of the Springer IAG Newsletters is limited to 3-4 pages due to a change in the editorial policy to improve the impact factor of the journal. We try to publish only new and/or relevant material here as well.

4. Outreach Activities

The COB has been active in the publishing of information material in the reporting period. A new version of the IAG brochure has been published (16 coloured pages), which targets the wider public and decision makers by introducing Geodesy in general as well as the role of the Association to the readers (Ádám and Rózsa, 2013). It has a chapter on the Global Geodetic Observing System, and provides information on the IAG components (Commissions, Inter-Commission Committee, Services, etc.).

The brochure can be downloaded from the opening page of the IAG website, together with the updated IAG leaflet (Ádám and Rózsa, 2013).

J. Ádám and H. Drewes (2012) prepared a summary on "The International Association of Geodesy (IAG) – Historical Overview".

Naturally, the task of the COB is the IAG public relation in particular by maintaining the IAG Homepage and publishing the monthly Newsletter online and in the Journal of Geodesy. It also keeps track of all IAG related events by the meetings calendar.

Furthermore, various examples for IAG gifts were prepared (badges in 1000 pieces, key rings in 600 pieces, wooden pencils in 1000 pieces, caps with 5 segments in 200 pieces, muslin scarfs in 200 pieces and bag hook in 200 pieces, etc.) and merchandised during the 150th anniversary year at the SA in Potsdam in 2013.

5. Summary

In sum, the following activities were done:

a) the IAG website was updated, improved and continuously maintained;
b) the IAG Newsletter was regularly issued monthly and distributed electronically, and selected parts of them were prepared to publish in the Journal of Geodesy as IAG News;
c) new version of the IAG Leaflet was prepared, printed in 1000 copies and distributed at different IAG meetings;
d) the large IAG Brochure was reprinted in 1000 copies and distributed at different IAG meetings;
f) some works were made in preparation and for finalizing The Geodesist's Handbook 2012 (Drewes et al., 2012),
g) various examples for IAG presents (badges, key rings, caps, wooden pencils, scarfs, bag hook, etc.) were prepared to be distributed before, during and after IAG Scientific Assembly/150 Years Celebration, and
h) many e-mail correspondences to the community as part of the outreach activities.

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Global Geodetic Observing System (GGOS)

http://www.ggos.org

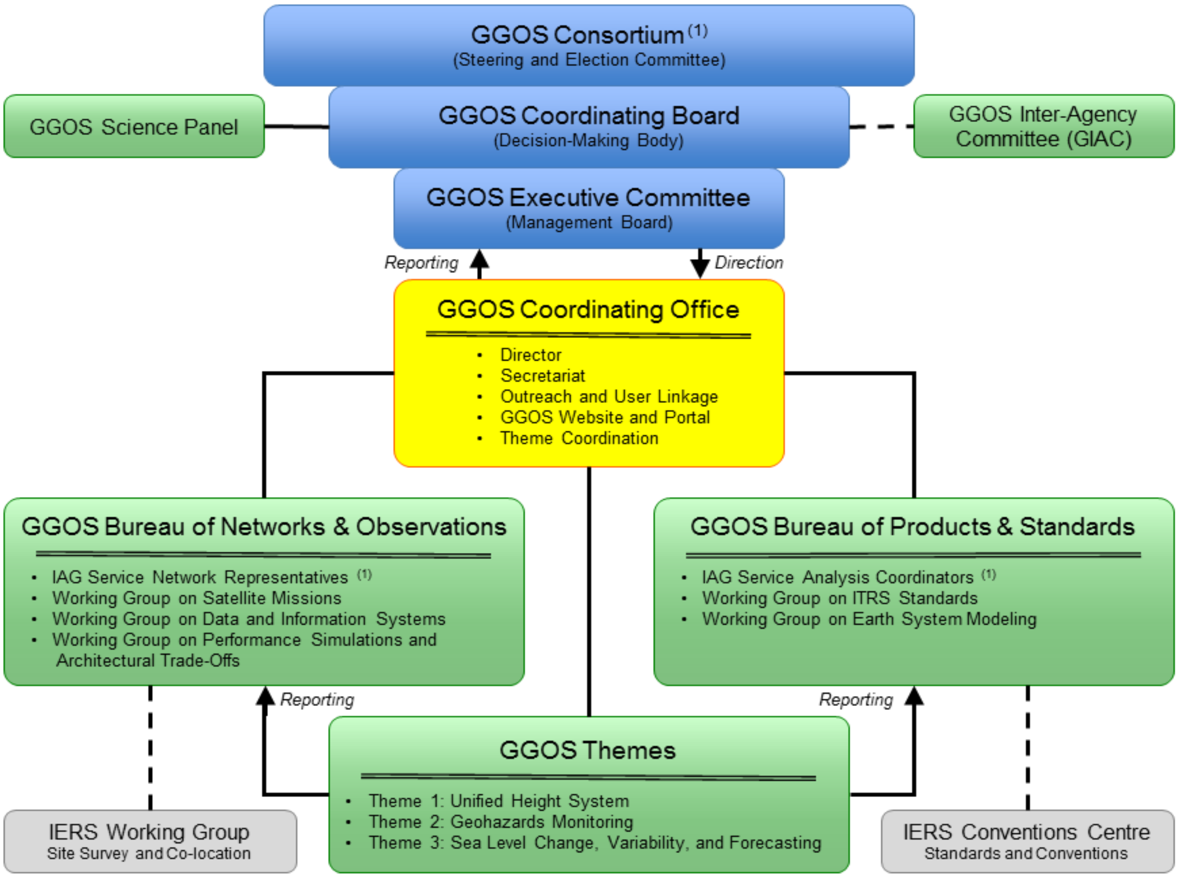
Chair: *Hansjörg Kutterer (Germany)*
Vice Chair: *Ruth Neilan (USA)*

As the observing system of the IAG, GGOS serves a unique and critically important combination of roles centering upon advocacy, integration, and international relations. GGOS also promotes high-level outcomes, such as the realization of the International Terrestrial Reference Frame through a variety of internal and external channels.

GGOS Structure and Overview

Structural Streamlining

In order to make optimal use of the GGOS structure introduced in 2011, streamlining efforts took place from late 2013 to early 2015, resulting in the following organizational structure:



[1] GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees

In this effort, the role of the Coordinating Office (CO) has been enhanced in order to best serve the Executive committee, Coordinating Board, and Consortium. The CO serves as a centralized administrative and organizational entity, and interacts with the Bureaus and Focus Areas (formerly Themes) for day-to-day organizational matters.

Working groups have been organized under one of the two bureaus, in order to make most efficient use of respective efforts. The Bureau of Standards and Conventions was renamed to the Bureau of Products and Standards, in order to better reflect its work as a bureau as well as its associated working groups. The Bureau of Networks and Communications was renamed to the Bureau of Networks and Observations, in order to better represent its work and the working groups within its authority.

Strategic Planning and Update of Terms of Reference

Starting with the 2013 Strategic Plan, GGOS has been making strides toward a goal, objective, and outcome-oriented strategic planning and implementation process. Subsequent yearly Strategic Implementation Plans have been drafted by the Science Panel, Coordinating Board, Coordinating Office, the Bureau of Networks and Observations, and the Bureau of Products and Standards. Each of the aforementioned components will use these plans to align their efforts with that of the overall Strategic Plan, and ensure progress toward the four GGOS goals.

In order to reflect the structural streamlining and strategic direction, the GGOS Terms of Reference have been updated in 2015.

GGOS Consortium

The GGOS Consortium is the collective voice for all GGOS matters. The elements of GGOS have the flexibility to determine and designate two representatives to the GGOS Consortium as each (Service, Commission, Inter-Commission Committee, or other entity) decides. The Consortium membership (see Table 1) is comprised of the Chairs of Services and the Directors of the Service's central offices or Central Bureaus; Presidents and Vice-Presidents of IAG Commissions, Inter-Commission Committees, and other entities essential to GGOS as determined by the Consortium. The GGOS Consortium is the nominating and electing body of elected positions on the GGOS Coordinating Board, with the Chair of GGOS acting as the Chair of the GGOS Consortium.

Table 1: Members of the GGOS Consortium (as of April 2015)

Services	Name	Title
GGOS	Hansjörg Kutterer	GGOS Chair
Int'l Gravimetric Bureau (BGI)	Sylvain Bonvalot	Director
Bureau International des Poids et Mesures (BIPM) - Time Section	Elisa Felicitas Arias	Director
International Altimetry Services (IAS)	Wolfgang Bosch Cheinway Hwang	Chair
IAG Bibliographic Service (IBS)	Annekathrin Michlenz	Chair
International Center for Earth Tides (ICET)	Jean-Pierre Barriot	Chair
International Centre for Global Earth Models (ICGEM)	Franz Barthelmes	Director
International Digital Elevation Model Service (IDEMS)	Philippa Berry R.G. Smith	Director
International Doris Service (IDS)	Laurent Soudarin Pascal Willis	Director Chair
International Earth Rotation and Reference Systems Service (IERS)	Daniela Thaller Thomas Herring	Director of the Central Bureau Analysis Coordinator
International Service for Geoid (ISG)	Mirko Reguzzoni Giovanna Sona	President Director
International Gravity Field Service (IGFS)	Riccardo Barzaghi Steve Kenyon	Chair Director of the Central Bureau
International GNSS Service (IGS)	Ruth Neilan Gary Johnston	Director Chair
The International Laser Ranging Service (ILRS)	Giuseppe Bianco Erricos Pavlis	Chair of Governing Board Analysis Coordinator
International VLBI Service for Geodesy and Astrometry (IVS)	Axel Nothnagel Dirk Behrend	Chair Coordinating Center Director
Permanent Service for Mean Seal Level (PSMSL)	Lesley J. Rickards Mark Tamisiea	Director

The Consortium meets annually, with the most recent meetings taking place in December of 2013 and 2014, in San Francisco, USA.

GGOS Coordinating Board

The GGOS Coordinating Board sets the strategic direction of GGOS in consultation with the GGOS Consortium and monitors the implementation of the adopted strategic plan. As such, the Coordinating Board monitors the GGOS Coordinating Office, which is tasked to manage and coordinate day-to-day activities leading to the fulfillment of strategic objectives. The Coordinating Board reports overall progress to the GGOS Consortium.

Table 2: Members of the GGOS Coordinating Board (as of April 2015)

Title	Name	Voting Rights
Voting Coordinating Board Members		
GGOS Chair	Hansjörg Kutterer	1 (voting)
Vice-Chair	Ruth Neilan	1 (voting)
Chair of GGOS Science Panel	Richard Gross	1 (ex-officio, voting)
Director of Coordinating Office	Giuseppe Bianco *(through April 2015)*	1 (ex-officio, voting)
Directors of GGOS Bureaus	Michael Pearlman Detlef Angermann	2 (ex-officio, voting)
IAG President (or designated representative)	Chris Rizos	1 (ex-officio, voting)
Service Representatives	Pascal Willis Ruth Neilan Erricos Pavlis Thomas Herring	4 (elected by the Consortium, voting)
IAG Commissions Representatives	Srinivas Bettadpur Tonie van Dam	2 (elected by the Consortium, voting)
Members-at-Large	Maria Cristina Pacino Yoichi Fukuda Yamin Dang	3 (elected by the Consortium, voting)
Non-voting Coordinating Board Members		
Chairs of GGOS Working Groups	Roland Pail Bernd Richter Maik Thomas Giuseppe Bianco Daniela Thaller	
Theme Leads	Michael G. Sideris Tim Dixon Tilo Schoene	
GGOS Portal Manager	Bernd Richter	
Immediate Past Chair of the CB	Markus Rothacher	
Representative of the GIAC/GIC	Per Erik Opseth	

The Coordinating Board answers to the GGOS Consortium for all of its assigned activities, and acts as the steering committee of GGOS, as outlined in the GGOS Terms of Reference. It meets twice per year, customarily the weekend before the EGU meeting in Vienna, Austria, and the AGU meeting in San Francisco, USA.

GGOS Executive Committee

The GGOS Executive Committee serves at the direction of the Coordinating Board to accomplish day-to-day activities of GGOS tasks. The membership (Table 3) consists of both ex-officio and elected positions, the latter of which is decided in a collaborative effort between the Chair and the Coordinating Board.

Table 3: Members of the GGOS Executive Committee

GGOS Executive Committee - April 2015	
Executive Committee Members	
GGOS Chair	Hansjörg Kutterer
GGOS Vice Chair	Ruth Neilan
Director of the GGOS Coordinating Office	TBD
Directors of the GGOS Bureaus	Michael Pearlman Detlef Angermann
Voting Members (elected by CB)	Erricos Pavlis Tom Herring
Permanently Invited Guests (ex-officio)	
Immediate Past Chair of GGOS	Markus Rothacher
Chair of the GGOS Science Panel	Richard Gross
President of the IAG *(or designated representative)*	Chris Rizos (Harald Schuh, IAG Vice President)
Invited Observers	
	Srinivas Bettadpur

GGOS Science Panel

Chair:	Richard Gross (USA)	
Members:	Jonathan Bamber (UK)	Sylvie Malardel (UK)
	Aleksander Brzezinski (Poland)	Rui Ponte (USA)
	Jim Davis (USA)	Matt Rodell (USA)
	Athanasios Dermanis (Greece)	Seth Stein (USA)
	Andrea Donnellan (USA)	Tonie van Dam (Luxembourg)
	Roger Haagmans (The Netherlands)	

Purpose and Scope

The GGOS Science Panel is a multi-disciplinary group of experts representing the geodetic and relevant geophysical communities that provides scientific advice to GGOS in order to help focus and prioritize its scientific goals. The Chair of the Science Panel is a member of the Coordinating Board and a permanent guest at meetings of the Executive Committee. This close working relationship between the Science Panel and the governance entities of GGOS ensures that the scientific expertise and advice required by GGOS is readily available.

Activities and Actions

The Science Panel provides scientific support to GGOS. During the 2011-2015 quadrennium this support included participation in Consortium, Coordinating Board, and Executive Committee meetings and conference calls.

The Science Panel continues to be involved in the GGOS Working Group on Performance simulations and Architectural Trade-Offs (PLATO) with the current Chair of the Science Panel, Richard Gross, being the Co-Chair of the Working Group.

The Science Panel has been actively promoting the goals of GGOS by helping to organize GGOS sessions at major scientific conferences. During the 2011-2015 quadrennium, GGOS sessions have been organized at:

- 2011 American Geophysical Union Fall Meeting in San Francisco
- 2012 American Geophysical Union Fall Meeting in San Francisco
- 2013 American Geophysical Union Fall Meeting in San Francisco
- 2014 American Geophysical Union Fall Meeting in San Francisco
- 2012 Asia Oceania Geosciences Society – American Geophysical Union Western Pacific Geophysics Meeting Joint Assembly in Singapore
- 2013 Asia Oceania Geosciences Society Annual Meeting in Brisbane
- 2014 Asia Oceania Geosciences Society Annual Meeting in Sapporo
- 2012 European Geosciences Union General Assembly in Vienna
- 2013 European Geosciences Union General Assembly in Vienna
- 2014 European Geosciences Union General Assembly in Vienna
- 2015 European Geosciences Union General Assembly in Vienna
- 2013 American Geophysical Union Meeting of the Americas in Cancun
- 2013 International Association of Geodesy Scientific Assembly in Potsdam

In addition to helping organize sessions at scientific conferences, the GGOS Science Panel also organizes topical science workshops in order to foster discussion about the geodetic observations and infrastructure required by different scientific disciplines. One such workshop was organized during 2011-2015:

> *International Symposium on Geodesy for Earthquake and Natural Hazards*
> *Matsushima, Miyagi, Japan; 22-26 July 2014*
>
> Monitoring temporal and spatial changes in the Earth's lithosphere is critical to disaster mitigation. Geodetic techniques, such as GNSS, SAR, satellite gravity missions, etc., have made significant contributions in this regard, and expectation for a greater role of the geodetic community is still growing. The Global Geodetic Observing System (GGOS) is one approach to move forward. In this symposium, 130 researchers from 16 countries met in Matsushima, northeastern Japan, to discuss the role of geodesy in disaster mitigation and how groups with different techniques can collaborate toward such a goal. A summary of the workshop was published in *Eos* [Hashimoto, M., R. Gross, and J. Freymueller, The Role of Geodesy in Earthquake and Volcanic Studies, *Eos Trans. AGU, 95*(42), 381, 2014] and peer-reviewed proceedings of the symposium will be published as a volume in the IAG Symposia series.

Objectives and Planned Efforts for 2015-2019 and Beyond

During the next quadrennium the Science Panel will continue to participate in Consortium, Coordinating Board, and Executive Committee meetings and conference calls as well as in the PLATO Working Group. In addition, the Science Panel will continue to help organize GGOS sessions at conferences and symposia including:

- American Geophysical Union Fall Meetings
- Asia Oceania Geosciences Society Annual Meetings
- European Geosciences Union General Assemblies
- International Association of Geodesy General and Scientific Assemblies

The Science Panel will also continue to organize topical science workshops in order to determine the requirements that different scientific disciplines have for geodetic data and products. The next such workshop will be held in conjunction with the *IAU/IAG/IERS Joint Symposium on Geodesy, Astronomy, & Geophysics in Earth Rotation* that will be held in Wuhan, China during 18-23 July 2016.

GGOS Bureau of Products and Standards

Chair:	Detlef Angermann (Germany)	
Co-Chair:	Thomas Gruber (Germany)	
Members:	M. Gerstl R. Heinkelmann U. Hugentobler	L. Sánchez P. Steigenberger
Associated Members and Representatives:	J. Ádám F. Barthelmes R. Barzaghi S. Bonvalot C. Boucher M. Craymer J. Gipso T. Herring	J. Ihde J. Kusche F. Lemoine E. Pavlis G. Pétit J. Ries M. Thomas
Working Groups affiliated with this Bureau:	GGOS Working Group on ITRS Standards GGOS Working Group on Earth System Modeling	

Purpose and Scope

The Bureau of Products and Standards (BPS) is a recent redefinition of the former Bureau for Standards and Conventions (BSC), which was established as a GGOS component in 2009. This redefinition is a consequence of a restructure of the GGOS organization in 2014. The Bureau is operated by the Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), the Lehrstuhl für Astronomische und Physikalische Geodäsie (APG) and the Forschungseinrichtung Satellitengeodäsie (FESG) of the Technische Universität München, within the Forschungsgruppe Satellitengeodäsie (FGS). The work of the BPS is primarily focused on the IAG Services and the products they derive on an operational basis for Earth monitoring making use of various space geodetic observation techniques such as VLBI, SLR/LLR, GNSS, DORIS, altimetry, gravity satellite missions, gravimetry, etc. The Bureau builds upon existing observing and processing systems of IAG and serves as a contact and coordinating point for the IAG Analysis and Combination Services. A representative from each of these services is included in the Bureau business as an Associated Member. Also associated with the BPS are two GGOS Working Groups: “Contributions to Earth system modeling” and “ITRS Standards” (their reports are given below).

The BPS supports the IAG in its goal to obtain products of highest possible accuracy, consistency, and temporal and spatial resolution, which should refer to a consistent reference frame, stable over decades in time. To achieve this important goal, it is a fundamental requirement that common standards and conventions are used by all IAG components for the analysis of the different space geodetic observations. The BPS also concentrates on the integration of geometric and gravimetric parameters and the development of new products, required to address important geophysical questions and societal needs.

Activities and Actions

Below is a summary of major activities and accomplishments achieved in the last two years:

- The BPS has compiled an inventory based on the standards and conventions currently in use by IAG and its components. The resulting publication "*GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG/GGOS Products*" has been reviewed by an external board and the revised version shall be published in the IAG Geodesist's Handbook 2016 and on the GGOS web site as a *living document*.
- As a major outcome this inventory presents the current status regarding standards and conventions, identifies gaps and inconsistencies and provides recommendations for improvements.
- The transition of the former BSC to the BPS, as a consequence of the restructure of the GGOS organization, has been accomplished, including the compilation of an implementation plan for the BPS and the associated GGOS components and the revision of its charter.
- The interaction between the BPS and the IAG Services as well as with other entities involved in standards and conventions has been strengthened by including representatives of these entities in the BPS board and by compiling a management plan.

Objectives and Planned Efforts for 2015-2017 and Beyond

Some major in-progress activities and planned efforts are summarized below:

- Publication of the inventory on standards and conventions in the IAG Geodesist's Handbook and on the GGOS web site as a *living document;*
- Discussion of recommendations given in the inventory and compilation of an action plan, including a task description, specification of responsibilities and time schedule;
- Evaluation of the current status of IAG/GGOS products, including an accuracy assessment with respect to the GGOS requirements;
- Initiation of efforts to identify user needs and requirements for products that are currently not provided by the IAG services;
- Supporting the GGOS Portal to provide the relevant information for IAG/GGOS products and contribute to promote geodetic products to the wider user community.

Website: http://ggos-bps.dgfi.tum.de

Selected Publications and Presentations

Angermann D., Gerstl M., Sánchez L., Gruber T., Hugentobler U., Steigenberger P., Heinkelmann R.: GGOS Bureau for Standards and Conventions: Inventory of Standards and Conventions for Geodesy. IAG Symposia 143, 2015

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sánchez L., Heinkelmann R., Steigenberger P.: Inventory of standards and conventions used for the generation of IAG/GGOS products. AGU Fall Meeting, San Francisco, USA, 2014 (Poster)

Angermann D.: Bureau for Standards and Conventions. Travaux, Vol. 38, Report of the International Association of Geodesy 2011-2013, 2013

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: The GGOS Bureau for Standards and Conventions. IAG Scientific Assembly, Potsdam, Germany, 2013

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: The need of common standards and conventions for homogeneous data processing and consistent geodetic products. EGU General Assembly, Vienna, Austria, 2013

Hugentobler U., Gruber T., Steigenberger P., Angermann D., Bouman J., Gerstl M., Richter B.: GGOS Bureau for Standards and Conventions: Integrated Standards and Conventions for Geodesy. In: Kenyon, S. C.; Pacino, M. C.; Marti, U. J. (eds.) Geodesy for Planet Earth, IAG Symposia, Vol. 136, pp 995-998, Springer, 10.1007/978-3-642-20338-1_124, 2012

GGOS Working Group on ITRS Standards

Chair: Claude Boucher (France)

Purpose and Activities

This group was initially established to investigate the strategy to obtain the adoption by the International Standardization Organization (ISO) of a standardization document related to ITRS.

Following the initial work done by the group, a proposal was submitted to ISO by France. This proposal was a New Work Item Proposal (NWIP) related to ITRS submitted to the ISO TC 211 on Geographical information, to which IAG is a liaison.

ISO finally decided that a preliminary study demonstrating the importance of geodetic references at large was necessary before going further in the direction of the initial proposal. A project (19161) was therefore established within ISO TC211 WG4 and chaired by Claude Boucher. The project report was finalized in January 2015, reviewed and finally submitted to WG4 for approval and decision of further actions.

Recommendations and Planned Efforts

The report ends with some recommendations :

- To develop a standard related to ITRS
- To make further studies about the interest and feasibility of a standard on vertical references
- To make similar action for universal identification of geodetic stations
- To work to improve geodetic terminology, including update of existing standards

The GGOS WG was in stand-by during this time. But assuming that the proposal about ITRS will be ultimately approved by ISO TC211, it seems opportune to reactivate this WG with a new mandate, namely drafting the document related to ITRS, and to update the membership of this WG.

GGOS Working Group on Contributions to Earth System Modeling

Chair: Maik Thomas (Germany)

Purpose and Scope

The GGOS Working Group on “Contributions to Earth System Modeling” was established in 2011 in order to promote the development of an integrated Earth system model that is simultaneously applicable to all geodetic parameter types, i.e., Earth rotation, gravity and surface geometry, and observation techniques. Hereby, the working group contributes to:

- a deeper understanding of dynamical processes in the Earth system integrally reflected in geodetic monitoring data;
- the establishment of a link between the global time series of geodetic parameters delivered by GGOS and relevant process models;
- a consistent integration and interpretation of observed geodetic parameters derived from various observation techniques;
- the utilization of geodetic observations for the interdisciplinary scientific community (in cooperation with GGOS WG on Data and Information Systems).

The overall long-term goal is the development of a physically consistent modular numerical Earth system model for homogeneous processing, interpretation and prediction of geodetic parameters with interfaces allowing the introduction of constraints provided by geodetic time series of global surface processes, rotation parameters and gravity variations. This ultimate goal implicates the following objectives:

- promotion of homogeneous processing of geodetic monitoring data (de-aliasing, reduction) by process modeling to improve analysis of geodetic parameter sets;
- contributions to the interpretation of geodetic parameters derived from different observation techniques by developing strategies to separate underlying physical processes;
- contributions to the integration of geodetic observations based on different techniques in order to promote validation and consistency tests of various geodetic products.

Current activities focus on

- the development of consistent standards, parameters, analysis strategies and formats for all components of the unconstrained modular system model approach;
- the identification of relevant interactions among subsystems and appropriate parameterizations, in particular to represent the dynamic links between near-surface fluids and the “solid” Earth;
- the development of strategies for the separation of temporal variations of Earth rotation, gravity and geoid into individual causative physical processes.

Activities and Actions

Concerning the main task of the WG, i.e., the establishment of a physically consistent modular system model for near-surface dynamics, the work concentrated on the realization of global mass conservation and the development of appropriate modules for the consideration of interactions with the lithosphere. In order to ensure mass conservation in the modular system model approach various correction algorithms have been implemented, compared and validated. It could be demonstrated that inconsistencies due to different grid characteristics, parameterizations and spatiotemporal resolutions of the sub-models can be minimized by most of the investigated correction algorithms. However, several problems in achieving physical consistency cannot be solved by the WG itself. This is mainly due to the fact that these difficulties can only be tackled by adequate source code developments, what is mainly the task of communities which are not focusing on geodetic observables. It is a remaining challenge to motivate these communities to remedy these deficiencies, e.g., by demonstrating the high potential of geodetic quantities in getting new insights into Earth system dynamics.

Closely related to physical consistency of sub-system models is the definition of parameter standards and of standard modules and analysis strategies for forward simulations of geodetic quantities. In several discussions it was pointed out that an achievement of these initial objectives of the WG would probably not adequately satisfy the demands of the geodetic community. Ground based, airborne and satellite based geodetic observations reflect Earth system processes on a broad range of spatial and temporal scales. The interpretation and prediction of variations of these observables require different geophysical models tailored to specific processes acting on various spatiotemporal scales. Thus, the availability of diverse model approaches and the provision of diverse model solutions does not only promote interpretations, but also offers opportunities to estimate model errors, e.g., by multi-model analyses.

The elastic response of the "solid" Earth to short-term variations of surface loading is usually modeled by applying a local isostatic model or a one-dimensional spherical Earth model from which unique sets of elastic Love numbers or elastic Green's functions are derived. These approaches implicitly ignore lateral inhomogeneities in the Earth's crustal structure. To overcome this drawback in the representation of interactions between atmosphere-hydrosphere and lithospheric dynamics a set of local Green's functions for a three-layer crustal structure has been derived. Time series of site displacements due to hydrological loading derived from model simulations applying these local Green's functions are operationally provided to the community via the GGFC/IERS Combination Center.

Objectives and Planned Efforts for 2015-2017 and Beyond

Important in-progress activities and future efforts focus on

- feasibility studies for the provision of error estimates of model-based predictions of geodetic quantities (EOP, deformation, gravity variations);
- application of forward modeling and inversion methods in order to predict geodetic quantities and to invert geodetic observations for the underlying causative processes;
- the preparation of numerical algorithms for the assimilation of geodetic products into the numerical system model approach in order to provide a tool for validation and consistency tests of various monitoring products.

GGOS Bureau of Networks and Observations

Prepared by Michael Pearlman, Carey Noll, Erricos Pavlis, Chopo Ma, Ruth Neilan, Frank Lemoine, Daniela Thaller, Bernd Richter, Roland Pail, and Sten Bergstrand

Director: Michael Pearlman (USA)

Deputy Director: TBD

Associated Members and Representatives:

- Director (Mike Pearlman/CfA),
- Secretary (Carey Noll/NASA GSFC),
- Analysis Specialist (Erricos Pavlis/UMBC),
- A representative from each of the member Services,
- A representative from the IERS, and
- A representative from each of the member working groups including the Missions Working Group, the PLATO WG, the Data and Information Working WG, and the IERS Survey and Co-location WG.

Working Groups affiliated with this Bureau:

- GGOS Working Group on Satellite Missions
- GGOS Working Group on Data and Information Systems
- GGOS Working Group on Performance Simulations and Architectural Trade-Offs (PLATO)
- IERS Working Group on Survey and Co-location

Purpose and Scope

The Bureau was organized to advocate for the implementation of ground system networks of sufficient global distribution and measurement capability to address the Earth Science and societal benefit requirements set by GGOS. At the base of GGOS are the sensors and the observatories situated around the world providing the timely, precise, and fundamental data essential for creating space geodesy products designated by GGOS. The Bureau has now been restructured into the Bureau of Networks and Observations to:

- Expand its role with the other services and techniques (gravity, tide gauges, etc.);
- Improve communication and information exchange and coordination with the space missions;
- Formally include the simulation activities;
- Formally include the site-tie component at core and co-located sites; and
- Include the Data and Information Systems activity.

Core sites are those with co-located SLR, VLBI, GNSS and DORIS (where available). Co-location sites are those with either SLR or VLBI, plus GNSS or DORIS. At some point it is anticipated that the complex of instruments will be expanded to include gravity field and other surface measurements.

To date, primary emphasis has been placed on improving the infrastructure needed to provide the evolving global reference frames. Studies and simulations tell us that we will need the equivalent of 32 new technology core sites with VLBI, SLR, GNSS and DORIS to achieve a reference frame that will permit mm accuracy at 0.1 mm/year stability over decades as specified by GGOS. A major focus of Bureau has been improved network capability, geographic coverage, and upgrade of the Core and Co-location Network sites necessary for the improvement of the reference frames. Activities include advocating for new and increased participation, encouraging formation of new partnerships to develop new sites, monitoring the status of the networks and projecting their future capabilities.

The Bureau has now been expanded to better define the requirements and integrate the non-geometric services of the IAG (gravity service, tide gauge networks, etc.) into the GGOS affiliated network. The expansion of the Bureau also includes capability to strengthen communication with the space missions, provide simulation activities to project network capability, improve data archiving/access functions, and standardize and improve site ties.

The Bureau looks to the GGOS Science Council and the Executive Committee for overall direction, but also recognizes that scientific and societal benefits will accrue through connection among ground based techniques and close support for satellite missions.

Elements within the Bureau are intended to work as an integrated team whose main focus is to deploy and upgrade the ground networks to collect the data necessary to support the required space geodesy data products. The Bureau consists of the following organizational elements:

- Services Network Representation (IGS, IVS, ILRS, IDS, IGFS, tide gauge network, etc.)
- Working Groups
  - Missions
  - Performance Simulations & Architectural Trade-Offs (PLATO)
  - Data and Information Systems
  - Ground Survey and Co-location (IERS WG)

The Bureau of Networks and Observations is the Bureau of the Services; it is run by the services and advocates for the services, and brings to GGOS the point of view of the services in policy and decision-making.

The Role of the Bureau is:

- Provide a forum for the Services and Working Groups to share and discuss plans, progress, and issues, and to develop and monitor multi-entity efforts to address GGOS requirements;
- Actively promote, sustain, improve and evolve the integrated global geodetic ground-based infrastructure needed to meet requirements for Earth science and societal benefits;
- Lead efforts for the integration of various ground observation networks within the GGOS affiliated Network;
- Coordinate the international geodetic services' activities that are the main source of key data and products needed to realize stable global reference frames and other data products essential to study changes in the dynamic Earth System and characterize key Earth Science parameters for societal benefits.

Activities and Actions

Meetings

Since 2009, the Bureau holds regular meetings, typically in conjunction with scientific meetings such as the Fall AGU and EGU; thus far, a total of thirteen Bureau meetings have been organized in this manner. These meetings provide a forum for various entities and service representatives to present progress and future plans. All presentations given during these meetings, summaries, and lists of attendees are available through the Bureau website (http://www.ggos.org/Components/BNC/BNChome.html).

GGOS Affiliated Network Developments

In August 2011 the Bureau developed and issued a Call for Participation (CfP) in the "Global Geodetic Core Network: Foundation for Monitoring Earth System" for the development, implementation, and operation of the GGOS affiliated core network. The long-term goal of the core network is to implement a global network of ground-based space geodetic sites that provide 1 mm and 0.1mm/year quality measurements to satisfy the GGOS Scientific Objectives (GGOS 2020). The network will evolve over time with new technologies replacing legacy technologies and new sites being established. The quality of geodetic data products will improve as the network progresses. With the long horizon required to achieve the full core network, sites with co-located, but less than the full core configuration, will continue to play a vital role in the evolution of the data products.

A total of 19 submissions were received covering 114 sites that included legacy core sites, legacy/new technology co-location sites, core and co-location sites under development, and sites offered for future participation; a summary of the CfP responses is available on the Bureau's website: (http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_CfPResponseSummaries_20150106.pdf).

Related Bureau Documentation

As part of the Core Network activity, the Bureau has facilitated the creation of several key documents:

- "GGOS Site Requirements for Fundamental Stations" document: http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_SiteReqDoc_1207.pdf
- A guidelines document for site characterization of the GGOS network sites was developed, "The Global Geodetic Core Network: Foundation for Monitoring the Earth System": http://192.106.234.28/Components/BNC/update%20Apr2013/GGOS_sitecategorization.pdf
- A plan to define the process by which GGOS determines the extent of the needed infrastructure, including the scope and specification of the network, conditioned on the existing or plausible technology available, "GGOS Infrastructure Implementation Plan": http://192.106.234.28/Components/BNC/GGOS_Infrastructure_Plan_V3_130321.pdf
- A plan to assess the current and future plans for a GGOS core network, including projections five to ten years in the future, "Space Geodesy Network Model": http://192.106.234.28/Components/BNC/candidatesites_130122.pdf
- Documents developed within the context of NASA's Space Geodesy Project, evaluating several sites as potential core sites; these documents are available from the SGP website at: http://space-geodesy.gsfc.nasa.gov/publications/papers.html
- A summary report issued from the TLS (Terrestrial Laser Scanner) Workshop that was held at NASA GSFC, September 08-10, 2008: http://192.106.234.28/Components/BNC/Summary%20report%20from%20the%20TLS%20(Terrestrial%20Laser%20Scanner).pdf

Objectives and Planned Efforts for 2015-2017 and Beyond

Plan for the Next Reporting Period

In its role to support the services and better serve the users, the GGOS Bureau of Networks and Observations will:

- Advocate for implementation of the global space geodesy network of sufficient capability to achieve data products essential for GGOS;
  - Update the Bureau section of the GGOS website for public use including status, plans, and issues for the Bureau entities (June 2015);
  - Provide status and plans reports from the Bureau at EGU, AOGS (August 2015), AGU (December 2015) and other public meetings; (April 2015),
  - Continue the Bureau Call for Participation and work with new potential groups interested in participation;
  - Meet with interested parties and encourage partnerships;
- Provide a forum for the Services and Working Groups to meet, discuss status and plans, and examine common interests and requirements;

– Organize meeting at EGU, AGU, and other opportunities;

- Update the Site Requirements Document (with the IAG Services) (July 30, 2015);
- Monitor and project the status and evolution of the GGOS space geodesy network in terms of location and performance (with the IAG Services);
  - Issue next questionnaire and compile responses (June 30, 2015};
- Coordinate the effort of the services to implement procedures to provide test-based estimates of their data quality and report (First discussion at the Bureau's meeting at EGU 2015);
- Facilitate efforts to integrate other ground networks (gravity field, tide gauges, etc.) into the GGOS Network to support GGOS requirements (progress report at EGU 2016);
- Support the technical services on the promotion of recommended technologies/configurations and procedures in the establishment of new sites and the upgrading of current sites, and in the evaluation of performance of new stations and new capabilities after they become operational;
- Working Group on PLATO: Project future network capability and examine trade-off options for station deployment and closure, technology upgrades, impact of site ties, etc.
  - Using simulation techniques already established, use the updated stations status and projections to project network capability over the next 5 and 10 years periods (first report EGU 2015 by Pavlis);
  - Based on the updated station projections, estimate the GNSS tracking load that the SLR Network can sustain (Bureau meeting at AGU 2015);
  - Make recommendations on network configuration based on simulations and trade-off studies.

    For more details see see the PLATO WG subsection, below.

    - Working Group on Data and Information: Develop a metadata strategy for all ground-based measurement techniques (WG on Data and Information)
  - Develop a document summarizing the need, the activities underway by independent groups, and the pertinent references (June 2015);

– Organize a meeting of the interested parties to discuss how we can integrate/utilize the separate space geodesy metadata activities, and provide organizational oversight to carry it through (October 2015).

  For more detail see WG on Data and Information Systems subsection, below.

- Working Group on Missions: Improve coordination and information exchange with the missions for better ground-based network response to mission requirements and space-segment adequacy for the realization of GGOS goals
  – Agree in the content and develop a missions section on the GGOS website for public assess; implement a procedure to keep the section up-to-date (September 2015);
  – Review of inventory/repository of current and near-future satellite missions (Bureau meeting at EGU 2016);
  – Evaluation of contribution of current and near-future missions to GGOS goals (Bureau meeting at AGU 2016)
  – Finalize Science and User requirements document for future gravity missions with IGFS and forward to the IUGG via ESA for formulation into a joint resolution (June 2015);

  For more detail see the WG on Satellite Missions subsection, below.

  - IERS Working Group on Survey and Co-location: Standardize site-tie measurement, archiving, and analysis procedures, maintain a current site-tie archive; and encourage additional groups to help support the network site-tie task
  – Develop a guidelines document of standard nomenclature (December 2015);
  – Develop a plan for an outreach approach to station managers at co-location sites to stress the need for accurate local ties and the need for seeking local survey capability; Stress outreach to surveying teams in China, Russia and Japan in order to establish common guidelines (EGU 2016);
  – Coordinate the effort of the services to implement procedures to determine system reference points and their accuracies (First discussion Bureau meeting in April 2015);

  For more detail see the IERS WG on Survey and Co-location subsection, below.

- Support GGOS submissions to GEO, CEOS and other international organizations.

The evolution of the networks will be a long-term endeavor (10-20 years), but the evolution in the networks, including both the core and participating co-location sites, and the associated modeling and analyses will provide steady and very useful improvements in the data products. The evolving data and data products will be a major driver for developing and validating of the new models and analysis techniques.

Website: See (http://www.ggos.org/Components/BNC/BNChome.html).

Publications and Presentations

M. Pearlman, E. Pavlis, C. Ma, Z. Altamimi, C. Noll, D. Stowers, "Space Geodesy Networks to Improve the ITRF", Abstract EGU2011, presented at EGU 2011-4786 General Assembly, Vienna Austria, April 04-08, 2011.

M. Pearlman, E. Pavlis, C. Ma, Z. Altamimi, C. Noll, D. Stowers, "Ground Based Space Geodesy Networks Required to Improve the ITRF", presented at the International Symposium on Space Geodesy and Earth System, Shanghai, China, August 18-20, 2012.

M. Pearlman, C. Ma, E. Pavlis, C. Noll, S. Wetzel, J. Park, R. Neilan, A. Ipatov, "Evolution of the Global Space Geodesy Network", Abstract EGU2013-3554, presented at EGU 2013 General Assembly, Vienna, Austria, April 07-12, 2013.

M. Pearlman, E. Pavlis, C. Noll, C. Ma, S. Wetzel, G. Appleby, R. Neilan, "GGOS Global Space Geodesy Networks and the Role of Laser Ranging", Abstract 13-0203, presented at the 18th International Workshop on Laser Ranging, Fujiyoshida, Japan November 11-15, 2013.

M. Pearlman, E. Pavlis, C. Ma, C. Noll, R. Neilan, D. Stowers, S. Wetzel, "The GGOS Global Space Geodesy Network and its Evolution", Abstract G53C-01, presented at 2013 Fall AGU Meeting, San Francisco, CA, December 9-13, 2013.

M. Pearlman, A. Ipatov, J. Long, C. Ma, S. Merkowitz, R. Neilan, C. Noll, E. Pavlis, V. Shargorodsky, D. Stowers, S. Wetzel, "The Global Space Geodesy Network: Activities Underway", Abstract EGU2014-3140, presented at EGU 2014, Vienna Austria, April 28-May 02, 2014.

M. Pearlman, "The Role of CORE and Co-location Sites and the Activities Underway to Improve the Global Space Geodesy Network", Abstract 3044, presented at the 19th International Workshop on Laser Ranging, Annapolis MD, Oct. 27-31, 2014.

M. Pearlman, A. Ipatov, F. Lemoine, J. Long, C. Ma, S. Merkowitz, R. Neilan, C. Noll, E. Pavlis, H. Schuh, V. Shargorodsky, D. Stowers, S. Wetzel, "The Expanding Core and Co-location Space Geodesy Network and the Importance of High Latitude Sites", presented at Fifth Symposium on Polar Science, December 02-05, 2014.

M. Pearlman, C. Ma, C. Noll, E. Pavlis, H. Schuh, T. Schoene, R. Barzaghi, S. Kenyon, "The GGOS Bureau of Networks and Observations and an Update on the Space Geodesy Networks", Abstract EGU2015-7420, presented at EGU 2015 General Assembly, April 13-17, 2015, Vienna, Austria, April 12-17, 2015.

GGOS Working Group on Satellite Missions

Chair: Roland Pail (Germany)
Co-Chair: Jürgen Müller (Germany)

Purpose and Scope

The GGOS Satellite Mission Working Group (SMWG) is established in December 2008, under the lead of C.K. Shum, and more than 20 members agreed to serve on this Working Group. In December 2010, Isabelle Panet was appointed as new Chair, and in December 2013 Roland Pail took over the Chair.

The purpose and scope is the coordination, advocating and information exchange with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals.

The SMWG is set-up as an international panel of experts, with consultants of national and international space agencies.

Satellite missions are a prerequisite for monitoring change processes in the Earth system on a global scale with high temporal and spatial resolution. Therefore, beyond purely scientific objectives they meet a number of societal challenges, and they are an integral part of the GGOS infrastructure and essential to realize the GGOS goals. The aspiration of the SMWG is to monitor the availability of satellite infrastructure, to propose and to advocate new missions or mission concepts, especially in case that a gap in the infrastructure is identified.

Activities and Actions

1. *Assessment of current and near-future satellite infrastructure, and their compliance with GGOS 2020 goals*

   An inventory of the GGOS satellite infrastructure has been finalized, and a list of satellite contributions to fulfil the GGOS 2020 goals is close to finalization. First steps towards identifying gaps in the future GGOS satellite infrastructure, to gather needs for future mission in order to achieve the GGOS 2020 goals, have been done.

2. *Support of proposals for new mission concepts and advocating needed missions*

   SMWG initiated and discussed an IUGG resolution (Melbourne, 2011) regarding the importance of future potential field missions, and initiated a letter from IUGG, signed by the IUGG president, to NASA and ESA headquarters to emphasize this resolution.

   Initiation and organization of an International Workshop on the “Consolidation of Science and User Requirements for a next gravity field mission configuration”, which was organized and held in Herrsching, 26./27. September 2014. Under the umbrella of IUGG and GGOS, a working team of more than 50 international lead scientists in the disciplines continental hydrology, cryosphere, ocean, and solid Earth agreed on consolidated science and user requirements for a sustained future satellite gravity observing system. This document is input to a joint ESA/NASA working group on a next generation gravity mission constellation (beyond GRACE-FO).

3. *Interfacing and outreach*

   The SMWG is consultant for the GGOS EC concerning CEOS issues. Close cooperation exists to the Bureau of Standards and Products, and the Sub-Commissions 2.3 and 2.6 of IAG. Additionally, there are strong interfaces to national and international space agencies.

Objectives and Planned Efforts for 2015-2017 and Beyond

- Work with the Coordinating Office to set up and maintain a Missions WG section on the GGOS website;
- Set-up and maintain an inventory/repository (accessible through the GGOS Website and/or Portal) of current and near-future satellite missions;
- Evaluate the contribution of current and near term satellite missions to the GGOS2020 goals;
- Work with the Focus Areas (formerly Themes) and the Science Committee to establish the required mission roles and to identify the critical gaps in mission infrastructure;
- Work with GGOS Executive Committee, Focus Areas, and data product development activities (e.g. ITRF) to advocate for new missions to support GGOS goals
- Support the Executive Committee and the Science Committee in the GGOS Interface with space agencies,
- Support the GGOS position at the next CEOS/GEO, etc. Meeting.

Action no.	Action	KO + 6 m	KO + 12 m	KO + 18 m	KO + 24 m
001	Set-up of Mission WG section on GGOS website				
002	Maintenance of Mission WG section on GGOS website				
003	Review of inventory/repository of current and near-future satellite missions				
004	Maintenance of inventory/repository of current and near-future satellite missions				
005	Evaluation of contribution of current and near-future mission to GGOS 2020 goals				
006	Interfacing with Focus Areas (formerly Themes) and GGOS Science Committee to identify critical gaps in the satellite infrastructure				
007	Finalization and publishing (outreach) of Science and User Requirements Document for future gravity field mission				
008	Support advocating of new missions				
009	Supporting GGOS EC and SC in the interfacing with space agencies				
010	Supporting GGOS positions in preparation to CEOS/GEO meetings				

These tasks will require interfacing with other components of the Bureau, especially the ground networks component, the simulation activity (PLATO), as well as the Bureau of Standards and Products.

Publications and Presentations

Pail R., Bingham R., Braitenberg C., Eicker A., Horwath M., Longuevergne L., Panet I., Rolstad-Denby C., Wouters B. (2015): Consolidated science and user requirements for a next generation gravity field mission. Geophysical Research Abstracts, Vol. 17, EGU2015-1648, EGU General Assembly 2015.

Pail R., Bingham R., Braitenberg C., Eicker A., Floberghagen R., Haagmans R., Horwath M., Johnson T., Longuevergne L., Panet I., Rolstad-Denby C., Wouters B. (2014): **Consolidated science requirements for a next generation gravity field mission.** 5th International GOCE User Workshop, Paris, 28.11.2014

GGOS Working Group on Data and Information Systems

Prepared by Carey Noll and Bernd Richter
Chair: Bernd Richter (Germany)
Co-Chair: Carey Noll (USA)

Role (Goals and Objectives)

- Promote the use of metadata standards and conventions and recommend implementations of metadata management for GGOS in the pursuit of a metadata policy;
- Promote interoperability among participating data centers with other databases and services;
- Develop strategies to protect the intellectual properties on data and products;
- Align metadata standards with GEOSS approach and methodology, interface on data standards with to GEO and ICSU.

The current focus of the WG is on developing standards for metadata that can be utilized by the space geodesy community. Metadata typically encompass critical information about the measurements that are required to turn these measurements into usable scientific data. Metadata also includes information that supports data management and provides a foundation for data discovery. Data centers extract metadata from incoming data sources and also augment that metadata with information from other sources. It is typical for data centers to store the metadata in databases in order to manage the data in their archives and to distribute both data and metadata to data users. Metadata can further be utilized by data discovery applications to allow users to find data sets of interest. In order to be effective, metadata need to be simple to generate and maintain. They must be consistent and informative for the archivist and the user.

GGOS is seeking a metadata schema that can be used by all of its elements for standardized metadata communication, archiving, and retrieval. First applications would be automated distribution of up-to-date stations configuration and operational information, data archives and catalogues, and procedures and central bureau communication. Several schemas that show promise have been under development by SOPEC (Scripps), GML (Australia/NZ), etc. The intent is that data need be entered only from an initial source (a station, a Data Center, an Operations Center, data products, etc.) and would then flow to and be integrated into those metadata files where users would have access. The plan is to organize a meeting, probably in early August at UNAVCO in Boulder, for representatives from the Services, the Data Centers, the Science Community, etc. to give each of the schema developers an opportunity to preach his wears and allow discussion on the pros and cons of each.

The objective is to try to come to closure on a schema that we could as a community adopt for general implementation. Groups would not be obligated to a rapid implementation schedule, but would commit to the agreed schema when they are ready to begin the process.

Tasks

- Develop a document summarizing the need, the activities underway by independent groups, and the pertinent references (June 2015);
- Organize a meeting of the interested parties to discuss how we can integrate/utilize the separate space geodesy metadata activities, and provide organizational oversight to carry it through (August 2015).

Gary Johnston has agreed develop a white paper to spell out the need and the plan to use as a basis for a Call for Participation in the meeting to be issued by the Bureau. This workshop is currently planned for August 2015 in Boulder, CO.

Organization

The WG will is currently chaired by Bernd Richter with current co-chair Carey Noll. Additional members with interest in data management within the services perform necessary research, provide material for the website, presentation material, and other documentation.

Reporting

The Working Group will give oral (PPT) reports on accomplishments, tasks underway, plans, and current obstacles at each of the Bureau meetings. Written reports may sometimes be required for Bureau reporting as required by the GGOS leadership. The WG will maintain a page on the GGOS website to keep the community aware of progress and work underway.
A report summarizing the planned metadata workshop and including actions and plans will be issued.

GGOS Working Group on Performance Simulations & Architectural Trade-Offs (PLATO)

Prepared by Daniela Thaller
Chair: Daniela Thaller (Germany)
Co-Chair: Richard Gross (USA)

Role (Goals and Objectives)

- Use simulation techniques to assess impact on reference frame products of: network configuration, system performance, technique and technology mix, co-location conditions, site ties, and space ties (added spacecraft, etc.);
- Use and develop improved analysis methods for reference frame products by including all existing data and available co-locations (i.e., include all satellites and use all data types on all satellites);
- Make recommendations on network configuration based on simulations and trade-off studies.

Tasks:

- Develop optimal methods of deploying next generation stations, and estimate the dependence of reference frame products on ground station architectures;
- Estimate improvement in the reference frame products as co-located and core stations are added to the network;
- Estimate the dependence of the reference frame products on the quality and number of the site ties and the space ties;
- Estimate the improvement in the reference frame products as other satellites are added, e.g., cannonball satellites, LEO, GNSS constellations;
- Estimate the improvement in the reference frame products as co-locations in space are added, e.g., use co-locations on GNSS and LEO satellites, add special co-location satellites (GRASP, NanoX, etc.);
- In support of the SLR tracking on GNSS satellites, use an agreed measure of SLR ranging performance, to examine optimal tracking strategies, and to develop the optimal deployment of the tracking data for reference frame products;
- Conduct simulations for co-location satellites – how much would it help us? How many data do we need? How accurately do we need to know the dimensions on the satellite and other s/c-related parameters (e.g., ties between instruments on board, satellite attitude);

Organization

The WG will have a chair, a co-chair and WG team members who will be involved with the planning and conduct of the simulations and the extended analysis methods. The WG will define the roles for its members' participation. Associate members may attend meetings, provide information, and contribute to the discussion.

The Chair and Co-Chair are Daniela Thaller and Richard Gross.

The Working Group will establish liaisons with the networks entity, the other GGOS working groups (e.g., Satellite Missions) and the Focus Areas (formerly Themes) to enhance communication and coordination, and other GGOS and IAG entities as necessary, especially the IERS WG on Site Survey and the ILRS Working Group LARGE.

Reporting

The Working Group will give oral (PPT) reports on accomplishments, tasks underway, plans, and current obstacles at each of the Bureau meetings. Written reports may sometimes be required for Bureau reporting as required by the GGOS leadership. The WG will maintain a page on the GGOS website to keep the community aware of progress and work underway.

The WG members will give presentations at scientific conferences about their individual contributions to fulfill the WG tasks. Publications in appropriate journals are also envisaged.

IERS Working Group on Survey and Co-location

Chair: Sten Bergstrand (Sweden)
Co-Chair: John Dawson (Australia)

Role (Goals and Objectives)

- Work with the IGN to maintain a comprehensive site survey and site tie data base;
- Standardize site-tie measurement procedures, standards and analyses techniques;
- Work with the Data Centers to have results from all of the site tie measurement;
- Work with the IERS, the Services and GGOS to encourage more groups to gain site tie survey and analysis capability;
- Help set site tie measurement priorities.

Tasks

- The IGN is working on a guideline document of standard nomenclature to overcome the present confusion among survey groups and between survey groups and users;
- Survey responsibilities have been too widespread and uncoordinated; knowledge on procedures and processing must be shared; dedicated point of contact with each of the Services have been assigned, The WG will try to reach out to surveying teams in China, Russia and Japan in order to establish common guidelines. The WG is discussing an out-reach approach to station managers at co-location sites to stress the need for accurate local ties and the need for seeking local survey capability;

  Issue: Do we need a policy shift for local ties?
  As long as there are researchers performing measurements and they thrive on publications, how can we increase the number of local ties? Publications rely on novelty, production on consistency. A remake of a local tie survey should ideally use exactly the same procedure and hopefully produce equivalent results. How do you publish local tie number two?

Organization

The WG will have a chair, a co-chair and WG team members who will be involved with the planning and conduct of WG activities. The WG will define the roles for its member's participation.

The Working Group will establish liaisons with the networks entity, the other working groups and the Themes to enhance communication and coordination, and other GGOS and IAG entities as necessary.

Reporting

The Working Group will give oral (PPT) reports on accomplishments, tasks underway, plans, and current obstacles at each of the Bureau meetings. Written reports may sometimes be required for Bureau reporting as required by the GGOS leadership. The WG will maintain a page on the GGOS website to keep the community aware of progress and work underway.

GGOS Focus Area 1: Unified Global Height System

Chair: Michael G. Sideris (Canada)
Co-Chair: Johannes Ihde (Germany)

Members: Colleagues who have contributed to the work of Theme 1 are basically the members of the JWG 0.1.1 and the Height System Unification ESA project (listed on the web sites given below)

Purpose and Scope

The main objective of Focus Area 1 (formerly Theme 1) is the unification of the existing vertical reference systems around the world through the definition and realization of a global vertical reference system that

- will support geometrical (ellipsoidal) and physical (normal, orthometric, geoidal) heights world-wide with centimetre precision (10^{-9}) in a global frame;
- will enable the unification of all existing physical height systems (i.e., all geopotential differences shall be referred to one and the same reference equipotential surface with potential W_o); and
- will provide high-accuracy and long-term stability of the temporal height changes (dh/dt, dH/dt, dN/dt) with 10^{-9} precision.

A World Height System (WHS) shall be realized with a global combined network, which will integrate at set of terrestrial reference stations high-precision absolute and relative gravity, levelling with gravity reductions, and GNSS and tide gauge observations. For this purpose, it will use contributions from all IAG Commissions, and the available databases, standards and infrastructure of the IAG/GGOS Services.

Activities and Actions

During the last four years, the Theme members developed and worked on a set of short- and medium-term goals. The short-term ones can be summarized under the banner "Establish a global vertical reference surface and its geopotential value W_o", and include the following:

1. Refinement of standards and conventions for the definition and realization of a WHS, including unification of standards and conventions that are used by the "geometry" and "gravity" Services of the IAG.
2. Establishment of a global vertical reference level.

The work of items #1 and #2 was accomplished by the Joint (Theme 1 with Commissions 1 and 2, and IGFS) Working Group JWG 0.1.1: Vertical Datum Standardization, chaired by L. Sánchez. The main purpose of the joint working group is to provide a reliable W_0 value to be introduced as the conventional reference level for the realization of a Unified Global Height System. The activities of JWG 0.1.1 during the reporting period concentrated on the empirical estimation of this value using the newest available representations of the Earth's surface and gravity field. The computation of a new *best estimate* for the global W_0 value has been accomplished, and a suitable W_0 as reference level for the Unified Heights System shall be recommended. This recommendation should be supported by an IAG resolution focused on the establishment of an International Height Reference System and to be adopted in the IUGG General Assembly in Prague. Activities and results of this working group were presented in

regional conferences and the 2013 IAG Scientific Assembly in Potsdam, and the 3rd IGFS General Assembly, in July 2014 in Shanghai.
The medium-term goals can be summarized under the banner “Develop GGOS products for the realization of a WHS”, and include the following:

3. Recommendation for a global vertical reference frame.
4. Guidelines/procedures for height system unification.

Regarding #3, members of GGOS Theme 1 and the Bureau for Standards and Conventions (BSC) prepared in 2014 a Proposal for the Definition and Realization of an International Height Reference System (IHRS); available from Johannes Ihde. Besides its importance to science in general, such an IHRS is also needed for GGOS’s Theme 3 - Understanding and Forecasting Sea-Level Rise and Variability, and for the joint activities of the IAG Commission 2 - Gravity Field and the Consultative Committee for Mass and related quantities (CCM) that have to agree on a Strategy for Metrology in Absolute Gravimetry. It is urgently necessary to remove the inconsistencies between geometric products and products related to the Earth’s gravity field, in order to enable the development of integrated geodetic applications. Taking a broader view, GGOS and IAG should maybe support the establishment of an International Height and Earth Gravity Reference System.

A lot of contributions to item #4 came for the project “GOCE+: Height System Unification with GOCE”, which was carried out by the Technical University of Munich (Germany), the University of Calgary (Canada), the National Oceanography Center (UK) and the Bundesamt für Kartographie und Geodäsie (Germany) in the frame of the Support to Science Element of ESA’s Earth Observation Envelope Program. The main objectives of this project, namely to (i) evaluate and improve the methodology for height determination and height system unification, (ii) demonstrate the feasibility of the height system unification using GOCE derived geoid models and investigate the impact of GOCE for this purpose, and (iii) provide a roadmap for the definition and realization of globally consistent and accurate height reference system, have been achieved. Documents can be found in the links provided below under Publications and Presentations.

Objectives and Planned Efforts for 2015-2017 and Beyond

The long-term objectives of Theme 1 can be placed under the banner “Maintain and use in practice the WHS” so that it can service the vertical datum needs of not only geodesy but also other geosciences such as, e.g., hydrology and oceanography. They include the following:

5. Development of a registry (metadata) containing the existing local/regional height systems and their connections to the global one.
6. Determination and modeling of the temporal changes of the vertical reference frame.
7. Update the Unified Global Height System definition and realization as needed, based on future improvements in geodetic theory and observations.

It is clear that in order to accomplish these objectives, the work of Theme 1 and JWG 0.1.1 should be continued by broader teams of researchers that will include colleagues from all continents.

Websites

JWG 0.1.1: http://whs.dgfi.tum.de/index.php?id=1
ESA project: www.goceplushsu.eu

Publications and Presentations

There is an extensive list of publications and presentations that cannot be listed in this brief report. However, many of them can be found in the following web sites:

Special issue of *Journal of Geodetic Science* on Regional and Global Geoid-based Vertical Datums, Eds. Michael Sideris and Georgia Fotopoulos: http://www.degruyter.com/view/j/jogs. 2012.2.issue-4/issue-files/jogs.2012.2.issue-4.xml

ESA project final documents: http://www.goceplushsu.eu/gpweb/gc-cont.php?p=65

ESA project presentations/publications: http://www.goceplushsu.eu/gpweb/gc-cont.php?menu=16

Joint Working Group 0.1.1: Vertical Datum Standardisation (JWG 0.1.1)

supported by GGOS Focus Area 1, IAG Commission 1 (Reference Frames), IAG Commission 2 (Gravity Field) and the International Gravity Field Service (IGFS)

Chair: Laura Sánchez (Germany)

Members:
J. Ågren (Sweden
R. Cunderlík (Slovakia)
N. Dayoub (Syria)
J. Huang (Canada)
R. Klees (The Netherlands)
J. Mäkinen (Finland)
K. Mikula (Slovakia)
Z. Minarechová (Slovakia)
P. Moore (United Kingdom)
D. Roman (USA)
Z. Šima (Czech Republic)
C. Tocho (Argentina)
V. Vatrt (Czech Republic)
M. Vojtiskova (Czech Republic)
Y. Wang (USA)

Report of Activities

During the 2011 IUGG General Assembly, GGOS, the IAG Commissions 1 (Reference Frames) and 2 (Gravity Field) and the IGFS established a joint working group devoted to the Vertical Datum Standardization. This working group (called JWG 0.1.1) supports the activities of GGOS Focus Area 1 (formerly Theme 1) Unified Global Height System; in particular, to recommend a reliable geopotential value W_0 to be introduced as the conventional reference level for the realization of an International Height Reference System (IHRS). At present, the most commonly accepted W_0 value corresponds to the best estimate available in 1998 (see Petit and Luzum 2010, Table 1.1); however, this value presents discrepancies larger than 2 m^2s^{-2} with respect to recent computations based on the latest Earth's surface and gravity field models. In this context, the first activities faced by JWG 0.1.1 concentrated on (1) making an inventory about the published W_0 computations to identify methodologies, conventions, standards, and models presently applied (cf. Sánchez 2012) and (2) bringing together the different groups working on the determination of a global W_0 in order to coordinate these individual initiatives for a unified computation (cf. Sánchez et al. 2014).

Following aspects were analysed in the unified computation:

- Sensitivity of the W_0 estimation on the Earth's gravity field model
- Dependence of W_0 on the omission error of the global gravity model
- Influence of the time-dependent Earth's gravity field changes on W_0
- Sensitivity of the W_0 estimation on the mean sea surface model
- Influence of time-dependent sea surface changes on W_0
- Effects of the sea surface topography on the estimation of W_0
- Dependence of the W_0 empirical estimation on the tide system
- Weighted computation based on the accuracy of the input data to estimate the influence of the input data uncertainties on the W_0 estimation.

The different calculations carried out within the JWG 0.1.1 demonstrate that the 1998 W_0 value (62 636 856.0 ± 0.5 m^2s^{-2}) is not in agreement with the newest geodetic models describing geometry and physics of the Earth (see Table 4). The estimations without considering the accuracy of the input data suggest as a best estimate the value 62 636 854.0 m^2s^{-2} (see presentation at the IAG General Assembly 2013 in Potsdam, Germany). However, if weights based on the accuracy of the input data are considered, the W_0 estimation decreases about 0.3 m^2s^{-2} (Fig. 1). Since the computations are based on yearly mean sea surface models, the mean value for W_0 would refer to the mean epoch between 1992.9 and 2013.5 (i.e. 2003.2). However, it would be convenient to adopt a W_0 value valid for a more recent epoch, for example 2010.0. As reference level, the adopted W_0 has to be fixed (without time variations); but it has to have a clear relationship with the mean sea surface level (as this is the convention for the realization of the geoid). According to this, a suitable recommendation for the IHRS reference level is to introduce the potential value (rounded to one decimal) obtained for the year 2010 after fitting the weighted yearly W_0 estimations by means of a lineal regression: 62 636 853.4 m^2s^{-2}. At the time presenting this report (May 2015), two publications are in preparation: the first one describes in detail the computation strategy, conventions and models applied for the W_0 estimation; the second one concentrates on supporting the recommendation of the W_0 value as reference level for the IHRS, including a description about the procedure to realize this value at regional and local level.

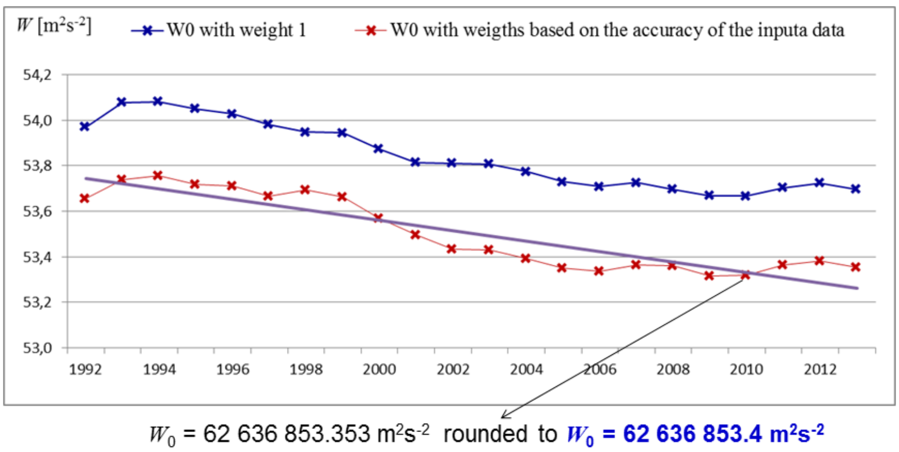


Fig. 1: Comparison of the W_0 estimation assuming the input data free of error and a weighed estimation including the inverse of the input data variances as weighting factor. The potential value (rounded to one decimal) obtained for the year 2010 after fitting the weighted yearly W_0 estimations by means of a lineal regression is a suitable recommendation to define the reference level of the International Height Reference System.

Table 4: W_0 estimations carried out by the members of the JWG 0.1.1 (taken from Sánchez et al. 2014, page 208)

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Table 1 Summary of the W_0 estimates delivered by the four groups working on the W_0 determination in the frame of the JWG 0.1.1

Group	MSS	Area	GOCO03S	EIGEN-6C	EGM2008
Prague	Jason 1	67°N/S	54.28	54.25	54.24
		60°N/S	53.75	53.73	53.96
Bratislava	DTU10	82°N/S	54.00	53.95	53.96
		67°N/S	53.53	53.49	53.49
	CLS11	82°N/S	54.30	54.26	54.26
		67°N/S	53.82	53.79	53.79
Latakia	DTU10	80°N/S	54.11	54.11	54.11
		70°N/S	53.91	53.92	53.92
		60°N/S	53.07	53.08	53.07
	CLS11	80°N/S	54.42	54.43	54.43
		70°N/S	54.23	54.24	54.23
		60°N/S	53.38	53.40	53.39
	DTU10 + ECCO2	70°N/S	53.94	53.95	53.95
		60°N/S	53.87	53.88	53.87
	CLS11 + ECCO2	70°N/S	54.26	54.27	54.26
		60°N/S	54.18	54.20	54.19
Munich	DTU10	82°N/S	54.02	53.98	53.97
		67°N/S	53.55	53.53	53.53
		60°N/S	53.11	53.12	53.12
	CLS11	82°N/S	54.31	54.29	54.30
		67°N/S	53.86	53.82	53.83
		60°N/S	53.44	53.41	53.40

The values are given in [m^2 s^{-2}] and the constant 62,636,800 should be added. Applied methodologies are described in Burša et al. (1999), Čunderlík and Mikula (2009), Dayoub et al. (2012) and Sánchez (2009), respectively

Publications

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Čunderlik R., Minarechová Z., and Mikula K.: Realization of WHS Based on the Static Gravity Field Observed by GOCE. In: Marti U. (ed,), Gravity, Geoid and Height Systems. IAG Symposia Series 141: 211-220, doi: 10.1007/978-3-319-10837-7_27, 2014

Dayoub N., Edwards S.J. and Moore P.: The Gauss-Listing potential value Wo and its rate from altimetric mean sea level and GRACE, J Geod, 86(9): 681-694, doi: 10.1007/s00190-012-1547-6, 2012. Sánchez L.: Towards a vertical datum standardisation under the umbrella of Global Geodetic Observing System. Journal of Geodetic Science 2(4): 325-342, Versita, 10.2478/v10156-012-0002-x, 2012

Sánchez L., Dayoub N., Cunderlík R., Minarechová Z., Mikula K., Vatrt V., Vojtísková M., Síma Z.: W0 estimates in the frame of the GGOS Working Group on Vertical Datum Standardisation. In: Marti U. (Ed.) Gravity, Geoid and Height Systems (GGHS2012), IAG Symposia 141: 203-210, 10.1007/978-3-319-10837-7_26, 2014

Presentations

Sánchez L., Cunderlík R., Dayoub N., Mikula K., Minarechová Z., Síma Z., Vatrt V., Vojtísková M.: Towards a new best estimate for the conventional value of W0. 3rd Int. Gravity Field Service (IGFS) General Assembly, 2014-07-02

Sánchez L., Dayoub N., Cunderlík R., Mikula K., Minarechová Z., Sí-ma Z., Vatrt V., Vojtíšková M.: Conventional reference level for a global unified height system. IAG Scientific Assembly, Potsdam, Germany, 2013-09-01

Sánchez L.: Vertical datum standardisation: a fundamental step towards a global vertical reference system. AGU Meeting of the Americas, Cancun, Mexico, 2013-05-16

Sánchez L.: Report on the activities of the Working Group Vertical Datum Standardisation. GGHS 2012, Venice, Italy, 2012-10-09

Sánchez L.: Towards a Vertical Datum Standardisation. AOGS-AGU (WPGM) Joint Assembly, Singapore, 2012-08-14

Sánchez L.: Towards a vertical datum standardisation based on a joint analysis of TIGA, satellite altimetry and gravity field modelling products. IGS Workshop 2012, Olsztyn, Poland, 2012-07-23/27

GGOS Focus Area 2 Geohazards Monitoring

Joint Working Group 0.2.1: 'New Technologies for Disaster Monitoring and Management'

Chair:	Ioannis (John) D. Doukas (Greece)	
Co-Chair:	Günther Retscher (Austria)	
Members:	Jorge Centeno (Brasil)	Melinda Laituri (USA)
	Joseph Dodo (Nigeria)	Jonathan Li (Canada)
	Jacob Ehiorobo (Nigeria)	Beniamino Murgante (Italy)
	Vassilis Gikas (Greece)	Urbano Fra Paleo (Spain)
	Mikhail Kanevski (Switzerland),	Barbara Theilen-Willige (Germany)
Members at Large:	Cheng Wang (China)	Gyula Mentes (Hungary)
	Allison Kealy (USA)	

Purpose and Scope

It is a relatively new group, started on 2011. Goals and purposes: To explore and test any available (or emerging) contemporary technologies that could relate with Disaster Monitoring (DM); to map and register all kinds of disasters, either natural or man-made. The creation of an up-to-date disaster catalogue (typical characteristics, major impacts and other related information etc.), in relation with an up-to-date technologies-catalogue (e.g. benchmark data-sets, hardware, software, methods, algorithms and applications etc.), will form the foundation of the coordination of research and other activities and tasks, as well. Furthermore, the topic is expected to attract a number of interdisciplinary aspects, a fact that will result into most interesting cooperation with a variety of other scientific and/or professional institutes, organizations, groups (including other IAG entities).

Activities and Actions

During the last eight (8) months, the group is under a full reformation process, which will conclude to a new setup, with new members, enrichment of its goals & objectives (by taking into account the rapid changes in the field of geosciences) etc.

Objectives and Planned Efforts for 2015-2017 and Beyond

In the middle of group's reformation, which is expected to finish by the end of the year

Website

http://doukas.civil.auth.gr/iag_sc41_sg41/

Publications and Presentations

Barbara Theilen-Willige and Doukas, I.D.: Remote Sensing and GIS Contribution to the Detection of Areas Susceptible to Earthquake Hazards. The Case Study of Northern Greece. 26th IUGG General Assembly, June 22-July 2, 2015, Prague

GGOS Focus Area 3: Sea-Level Change, Variability and Forecasting

Chair: Tilo Schöne (Germany)
Co-Chair: CK Shum (USA), Mark Tamisiea (UK), Phil Woodworth (UK)

Purpose and Scope

Sea level rise and its impact on human habitats and economic well-being have received considerable attention in recent years by the general public, engineers, and policy makers. A GGOS retreat in 2010 has identified sea level change as one of the cross-disciplinary focus areas for geodesy. Sea Level is also a major aspect in other observing systems, like e.g. GEO or GCOS. The primary focus of GGOS Focus Area 3 (formerly Theme 3) is to demonstrate and apply geodetic techniques, under the umbrella of GGOS, to the possible mitigation or adaption of sea level rise hazards including studies of the impacts of its change over the world's coastal and deltaic regions and islands, and to support practical applications such as sustainability. One major topic is the identification of gaps in geodetic observing techniques and to advocate enhancements to the GGOS monitoring network and Services where necessary.

Activities and Actions

Focus Area 3 has identified actions to be undertaken to advance geodetic techniques and technologies applied to sea level research. These are

- Identification or (re)-definition of the requirements for a proper understanding of global and regional/local sea-level rise and its variability especially in so far as they relate to geodetic monitoring provided by the GGOS infrastructure, and their current links to external organizations (e.g., GEO, CEOS, and other observing systems).
- Identification of organizations or individuals who can take forward each requirement, or act as points of contact for each requirement, where they are primarily the responsibility of bodies not related to GGOS.
- Identification of a preliminary set of practical or application (as opposed to scientific) pilot projects, which will demonstrate the viability, and the importance of geodetic measurements to mitigation of sea-level rise at a local or regional level. This identification will be followed by construction of proposals for pilot projects and their undertaking.

In the long-term, the aim is to support forecasting of global and regional sea level for the 21st century with an expected forecast period of 20 to 30 years or longer.

The Call for Participation (http://www.ggos-portal.org/lang_en/nn_261554/GGOS-Portal/EN/Themes/SeaLevel/seaLevel.html?__nnn=true) was issued in 2012. Special emphasis is given to local and regional projects which are relevant to coastal communities, and which depend on the global perspective of GGOS. Since than three projects have been submitted and are accepted.

Thus, GGOS Focus Area 3 now has three approved "Landmark" projects

- The Use of Continuous GPS and Absolute Gravimetry for Sea Level Science in the UK (NERC British Isles continuous GNSS Facility (BIGF), University of Nottingham, UK), (NERC National Oceanography Centre (NOC), Liverpool, UK)
- Revisiting the Threat of Southeast Asian Relative Sea Level Rise by Multi-Disciplinary Research (Delft University of Technology (DUT), Delft, Netherlands; University of Leeds, Leeds, United Kingdom; Ecole Normale Supérieure, Paris, France; Chulalongkorn University, Bangkok, Thailand; Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands)

- Bangladesh Delta Relative Sea-Level Rise Hazard Assessment (Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, Ohio, USA; University of Bonn, Bonn, Germany; GeoForschungsZentrum Potsdam (GFZ), Germany)

Another project may join Focus Area 3:

- Subsidence Monitoring in Urban Areas of the Republic of Indonesia with GNSS-controlled tide gauges and supporting methods (National Geospatial Agency (BIG) of Indonesia; Helmholtz Centre Potsdam GFZ, Germany; Institut Teknologi Bandung, Indonesia)

All projects have their major focus on the combination of sea level and geodetic monitoring in an integrative approach. Focus Area 3 will now work with these projects to carry on actions defined in the Focus Area 3 Action Plan. In addition we are continuing to encourage the development of more proposals.

Also in the reporting period, Focus Area e 3 continued communications with organizations, dealing with other than geodetic aspects of sea level monitoring. These are the UNESCO International Oceanographic Commission Group of Experts (UNESCO/IOC GE) and the World Glacier Monitoring Service (WGMS), and the European COPERNICUS programme. Also cooperation with the IGS Tide Gauge Benchmark Monitoring Working is continued.

A major step for GGOS Focus Area 3 is also the alignment of activities with the GGOS Bureau of Networks and Observations. The improvement of the observation network for sea level research is a major open topic. In 2015, the GLOSS Group of Experts (GLOSS-GE), the IGS TIGA-WG and the GGOS Focus Area 3 has submitted the Report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges" for consideration by GGOS with its entities and by GIAC.

The GNSS-controlled tide gauges are an important monitoring component in climate and geodetic science. Over the years, the network of collocated stations has been growing, not at least through the constant effort of IOC/GLOSS Group of Experts, the IGS TIGA-WG, and GGOS. The report identifies, under various assumptions, tide gauges, where the community sees a priority need of additional GNSS installations.

Objectives and Planned Efforts for 2015-2017 and Beyond

- Review and Refine current and future aspects of geodetic contributions for sea level research with groups identified in AS-SL-01/AS-SO-02
- Work on to identify and contact emerging Focus Area 3 pilot projects
- Improve discussion with the GGOS Bureau for Networks and Observation about monitoring infrastructure need
- Establish/improve the outreach activities with the help of the GGOS-CO
- Coordinate with GGOS Focus Area 1
- Work with IGS/TIGA on results of the TIGA reprocessing
- Support Focus Area 3 projects
- Work with GGOS and GIAC on the findings of the report "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges"
- Identify geodetic monitoring aspects relevant to Focus Area 3
- Develop and maintain a specific web site for the Focus Area 3 projects

Website

http://www.ggos-portal.org/lang_en/GGOS-Portal/EN/Themes/SeaLevel/seaLevel.html

Publications and Presentations

Pearlman M. R., C. Ma, C. Noll, E.C. Pavlis, H. Schuh, T. Schoene, R Barzaghi, S. Kenyon: The GGOS Bureau of Networks and Observations and an Update on the Space Geodesy Networks, (http://meetingorganizer.copernicus.org/EGU2015/EGU2015-7420.pdf). 2015

Schöne, T., CK. Shum, M. Tamisiea, P. Woodworth: GGOS Theme 3: Understanding and Forecasting Sea-Level Rise and Variability, OSTST2014, Ocean Surface Topography Science Team Meeting, Lake Constance, Germany, October 2014 (http://www.ostst-altimetry-2014.com/wp-content/uploads/abstracts_books-OSTST_141027.pdf), 2014

Schöne, T., CK. Shum, M. Tamisiea, P. Woodworth: GGOS Theme 3: Understanding and Forecasting Sea-Level Rise and Variability, International Association of Geodesy Scientific Assembly, 150th Anniversary of the IAG, Potsdam, 1.-6. Sep.2013, http://www.iag2013.org/IAG_2013/Welcome_files/abstracts_iag_2013_2808.pdf, 2013

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Merrifield, Mark, Simon Holgate, Gary Mitchum, Begoña Pérez, Lesley Rickards, Tilo Schöne, Philip Woodworth and Guy Wöppelmann, Thorkild Aarup: Global Sea Level Observing System (GLOSS) Implementation Plan – 2012, UNESCO/IOC, 41pp. 2012. (IOC Technical Series No. 100), http://www.unesco.org/ulis/cgi-bin/ulis.pl?catno=217832&set=50929BE4_3_465&gp=1&lin=1&ll=1, 2012

Bureau International des Poids et Mesures (BIPM) – Time Department–

http://www.bipm.org/metrology/time-frequency/

Director of Department: Elisa Felicitas Arias

Overview

The international time scales TAI and UTC have been regularly computed during the period of the report. Results have been published in monthly *BIPM Circular T*, which represents the key comparison CCTF-K001.UTC. The frequency stability of TAI, expressed in terms of an Allan deviation, is estimated to 3×10^{-16} for averaging times of one month.

Sixteen primary frequency standards contributed during the period 2011-2015 to improve the accuracy of TAI, fourteen providing regularly measurement reports since 2012. They all are caesium fountains developed and maintained in metrology institutes in China, France, Germany, India, Italy, Japan, the Russian Federation, the United Kingdom and the United States of America. The scale unit of TAI has been estimated to match the SI second to about 2 to 9 parts in 10^{16} within the period.

Routine clock comparison for TAI/UTC is undertaken using different techniques and methods of time transfer. All laboratories contributing to the calculation of UTC at the BIPM are equipped for Global Navigation Satellite Systems (GNSS) signals reception. GPS C/A observations from time and geodetic-type receivers are used with different methods, depending on the characteristics of the receivers. Dual-frequency receivers allow performing iono-free solutions. Also observations of GLONASS are used for the computation of TAI/UTC. Thanks to this evolution, the statistical uncertainty of time comparisons is at the sub-nanosecond level for the best GNSS time links. Some laboratories operate two-way satellite time and frequency transfer (TWSTFT) stations allowing time comparisons independent from GNSS through geostationary communication satellites. Combination of time links (TWSTFT/GPS PPP (Precise Point Positioning) and GPS/GLONASS) has been routinely used in the computation of TAI since 2011. The uncertainty of time comparison by GNSS has been limited by the calibration of the equipment to 5 ns; in 2014 the BIPM established a new calibration scheme, supported by some regional calibrations that will allow reducing the uncertainty of GNSS calibrations by a factor 2 at least. The calibration of TWSTFT links can be maintained at the nanosecond order.

Extensive comparisons of the different techniques and methods for clock comparisons are computed regularly and published on the ftp server of the section, as well as complete information on data and results (ftp://tai.bipm.org/TimeLink/).

Because TAI is computed on a monthly basis and has operational constraints, it does not provide an optimal realization of Terrestrial Time (TT), the time coordinate of the geocentric reference system. The BIPM therefore computes an additional realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluation of the TAI frequency by the primary frequency standards. The last updated computation of TT(BIPM), named TT(BIPM14) has an estimated accuracy of order 3×10^{-16}. The monthly extension of TT(BIPM) can be directly derived from TAI (ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.14).

The algorithm used for the calculation of TAI has been significantly improved during the period covered by this report. The model for clock frequency prediction was revised, and a new model is in use since August 2011. As a consequence of this modification, the drift observed in the atomic free scale (EAL) with respect to the primary standards has completely disappeared. A new algorithm for the computation of clock weights has been developed and implemented in the calculation of TAI since January 2014. It is based on the principle that a good clock is a predictable clock, instead of using stability criteria as before. This method leads to a better distribution of weights among the different types of clocks, in particular gives a stronger role of the hydrogen-masers. The consequence is an improvement of the frequency stability of EAL at short- and long-term.

Radiations other than the caesium 133, most in the optical wavelengths, have been recommended by the International Committee for Weights and Measures (CIPM) as secondary representations of the second. These frequency standards are at least one order of magnitude more accurate than the caesium. Their use for time metrology is still limited by the state of the art of frequency transfer. Experiments using optical fibres on baselines up to 1000 km confirmed the capabilities of the method. It remains, however, limited to continental time and frequency transfer. New techniques are under study for extending the transfer onto intercontinental scale. This is part of the collective effort of the time metrology community aiming at a possible redefinition of the SI second.

Research work is also dedicated to space-time reference systems. The BIPM provides, in partnership with the US Naval Observatory, the Conventions Product Centre of the International Earth Rotation and Reference Systems Service (IERS). IERS activities in cooperation with the Paris Observatory on the realization of reference frames for astrogeodynamics, contribute to the maintenance of the international celestial reference frame in the scope of the IAU activities.

In January 2012 the Time Department started a pilot experiment for the implementation of a rapid UTC (*UTCr*). The aim of this project was to study the feasibility of providing some link to UTC on a more frequent basis than that of monthly *Circular T*. This experiment proved the capacities at the BIPM and at the contributing laboratories for assuring this rapid provision and after approval by the Consultative Committee for Time and Frequency (CCTF), *UTCr* will become a routine weekly publication. About 50% of the laboratories in UTC participate to *UTCr*, representing more than 60% of the clock weight. *UTCr* has been published without interruption since 1 July 2013.

Results for UTC and *UTCr* are available at http://www.bipm.org/en/bipm-services/timescales/time-ftp/publication.html.

A considerable amount of effort has been put in contributing to the discussions on a redefinition of UTC without leap seconds at the International Telecommunication Union (ITU). In particular, the BIPM organized jointly with the ITU a workshop on the future of the international time scale on 19-20 September 2013.

The total number of publications of the Time Department staff during the period is around 75.

Activities

Coordinated Universal Time (UTC), rapid UTC (UTCr) and TT(BIPM)

The reference time scale Coordinated Universal Time (UTC), is computed from data reported regularly to the BIPM by about 75 timing centres that maintain a local UTC; monthly results are published in *Circular T*. The rapid solution UTCr is computed for about 40 laboratories contributing also to UTC, and published every Wednesday. The realization of terrestrial time TT(BIPMxy) is computed for the year 20xy, with monthly extrapolations that can be derived from TAI. The *BIPM Annual Report on Time Activities for 2011, 2012, 2013 and 2014* have been published in electronic version and are available on the BIPM website at http://www.bipm.org/en/bipm/tai/annual-report.html.

Algorithms

The algorithm used for the calculation of time scales is an iterative process that starts by producing a free atomic scale (*Échelle atomique libre* or EAL) from which TAI and UTC are derived.

EAL is optimized in frequency stability, but nothing is done for matching its unit interval to the second of the International System of Units (SI second). In a second step, the frequency of EAL is compared to that of the primary frequency standards, and the frequency accuracy is improved by applying whenever necessary a correction to the frequency of EAL. The resulting scale is TAI. Finally, UTC is obtained by adding an integral number of seconds (leap seconds). Research into time scale algorithms is conducted in the Time Department with the aim of improving the long-term stability of EAL and the accuracy of TAI/UTC.

Since August 2011 the clock frequency prediction model in the algorithm of calculation of TAI has been improved. The new algorithm uses the same quadratic model for predicting the frequency of all clocks (caesium and hydrogen-maser clocks). This model takes into account the drift of the hydrogen-masers frequency and the effects coming from the ageing of the caesium clocks. In consequence, the drift that had been observed in the frequency of EAL with respect to the primary frequency standards, amounting -1.3×10^{-17}/day has been completely removed.

The old frequency prediction model (linear) did not take into account the drift of the hydrogen-masers frequency, and consequently these clocks were not properly used. After the change in the prediction model, it was clearly necessary to make a revision of the clock weighting procedure so that all clocks could contribute in function of their quality. A new weighting algorithm has been implemented in the calculation of TAI since January 2014, based on the criteria that a good clock is a predictable one, instead of using the frequency stability as indicator of its quality.

Stability of TAI

About 450 clocks contribute as in April 2015 to the construction of TAI/UTC at the BIPM. Some 87 % of these clocks are either commercial caesium clocks or active, auto-tuned hydrogen-masers. To improve the stability of EAL, a weighting procedure is applied to clocks where the maximum relative weight each month depends on the number of participating clocks. Until December 2013, the weighting procedure was based on clock stability and assigned the maximum weight to about 14 % of the participating clocks on average, per year; this process made the caesium clocks predominant. When the criteria for clock weighting is based on the predictability of the clock frequency, as from January 2014, the weight distribution is different; in average, over one year, about 10% of the participating clocks reach the maximum weight, including 38% of the hydrogen-masers, and less than 1% of caesium clocks. This procedure generates a time scale which relies mostly upon the best hydrogen-maser clocks.

The stability of EAL, expressed in terms of an Allan deviation, has been about 3×10^{-16} for averaging times of one month. Studies indicate that the changes introduced in the algorithm will improve both, the short- and long-term stability of TAI/UTC.

Accuracy of TAI

To characterize the accuracy of TAI, estimates are made of the relative departure, and its uncertainty, of the duration of the TAI scale interval from the SI second, as produced on the rotating geoid, by primary and secondary frequency standards. In the period of this report individual measurements of the TAI frequency have been provided by sixteen caesium and one rubidium fountains, this last one providing a secondary representation of the second. Reports on the operation of the primary and secondary frequency standards are regularly published in the *BIPM Annual Report on Time Activities* and on the BIPM website.

Monthly steering corrections can be applied if necessary to put the frequency of TAI as close as possible to that of the primary/secondary frequency standards. Corrections of maximum 0.5×10^{-15} were applied until October 2012. Until then, the global treatment of individual measurements has led to a relative departure of the duration of the TAI scale unit from the SI second on the geoid ranging from $+5.9 \times 10^{-15}$ in July 2011 to -0.99×10^{-15} in June 2014 with a standard uncertainty of less than 0.37×10^{-15}. As a consequence of the implementation of the quadratic frequency prediction model no steering corrections have been applied since November 2012.

BIPM realization of terrestrial time TT(BIPM)

Because TAI is computed in "real-time" and has operational constraints, it does not provide an optimal realization of Terrestrial Time (TT), the time coordinate of the geocentric reference system. The BIPM therefore computes an additional realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluation of the TAI frequency by the primary frequency standards, and since July also the Rb secondary standard. The last updated computation of TT(BIPM), named TT(BIPM14), valid until December 2014, has an estimated accuracy of order 3×10^{-16}. Extrapolations over 2015 can be obtained from TAI from the equation

$$\mathrm{TT(BIPM14)} = \mathrm{TAI} + 32.184\ \mathrm{s} + 27697.0\ \mathrm{ns}.$$

Primary frequency standards and secondary representations of the second

Members of the BIPM Time Department are actively participating in the work of the CCL/CCTF Frequency Standards Working Group created jointly at the Consultative Committee for Length (CCL) and the CCTF, seeking to encourage knowledge sharing between laboratories, the creation of better documentation, comparisons, and the use of highly accurate primary frequency standards (Cs fountains) for TAI. A mission of this working group it to maintain a list of frequencies recommended for applications including the practical realization of the metre and secondary representations of the second. Updates of this list are proposed to the CCL and CCTF, and are finally recommended by the International Committee for Weights and Measures (CIPM).

Other microwave and optical atomic transitions have been approved and are recommended by the CIPM as secondary representations of the second. Frequency values and uncertainties for transitions in Rb, and various atom and single ion species have been included in the list of recommended frequencies as secondary representations of the second at its last update in September 2012. The list is available at http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html.

BIPM staff participates in the rapidly evolving field of optical frequency standards, addressing, for example, the issue of their comparison at the 10^{-17} uncertainty level or below.

Reports of frequency measurements of the Rb transition at the French national metrology institute are regularly submitted to the Time Department. Based on these reports, results of the comparison of the secondary standard with TAI are published in *Circular T* since the beginning of 2012. Starting in July 2013 Rb measurements have been officially used for the accuracy of TAI, and included in the computation of TT(BIPM13) and TT(BIPM14).

Clock comparison for TAI

TAI/UTC rely on about 75 participating time laboratories equipped with GNSS receivers and/or operating TWSTFT stations.

The GPS all-in-view method has currently been used taking advantage of the increasing quality of the International GNSS Service (IGS) products (clocks and IGS time). Most clock comparison links are based on GPS satellites observations. Data from multi-channel dual-frequency GPS geodetic-type receivers are regularly used in the calculation of time links. Single-frequency GPS data are corrected using the ionospheric maps produced by the Centre for Orbit Determination in Europe (CODE); all GPS data are corrected using precise satellite ephemerides and clocks produced by the International GNSS Service (IGS).

GPS links are computed using the method known as “GPS all in view”, with a non-redundant network of time links that uses a unique pivot laboratory for all the GPS links. Since September 2009, links equipped with geodetic-type receivers are computed with the “Precise Point Positioning” method GPS PPP.

Clock comparisons using GLONASS C/A (L1C frequency) satellite observations with multi-channel receivers have been introduced since October 2009. These links are computed using the “common-view” method; data are corrected using the IAC ephemerides SP3 files and the CODE ionospheric maps.

Combination of individual TWSTFT and GPS PPP links and of individual GPS and GLONASS links were introduced in January 2011 and are currently used in the calculation of TAI.

Results of time links and link comparison using GNSS and TW observations are published monthly on the ftp server of the Time Department (ftp://tai.bipm.org/TimeLink/).

Characterization of delays of time transfer equipment

The BIPM continuously organizes and runs campaigns for measuring the relative delays of GNSS (GPS and GLONASS) time equipment in laboratories which contribute to TAI. The BIPM supports the TWSTFT calibration trips organized by the contributing laboratories in the frame of the relevant CCTF Working Group. Collaboration with the regional metrology organizations has been established in 2014 for maintaining the GNSS calibrations up-to-date.

Advanced time and frequency transfer

In the frame of cooperation with the French space agency (CNES), frequency transfer with GPS has been achieved at the level of 1×10^{-16} with the integer ambiguities PPP solution (IPPP).

Another innovative activity of the BIPM in this field is related to the establishment of optical fibre links between certain laboratories which maintain local representations of UTC. A successful experiment was conducted using the BIPM GPS equipment in parallel with the optical fibre link regularly operated between two institutes that represent UTC in Poland. This experiment demonstrated excellent agreement (at the level of the GPS PPP uncertainty) between the GPS PPP link calculated with the BIPM equipment and the optical fibre link. The optical fibre link can be used to assess the calibration of a UTC link calculated with the current time transfer techniques as a result of the small (hundred picoseconds) and stable calibration uncertainty. This experiment enabled the validation of the new BIPM calibration system with u_B within 1 ns. It also allowed validation of the results of the newly developed IPPP processing technique. Several other fibre links between contributing laboratories are calculated on a regular basis and are anticipated to achieve a potential measurement uncertainty of about 100 ps in the future. In order to benefit from the quality of these links, the Time Department has initiated discussions with the laboratories that already implement time transfer via optical fibres with the aim of establishing standards for data transmission and to validate the compatibility of the different techniques.

Collaboration continues with the Observatoire Midi-Pyrénées (OMP), Toulouse (France), and other radio-astronomy groups observing pulsars and analyzing pulsar data to study the potential capability of using millisecond pulsars as a means of sensing the very long-term stability of atomic time. The Time Department provides these groups with its post-processed realization of Terrestrial Time TT(BIPM). The IAU Division A created in 2012 a working group on Pulsar-based timescales, to which staff of the Time Department contributes.

The BIPM shares with the US Naval Observatory the responsibility for providing the IERS Conventions Centre. Updates to the IERS Conventions (2010) are published since May 2011 at http://tai.bipm.org/iers/conv2010/conv2010.html. The text of the conventions, in IERS Technical Note N°36 is also available at (http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn36.html).

Activities related to the realization of reference frames for astronomy and geodesy are developing in cooperation with the IERS. In these domains, improvements in accuracy will enhance the need for a full relativistic treatment and it is essential to continue participating in international working groups on these matters; e.g. through the IAU Commission “Relativity in Fundamental Astronomy”. Cooperation continues for the maintenance of the international celestial reference system. The IAU Division A established a working group for realizing the

3rd version of the international celestial reference frame, ICRF3. Staff of the Time Department contributes to this working group.

A change in the definition of UTC is under discussion at the ITU since year 2000, and the BIPM has permanently contributed as a Member of the ITU Radiocommunication Sector. Final decision on the adoption of a proposed recommendation of implementing a continuous time scale, namely stopping the insertion of leap seconds in UTC, will be taken at the World Radioconference in 2015. For complementing the effort of disseminating all relevant information, a workshop jointly organized by the ITU and the BIPM took place in Geneva in September 2013. Information on this event is provided at http://www.itu.int/ITU-BIPM_Workshop.

Activities in Frequency

Frequency comb, calibration and measurement service

The frequency comb activities are limited to the comb maintenance for BIPM internal applications. The combs are passively kept in running conditions and used when needs appear. The Department has provided calibration and measurement service for combs and reference lasers for internal needs only. This includes the periodic absolute frequency determination of our reference lasers, both at 633 nm and 532 nm, used for iodine cell quality testing lasers and for the calculable capacitor project at the BIPM. Support to the development of a watt balance is also provided with the construction of interferometers.

Gravimetry

Gravimetry for the BIPM watt balance project

At the International Comparison of Absolute Gravimeters in 2009, the very last one organized by the BIPM, the first measurements for determining the free-fall acceleration in the watt balance room were made with three absolute gravimeters participating to the comparison. The Consultative Committee for mass and related quantities (CCM) has required a total relative standard uncertainty of 2×10^{-8} (corresponding to 20 µGal) for the determination of the Planck constant *h* as a condition for the redefinition of the kilogram. Taking into account all effects that can be sources of uncertainty, the demonstrated uncertainty of the determination of the free-fall acceleration at the test mass centre is of 4.5 µGal. Studies made at the BIPM Time Department as a contribution to the watt balance project have been published.

Staff of the Department

Dr Elisa Felicitas Arias, Principal Research Physicist, Director

Ms Aurélie Harmegnies, Assistant

Dr Zhiheng Jiang, Principal Physicist

Mrs Hawaï Konaté, Principal Technician

Dr Wlodzimierz Lewandowski, Principal Physicist (retired May 2014)

Dr Gianna Panfilo, Physicist

Dr Gérard Petit, Principal Physicist

Dr Lennart Robertsson, Principal Physicist

Mr Laurent Tisserand, Principal Technician

Publications of the staff

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BIPM publications

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ICET Data Base (May 31, 2015)

Status Report

It has been decided to present the tidal data stored in the ICET in a uniform way after a careful check of the series.

The data base is organised in directories corresponding to the different stations ordered by station number SSSS following the ICET list of stations (Figure).

In each station directory there is a subdirectory for each instrument IIII operated at the station. The name of the subdirectory is CIIISSSS, where C corresponds to the corresponding tidal component: gravity, tilt, strain….

Different files can be found in the subdirectory with specific qualifiers i.e.

- OUT: raw uncalibrated data in ETERNA format,
- TIT: description of station and instrument,
- V66: old analysis performed with Venedikov (VEN66) analysis method,
- PRN: old analysis performed with ETERNA34 analysis method,
- CAL: calibration table (if any),
- MIN: filtered values for VEN66 input, including interpolated calibrations,
- DA1: data calibrated using *.CAL calibration table,
- DA2: data calibrated using the interpolated calibration table in *.MIN,
- INI: input file with parameters for ETERNA34 analysis method,
- ANA: new analysis performed with ETERNA34 analysis method (.AN1 obtained with DA1 and *AN2 obtained with DA2).

The information is summarized in the *.DAT file which is duplicated in the root directory.

When a same instrument was used at different epochs in the same station with different settings, it is not always possible to provide unified data sets. The files corresponding to the different data sets are discriminated by changing the qualifier of the file names in the following way:OUA and OUB, DA1 and DB1, DA2 and DB2, DAT and DBT, ANA and ANB, …. Some files such as *.TIT are often shared.

Applications of the new ICET data base

The main goal of the new data base is indeed to save the wealth of tidal records gathered during 50 years at ICET. These data are well documented and could be used for further investigations using new methods. The user which is not interested by the different steps of the transformation can safely use the CIIISSSS.DAT files located in the root directory of the station SSSS to perform new analyses.

For a full exploitation of the tidal analysis results it is necessary to compute the different tidal vectors from the tidal analysis results. These vectors should be compared with the solid Earth tidal response and the ocean tides loading.

.
All information for the instrument II1, held in subdirectory CII1SSS1 is summarized in one single file CII1SSS1.dat located in the root directory SSS1.

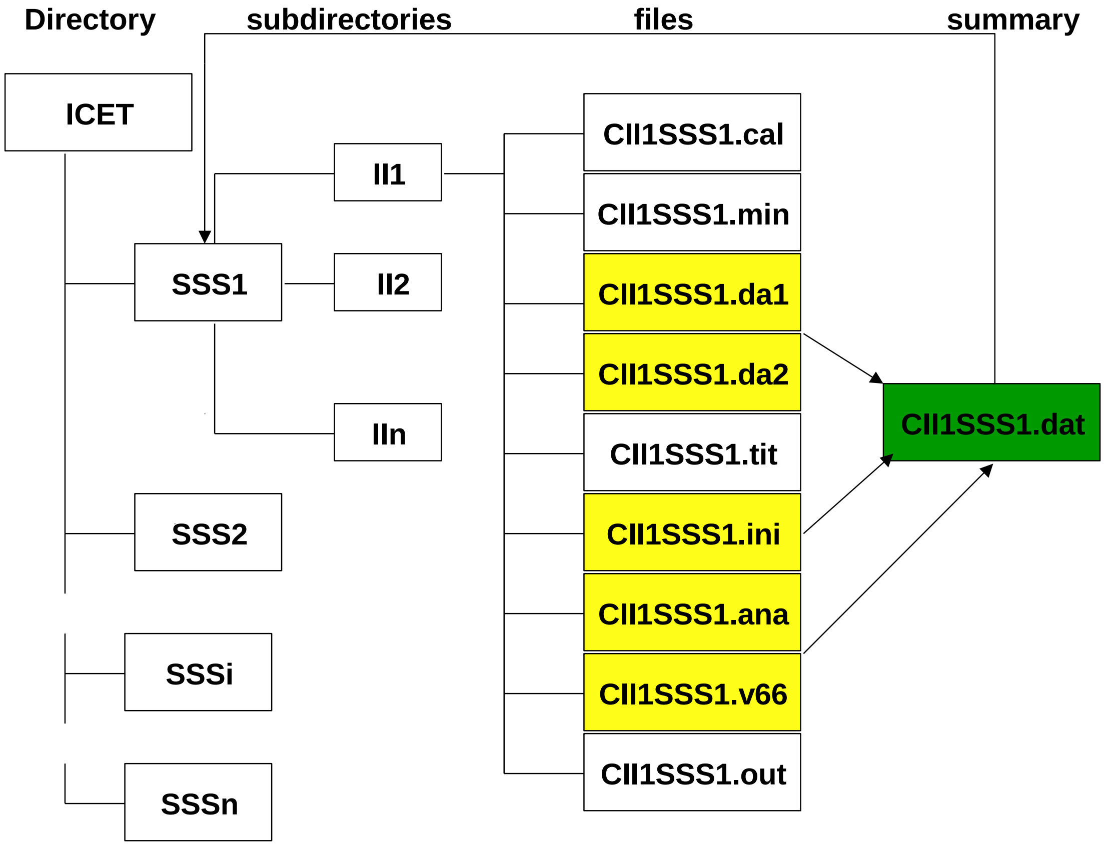

Figure: Information available in the new ICET data bank for a given station SSS1.

Status of the Global Geodynamics Program (GGP) data processing at ICET

2011-2015

Jean-Pierre Barriot[1], Bernard Ducarme[2] and Youri Verschelle[1]

INTRODUCTION

The Global Geodynamics Program (GGP) raw minute data (GGP-SG-MIN) are preprocessed and validated at ICET in order to provide reliable hourly data sets for tidal analysis. In a first step, gaps and spikes in the monthly raw data files are corrected using the T-soft software. The corrected minute data (GGP-SG-CORMIN) are then uploaded on the Information System and Data Center (ISDC at isdc.gdz-postdam.de) with repair codes 12 or 22. The corrected minute data are decimated to one hour sampling and submitted to tidal analysis. The hourly data are also uploaded as one-year blocks (GGP-SG-HOUR, code h2) on the same site. We summarize the current status of our processing for all the GGP stations between 2011 and 2015.

We summarize in Table 1 the preprocessing and analysis work performed at ICET in the framework of the Global Geodynamics Program (GGP). Several stations are no more operating: BA, BE, BO, BR, KY, MA, PO, SY, VI. Other ones did not provide recently data on a regular basis: CO, MB and the stations depending from the Japanese computing center (CB, KA, NY), who did no more send data since 2013. Since last year most of the stations have been updated until end of 2014 (in red in the Table 1). It corresponds to a total of 203 months of data. Since 2011 some 880 months of data from 20 superconducting gravimeters have been preprocessed.

The standard deviation STD computed with ETERNA (ANALYZE) is also given in Table 1. As the stability of the sensitivity of the superconducting gravimeters is better than 0.1%, the STD is a measure of the signal to noise ratio in the station. For 25 series the STD is lower than $1nm/s^2$. When the STD is larger than $2nm/s^2$ the data set is not suitable for a precise determination of the fine tidal spectrum.

It was found that the Tsoft filter of half-length 8 hours, sometimes used to decimate the minute data to hourly values, was too short. As a result a significant attenuation of the semi-diurnal waves was observed when an analysis based on hourly values was compared with the direct analysis of the original data sampled at one minute internal. The series marked with Y in the last column of Table 1 have been recomputed with a longer filter (24 hours) to suppress this effect. Several anomalies were found and corrected in the previous minute data.

In the framework of the new IGETS Service it has been decided to provide corrected minute data expressed in mV to allow easy modifications of the calibration when new or more accurate values become available. In the same time the corrections applied during the

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preprocessing will be documented. It is especially important for the step corrections which could spoil the long term gravity variations recorded by the instrument.

Table 1: Status of preprocessed and analyzed GGP data on May 2015
n: number of preprocessed months since last year
N: number of days effectively used in the global tidal analysis
STD: standard deviation of the global analysis (ETERNA)

Code	Location	SG Instr.	ICET Code	RAW	Corrected	n (months)	N (days)	STD (nm/s²)	Hourly check
AP	Apache Point, USA	SG046	00466090	150200	150222	17	1695	1.169	Y
BA*	Bandung, Indonesia	T008	00084100	030600	030622		1104	2.938	
BE*	Brussels, Belgium	T003	07790200	000900	000901		¶6692	1.641	
BF	Black Forest, Germany	CD056_L CD056_H	01560716 02560716	130900 130900	130922 130922	15 15	1134 1136	0.611 0.670	Y
BH	Bad Homburg, Germany	(T001) CD030_L CD030_U SG044	 01300734 02300734 00440734	 070400 070400 150200	 070422* 070422* 150222	 16	¶1005 2222 2218 2886	0.950 0.783 0.835 0.610	 Y Y Y
BO*	Boulder, USA	C024	00246085	031000	031022		1850	1.109	
BR*	Brasimone, Italy	T015	00150515	991200	991222		1428	2.954	
CA	Cantley, Canada	T012	00126824	150300	150300	15	5472 ¶6634	1.421 1.390	Y
CB	Canberra, Australia	C031	00314204	130700	130722	22	5591	0.792	Y
CO	Conrad	(C025)	00250699				1877	0.565	Y
ES	Esashi, Japan	T007	00072849	081200	081222?	→200402 25	2274	1.491	
HS	Hsinchu, Taiwan	T048	00482695	120800	081222		898	2.249	
KA	Kamioka, Japan	T016	00162828	130700	130722	22	3006	1.229	Y
KY*	Kyoto, Japan	T009	00092823	030600	030622	→200207 31	1533	3.691	
MA*	Matsushiro, Japan	T011	00112834	080600	080622		3954	1.008	
MB	Membach, Belgium	C021	00210243	120900	111222	!	5907	0.705	Y
MC	Medicina, Italy	C023	00230506	150200	150222	13	6174	0900	Y
ME	Metsahovi, Finland	T020	00200892	131200	131222	14	5409 ¶5564	1.167 1.166	Y
MO	Moxa, Germany	CD034_L CD034_U	01340770 02340770	140200 140200	140222 140222	19 19	4841 4913	0.550 0.564	Y
NY	Ny Alesund,	C039	00390005	120100	120122		3776	2.687	

	Norway								
PE	Pecny,CZ	OSG050	00500930	141200	141222	17	2758	0.562	Y
PO*	Potsdam, Germany	T018	00180765	980900	980912		2250	0.856	
ST	Strasbourg, France	(T005) C026	 00260306	 150100	 150122	 25	¶3272 6134	2.265 0.633	 Y
SU	Sutherland, South Africa	CD037_L CD037_U SG052	01373806 02373806 00523806	141200 141200 141200	141222 141222 141222	12 12 12	3925 3748 2195	0.917 0.945 0.944	Y Y Y
SY	Syowa, Antarctic	T016	00169960	030100	030122*	→20001231	1279	1.387	
TC	Tigo, Concepcion, Chile	RT038	00387621	141200	141222	14	3450	1.075	Y
VI*	Vienna, Austria	C025	00250698	061200	061222		3402 ¶4278	0.525 0.463	Y
WE	Wettzell, Germany	(SG103) CD029_L CD029_U CD030_L CD030_U	01030731 01290731 02290731 01300731 02300731	980900 101000 101000 150200 150200	980921* 101022* 101022* 150222 150222	 18 18	¶726 4264 4226 1665 1679	2.639 0.579 0.597 0.644 0.609	 Y Y Y Y
WU	Wuhan, China	T004	00322647	120700	120712•		3844	0.937	
					TOTAL	203			

* instrument stopped

? status unknown

• preprocessed by data owner

( ) not included in GGP

¶ with data before 1997/07

→ end of the global analysis

International Centre for Global Earth Models (ICGEM)

http://icgem.gfz-potsdam.de

Director: Franz Barthelmes (Germany)

Overview

The International Centre for Global Earth Models was established in 2003.

It is mainly a web based service and comprehends:

- collecting and long-term archiving of existing global gravity field models; solutions from dedicated time periods (e.g. monthly GRACE models) are included
- making them available on the web in a standardised format (self-explanatory)
- interactive visualisation of the models (geoid undulations and gravity anomalies)
- animated visualization of monthly GRACE models
- web-interface to calculate gravity functionals from the spherical harmonic models on freely selectable grids (filtering included)
- web-interface to calculate and plot the time variation of the gravity field at freely selectable positions or over defined basins → the G^3-Browser (GFZ Grace Gravity Browser)
- theory and formulas of the calculation service in STR09/02 (downloadable)
- the ICGEM web-based discussion forum (answering questions)
- evaluation of the models
- visualisation of surface spherical harmonics as tutorial

Thanks to the availability of the monthly model series from GRACE, the static models from the recent GOCE mission, and their combined models of high spatial resolution, the importance of gravity field functionals for nearly all geosciences is rising permanently. In addition to its use for educational purposes, ICGEM helps researchers from different geoscientific fields to overcome the first obstacles in using these models and to get acquainted with the mathematical representation of gravity field in terms of spherical harmonic series. In this way ICGEM enables and stimulates the research based on these products, which are primarily the result of rapid and fruitful development of the satellite based geodetic gravity field determination methods in the past decades.

To avoid the latest restrictions concerning Java Applets, since 2015 all web-interactions are implemented in Java Script and should run on all operating systems and browsers including tablet computers and smartphones.

Services

The Models

Currently, 149 models are listed with their references and 135 of them are available in form of spherical harmonic coefficients. If available, the link to the original model web site or to a freely available publication has been added. Models from dedicated time periods (e.g. monthly solutions from GRACE) of different analysing centres are also available.

The Format

The spherical harmonic coefficients are available in a standardised self-explanatory format which has been accepted by ESA as the official format for the GOCE project.

The Visualisation

An online interactive visualisation of the models (height anomalies and gravity anomalies) as illuminated projection on a freely rotatable sphere is available (fig. 1). Differences of two models, arbitrary degree windows, zooming in and out, are possible. To get an impression of the time variations there is an animation of the monthly solutions (fig. 2). The visualisation of single spherical harmonics is possible for tutorial purposes.

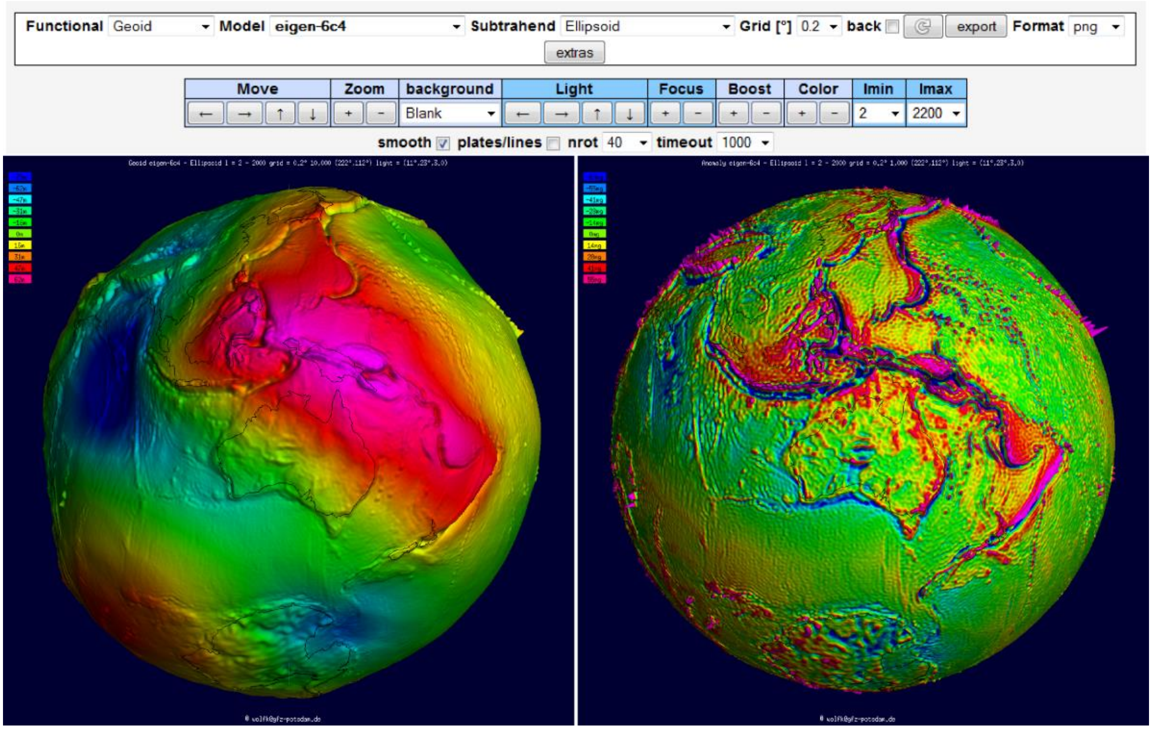


Fig. 1: Visualisation of a global gravity field model, geoid undulations (left) and gravity anomalies (right)

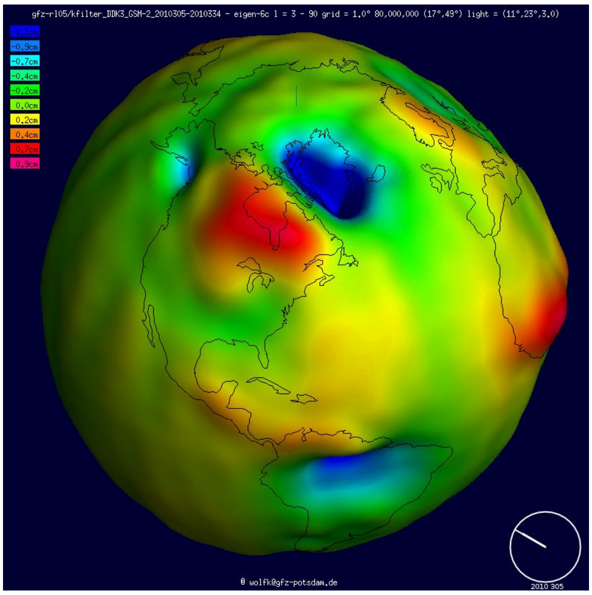


Fig. 2: Snapshot from the animation of the monthly models: geoid differences of the model for November 2010 to the mean model EIGEN-6C. Visible are the effect of mass loss (blue) due to deglaciation during the last years in Greenland and Alaska (eyes ☺), as well as the snapshot of the annual hydrological mass variations in the basin of the Amazon (mouth ☺), and the effect of increasing mass (red) due to postglacial uplift in North America (nose ☺).

The G³-Browser (GFZ Grace Gravity Browser)

To calculate and visualise the time variation of the gravity field at any desired point on the Earth or as mean over predefined basins, a specific web-interface has been developed. The results can be downloaded as plots or ASCII data. Figures 3 and 4 show to examples.

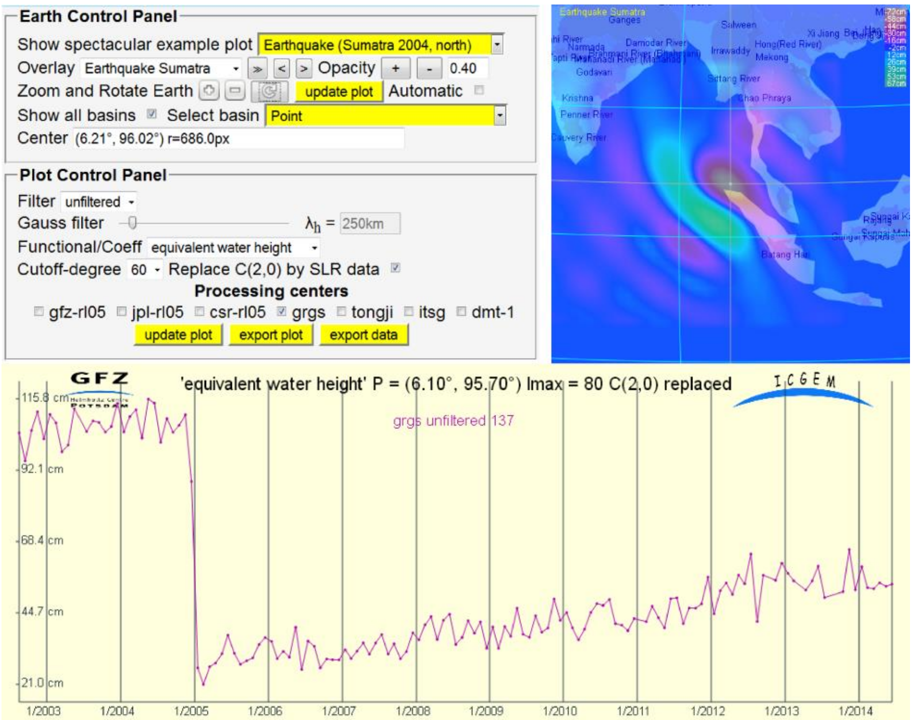


Fig. 3: Snapshot of the G³-Browser; selected is a point affected by the Sumatra earthquake of 2004; the time series is computed from the GRGS monthly solutions

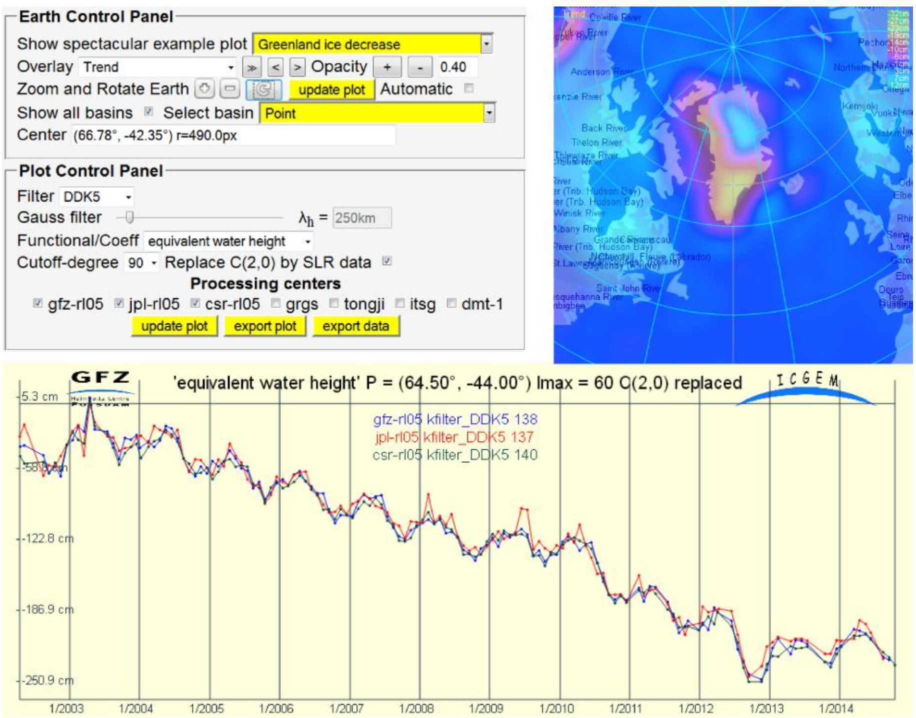


Fig. 4: Snapshot of the G³-Browser; the plot shows the time series of the anisotropically filtered (DDK5) monthly solutions from GFZ, JPL and CSR at a point affected by the ice loss in Greenland

The Calculation Service

A web-interface to calculate gravity functionals from the spherical harmonic models on freely selectable grids, with respect to a reference system of the user's choice, is provided. The following functionals are available:

- pseudo height anomaly on the ellipsoid (or at arbitrary height over the ellipsoid)
- height anomaly (on the Earth's surface as defined)
- geoid height (height anomaly plus spherical shell approximation of the topography)
- gravity disturbance
- gravity disturbance in spherical approximation (at arbitrary height over the ellipsoid)
- gravity anomaly (classical and modern definition)
- gravity anomaly (in spherical approximation, at arbitrary height over the ellipsoid)
- simple Bouguer gravity anomaly
- gravity on the Earth's surface (including the centrifugal acceleration)
- gravity on the ellipsoid (or at arbitrary height over the ellipsoid, including the centrifugal acceleration)
- gravitation on the ellipsoid (or at arbitrary height over the ellipsoid, without centrifugal acceleration)
- potential on the ellipsoid (or at arbitrary height over the ellipsoid, without centrifugal potential)
- second derivative in spherical radius direction of the potential (at arbitrary height over the ellipsoid)
- equivalent water height (water column)

Filtering is possible by selecting the maximum degree of the used coefficients or the filter length of a Gaussian averaging filter. The models from dedicated time periods (e.g. coefficients of monthly solutions from GRACE) are also available after non-isotropic smoothing (decorrelation). The calculated grids (self-explanatory format) and corresponding plots (post-script or png-format) are available for download after a few seconds or a few minutes depending on the functional, the maximum degree and the number of grid points

.

Figure 5 shows the input mask of the calculation service and figures 6 to 8 show examples of plots (based on the grids) generated by the calculation service.

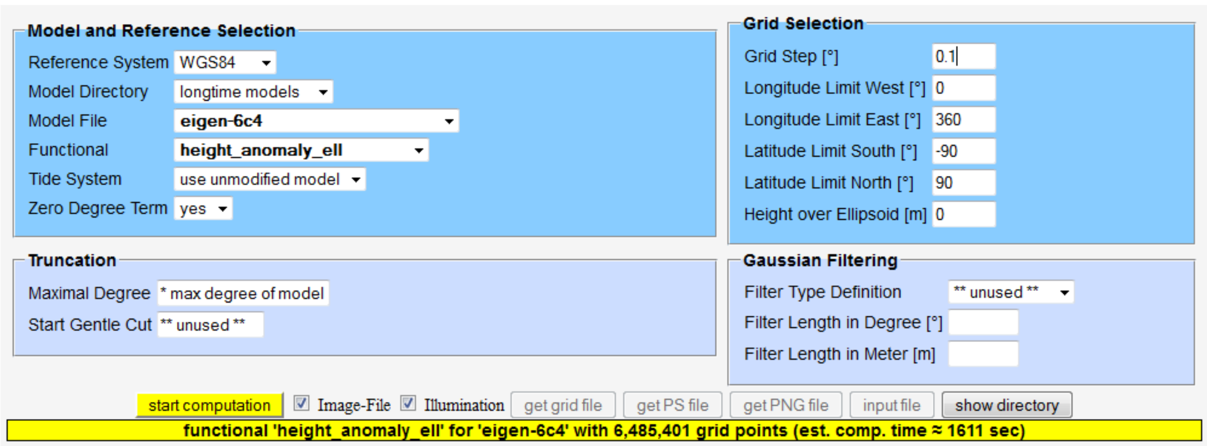


Fig. 5: Input mask of the calculation service

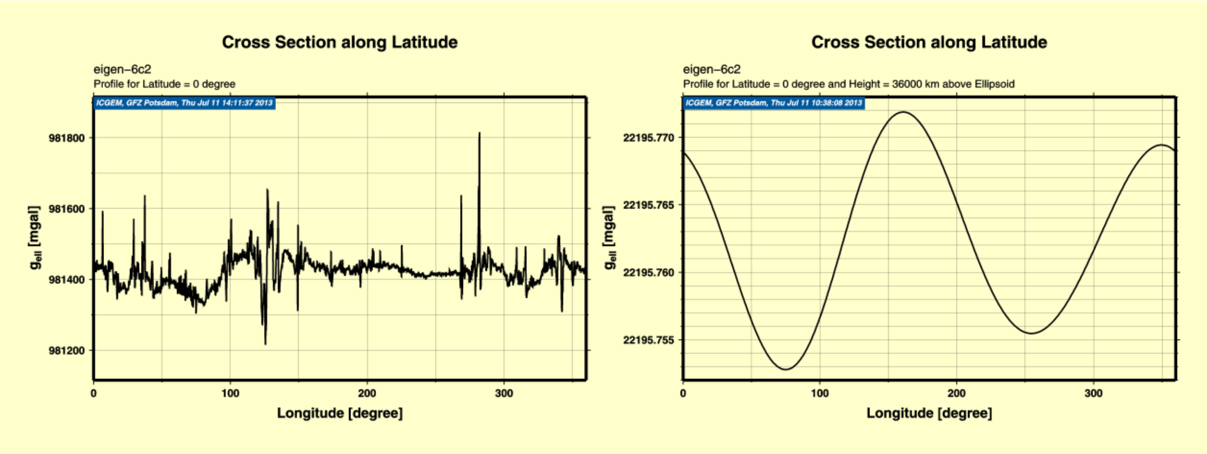


Fig. 6: Example of grid and plot generation by the calculation service: gravitation along the equatorial cross section on the ellipsoid (left), and 36000 km above the ellipsoid (right) from the model EIGEN-6C2

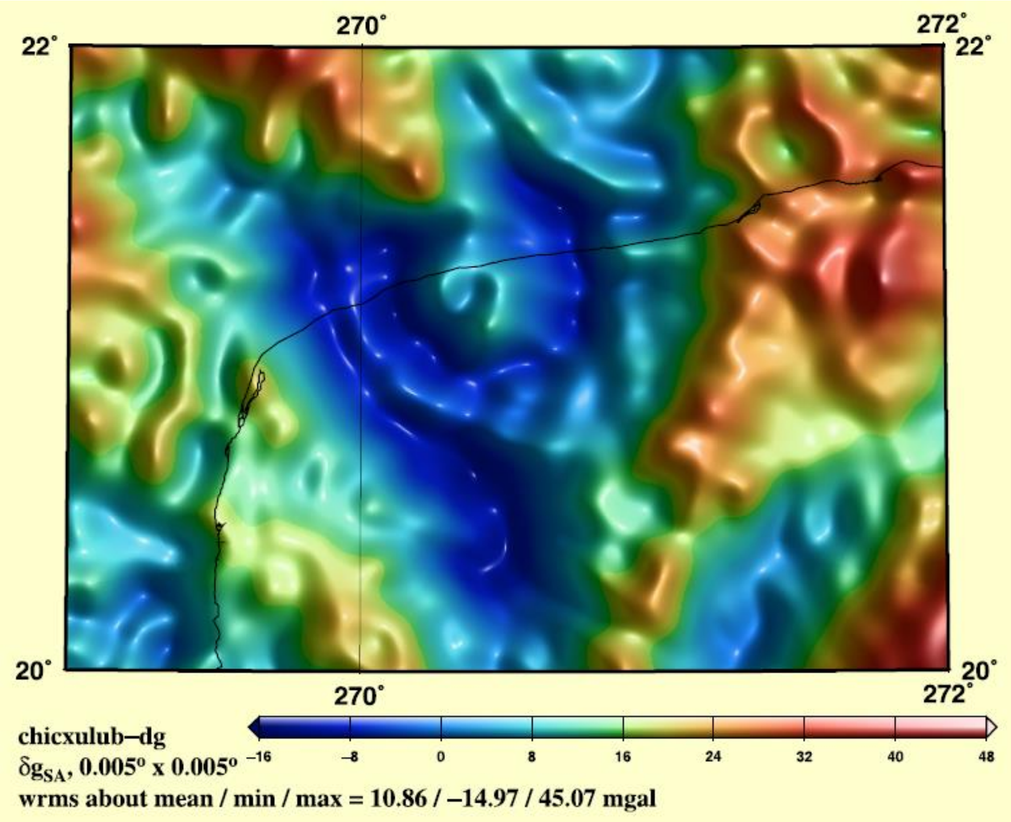


Fig. 7: Example of grid and plot generation by the calculation service: gravity disturbances of the Chicxulub crater region from the model EGM2008

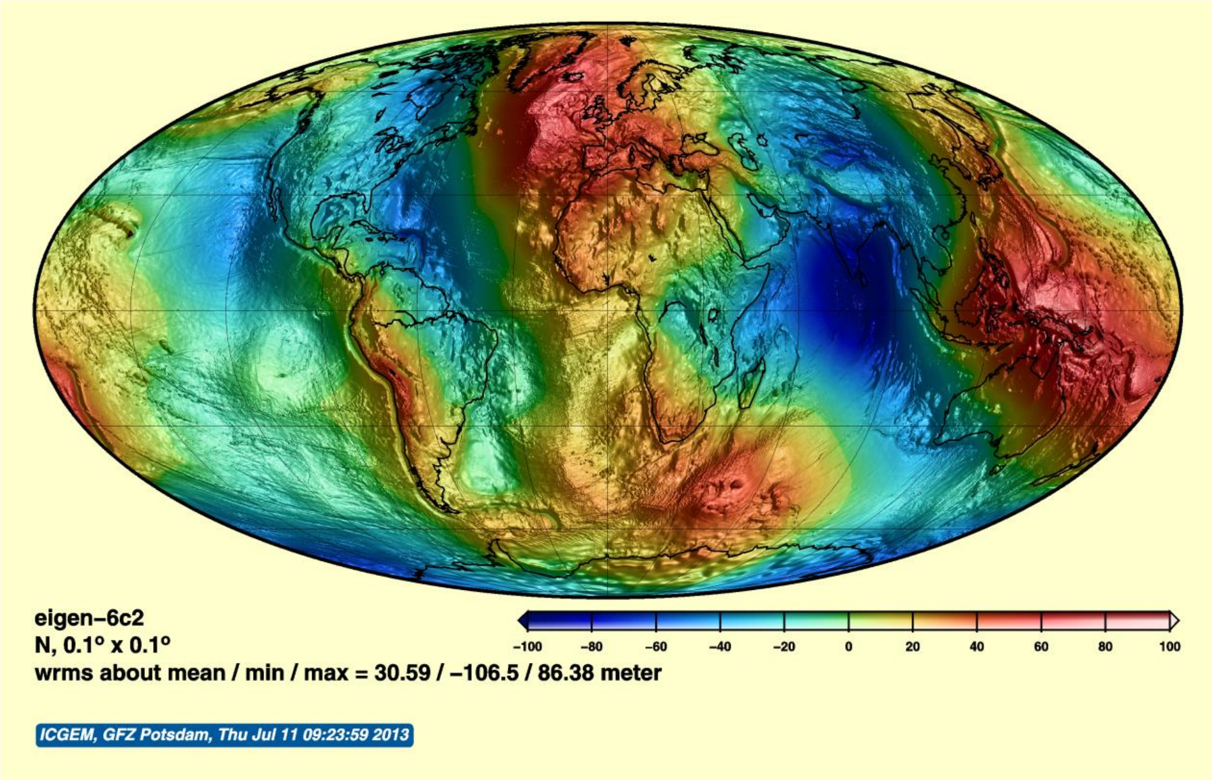


Fig. 8: Example of grid and plot generation by the calculation service: global geoid undulations from the model EIGEN-6C2 (with respect to WGS84)

Evaluation

For a concise evaluation of the models, comparisons with GPS-levelling data and with the most recent combination model in the spectral domain are provided (see figures 9 and 10). A visualisation of the improvement of the satellite-only models over the past decades is also provided (fig. 11).

The table is interactively re-sortable for all columns by clicking in the header cells.

Nr	Model ⇅	Nmax ⇅	USA ⇅ 6169 points	Canada ⇅ 2691 points	Europe ⇅ 1235 points	Australia ⇅ 201 points	Japan ⇅ 816 points	Brazil ⇅ 1112 points	All ▲ 12224 points
134	EIGEN-6C4	2190	0.247 m	0.126 m	0.210 m	0.212 m	0.079 m	0.446 m	0.2408 m
125	EIGEN-6C3STAT	1949	0.247 m	0.129 m	0.212 m	0.213 m	0.078 m	0.447 m	0.2415 m
117	EIGEN-6C2	1949	0.249 m	0.129 m	0.212 m	0.214 m	0.080 m	0.445 m	0.2423 m
112	EIGEN-6C	1420	0.247 m	0.136 m	0.214 m	0.219 m	0.082 m	0.448 m	0.2429 m
91	EGM2008	2190	0.248 m	0.128 m	0.208 m	0.217 m	0.083 m	0.460 m	0.2439 m
111	GIF48	360	0.319 m	0.209 m	0.275 m	0.236 m	0.275 m	0.474 m	0.3082 m
100	EIGEN-51C	359	0.335 m	0.234 m	0.289 m	0.234 m	0.312 m	0.476 m	0.3242 m
99	EIGEN-5C	360	0.341 m	0.278 m	0.303 m	0.244 m	0.339 m	0.524 m	0.3444 m
86	EIGEN-GL04C	360	0.339 m	0.282 m	0.336 m	0.244 m	0.321 m	0.541 m	0.3484 m
94	GGM03C	360	0.347 m	0.337 m	0.334 m	0.259 m	0.316 m	0.513 m	0.3588 m
81	EIGEN-CG01C	360	0.351 m	0.335 m	0.370 m	0.263 m	0.351 m	0.543 m	0.3700 m
84	EIGEN-CG03C	360	0.346 m	0.373 m	0.355 m	0.260 m	0.326 m	0.534 m	0.3714 m
131	GO_CONS_GCF_2_TIM_R5	280	0.398 m	0.310 m	0.371 m	0.336 m	0.450 m	0.505 m	0.3919 m
130	GO_CONS_GCF_2_DIR_R5	300	0.405 m	0.299 m	0.373 m	0.327 m	0.447 m	0.507 m	0.3937 m
118	GO_CONS_GCF_2_DIR_R4	260	0.404 m	0.322 m	0.393 m	0.337 m	0.476 m	0.512 m	0.4020 m
127	EIGEN-6S2	260	0.405 m	0.322 m	0.393 m	0.337 m	0.476 m	0.512 m	0.4025 m

Fig. 9: Table (truncated) of comparison of the models with GPS-levelling: Root mean square (rms) about mean of GPS / levelling minus gravity field model derived geoid heights [m]

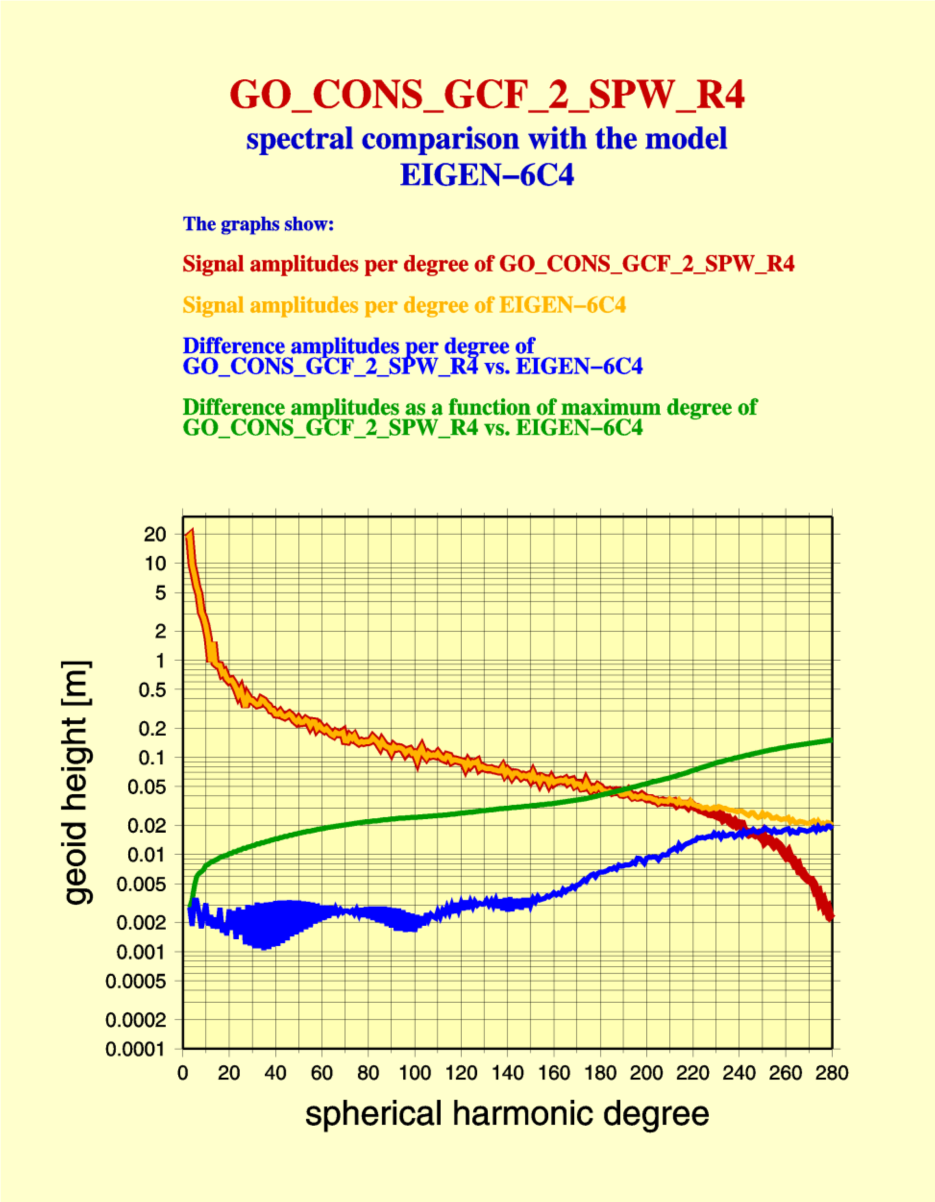


Fig. 10: Comparison of the models in the spectral domain (e.g.: GO_CONS_GCF_2_SPW_R4) with one of the most recent combination models (e.g. EIGEN-6C4)

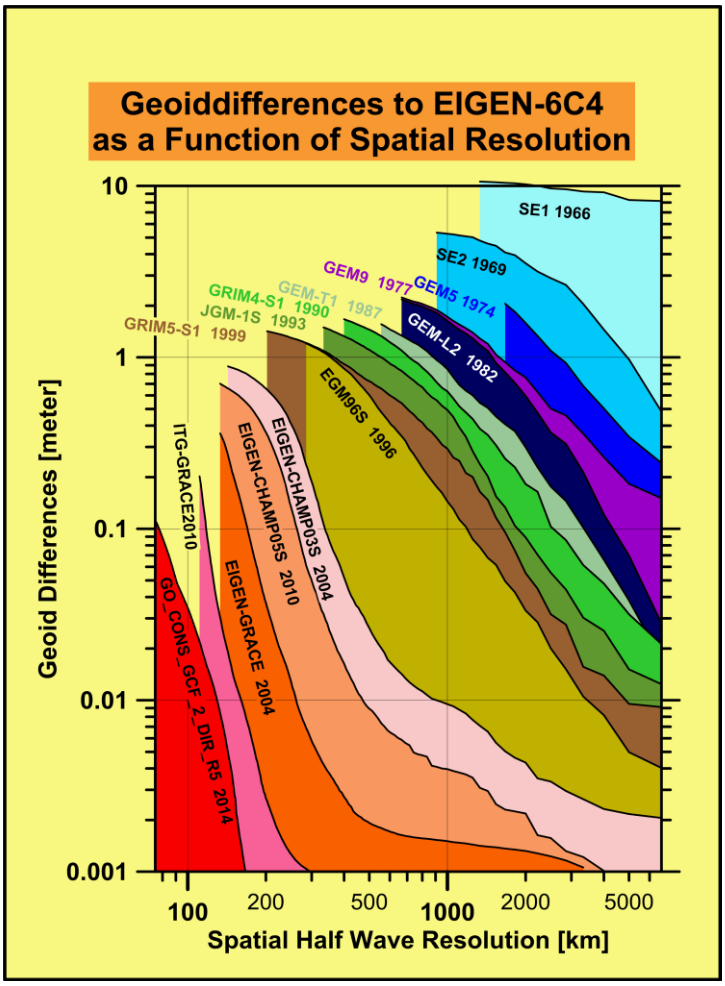


Fig. 11: Visualisation of the improvement of satellite-only models over the past decades: Geoiddifferences to the model EIGEN-6C4 as a function of spatial resolution.

Publications

Barthelmes, F.; Köhler, W., 2012: International Centre for Global Earth Models (ICGEM), Journal of Geodesy, The Geodesists Handbook 2012, 86(10), 932-934.

Barthelmes, F.; Köhler, W (2010): ICGEM - The International Centre for Global Earth Models, Second International Symposium of the International Gravity Field Service (Fairbanks, USA 2010).

Barthelmes, F.; Köhler, W. (2010): ICGEM - a Web Based Service for Using Global Earth Gravity Field Models. IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements (TG-SMM2010) (Saint Petersburg, Russia 2010).

Barthelmes, F.; Köhler (2010): ICGEM – A Web Based Service for Using Global Earth Gravity Field Models, Arbeitskreis Geodäsie/Geophysik, Herbsttagung (Smolenice, Slovakia 2010)

Barthelmes, F. (2009): Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM), http://icgem.gfz-potsdam.de, Scientific Technical Report 09/02, Revised Edition, January 2013, Deutsches GeoForschungsZentrum GFZ, DOI 10.2312/GFZ.b103-0902-26

Barthelmes, F.; Köhler, W.; Kusche, J. (2008): ICGEM The International Centre for Global Earth Models, Observing and Forecasting the Ocean GODAE Final Symposium (Nice, France 2008).

Barthelmes, F.; Köhler, W.; Kusche, J. (2007): ICGEM - The International Centre for Global Earth Models, General Assembly European Geosciences Union (EGU) (Vienna, Austria 2007).

Barthelmes, F.; Köhler (2006): ICGEM - The International Centre for Global Earth Models, General Assembly European Geosciences Union (EGU) (Vienna, Austria 2006).

International DORIS Service (IDS)

http://ids-doris.org/

Chairman of the Governing Board: Pascal Willis (France)

Overview

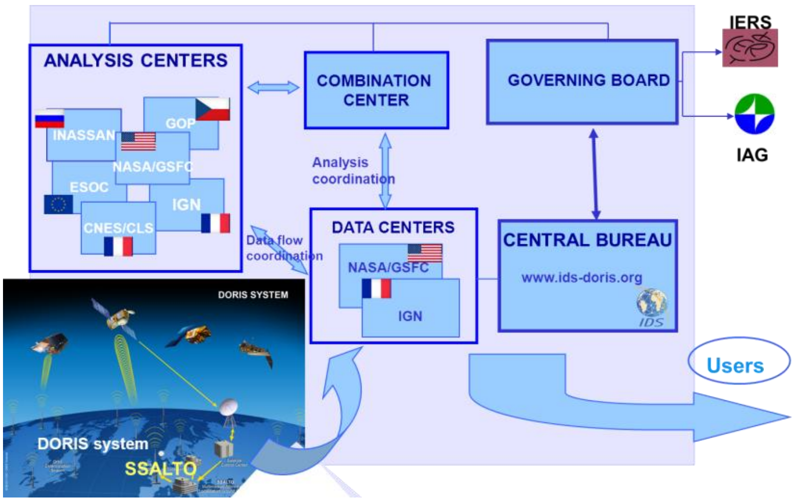
Using the experience gained in the preparation of the ITRF2008, the International DORIS Service (IDS) is now based on a reinforced structure. Six Analysis Centers from five different countries using five different software packages provide regular products to the IDS. The combination of the weekly solutions for the station coordinates and the EOPs is realized by the Combination Center with close collaboration with the Analysis Coordinator and the Analysis Centers. All these components cooperate through the Analysis Working Group (AWG), the meetings of which lead to improvements in DORIS analysis strategies and DORIS-derived geodetic products. Data and products are archived at the two Data Centers. The Governing Board provides long-term direction while the Central Bureau manages the day-to-day activities, brings its supports to the IDS components and operates the information system.

The current report presents the different activities held by all the components of the IDS for the period from the middle of 2011 to the middle of 2015.

Structure

The IDS organization is very similar to the other IAG Services. The service accomplishes its mission through the following components:

- Satellites carrying a DORIS receiver
- Network of tracking stations
- Data Centers
- Analysis centers and Analysis Coordinator
- Combination Center
- Working Groups
- Central Bureau
- Governing Board



Activities

1. DORIS system

1.1 DORIS satellites

As described in Table 1.1, two new satellites were launched in the last four years: HY-2A and SARAL, both using the new 7-channel DG-XX DORIS receiver on-board the satellite. The DORIS constellation then steadily increased, including currently five satellites at altitudes of 720 and 1300 km, with almost polar or TOPEX-like inclination (66 deg).

Table 1.1: DORIS data available at IDS data centers. As of May 2015

Satellite	Start	End	Space Agency	Type
SPOT-2	31-MAR-1990 04-NOV-1992	04-JUL-1990 15-JUL-2009	CNES	Remote sensing
TOPEX/Poseidon	25-SEP-1992	01-NOV-2004	NASA/CNES	Altimetry
SPOT-3	01-FEB-1994	09-NOV-1996	CNES	Remote sensing
SPOT-4	01-MAY-1998	24-JUN-2013	CNES	Remote sensing
Jason-1	15-JAN-2002	21-JUN-2013	NASA/CNES	Altimetry
SPOT-5	11-JUN-2002	PRESENT	CNES	Remote sensing
Envisat	13-JUN-2002	08-APR-2012	ESA	Altimetry, Environment
Jason-2	12-JUL-2008	PRESENT	NASA/CNES	Altimetry
Cryosat-2	30-MAY-2010	PRESENT	ESA	Altimetry, ice caps
HY-2A	1-OCT-2011	PRESENT	CNSA, NSOAS	Altimetry
SARAL/ALTIKA	14-MAR-2013	PRESENT	CNES/ISRO	Altimetry

In the next few years, more DORIS satellites are foreseen: first Jason-3 (USA) and Sentinel-3A (GMES/ESA) in 2015, then Sentinel-3B 12 to 30 months later. Some missions are announced and pending approval: Sentinel-3C, Sentinel-3D, Jason CS1, Jason CS2, SWOT. The Chinese HY-2A satellite for altimetry could be followed by other satellites of the same type (HY-2B, HY-2C, HY-2D). Furthermore, other missions are in consideration. Of particular interest is GRASP (Geodetic Reference Antenna in Space), providing on board the same spacecraft several well calibrated geodetic systems such as GNSS, DORIS, SLR, and VLBI.

Figure 1.1 summarizes the evolution of the DORIS constellation since the launch of the SPOT-2 satellite in 1990, and includes already foreseen satellites. It must be noted that in the past last years, four or more DORIS satellites were available to IDS users, which is a key requirement for the precision of the geodetic products.

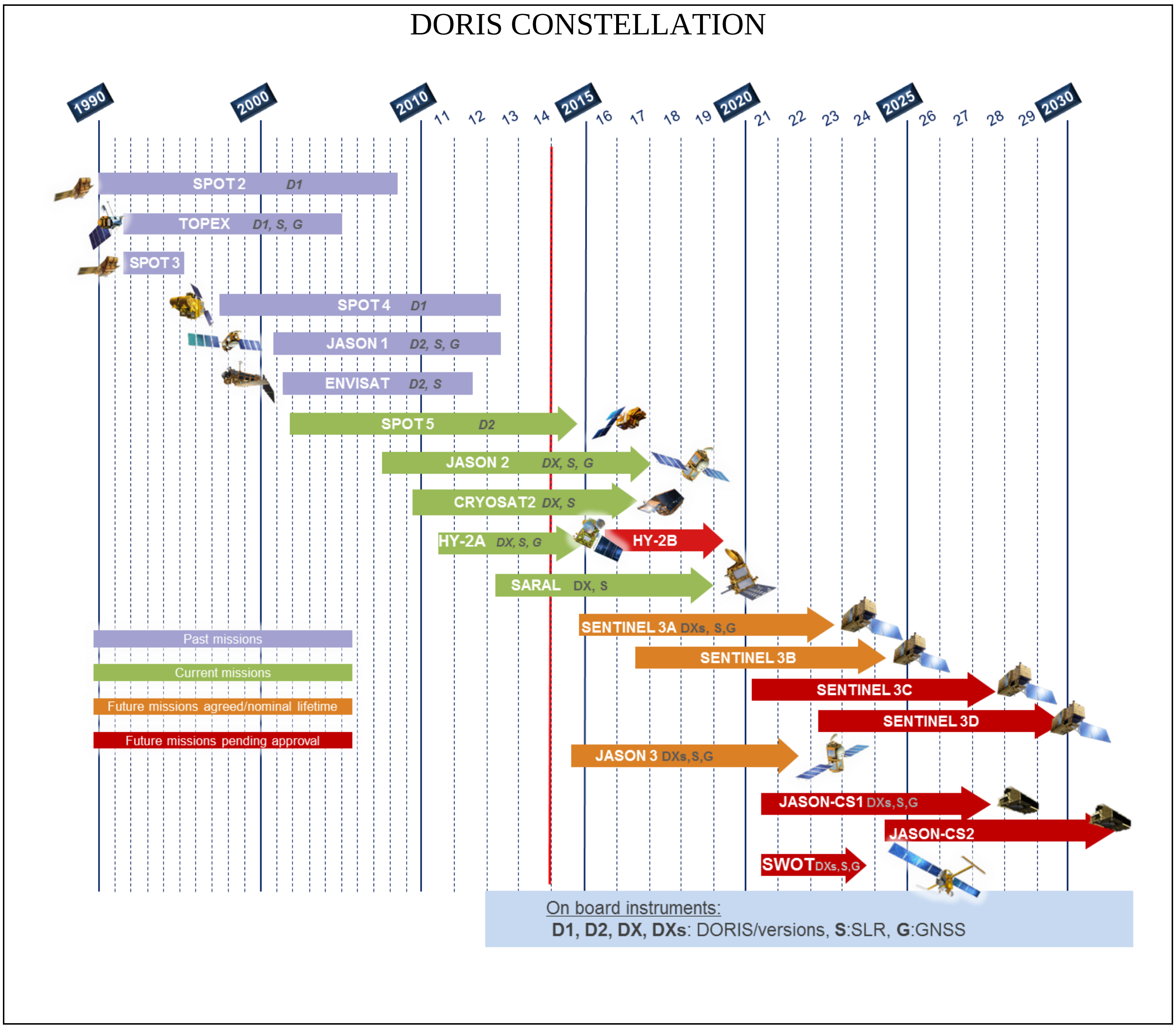


Figure 1.1: DORIS satellite constellation. As of May 2015.

1.1 DORIS network

The DORIS network maintained a high level of performance: many prompt and effective maintenance operations (equipment replacement) and the return to service of Socorro in June 2014 eagerly awaited since several years made it possible to keep up the network availability rate with of a 91% annual mean of operating stations.

At the end of 2014, the DORIS permanent network is made up of 55 stations and an additional station in Grasse, France, is dedicated to experimentation (see Figure 1.2).

With regard to the off-network stations dedicated to IDS for scientific purposes, objectives and priorities have been redefined early 2014 as follows:

- Wettzell, Germany: 4 techniques GGOS site; DORIS station installation planned in 2015
- Guam island, North Pacific Ocean: IGS “GUUC” + tide gauge co-location
- Sejong, Korea: future 4 techniques GGOS site

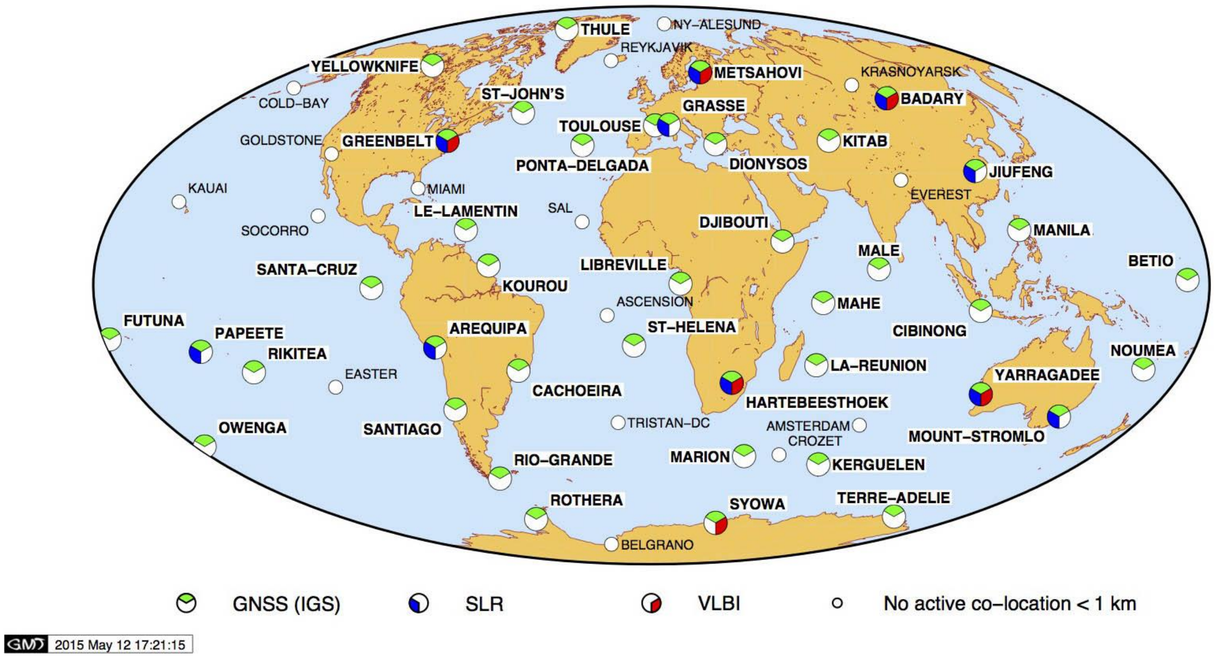


Figure 1.2: DORIS tracking network. Co-location with other IERS techniques As of May 2015.

As regards the ground equipment, the deployment of the remote control system allowing more rapid reaction to hardware failure is mostly complete. A new antenna type begins to roll out across the network. The letter "C" appears at the end of acronyms when this antenna type is used. This antenna is the same as the former one but the manufacturing process has been consolidated with more stringent specifications in order to better characterize the relative position of all the characteristic points of the antenna and draw up a more realistic error budget.

Efforts continued in the field to improve the monument stability at any new installation and to carry out high precision local tie surveys.

2. IDS organization

Like the other IAG Services, an IDS Governing Board (GB), helped by a Central Bureau (CB), organizes the activities done by the Analysis Centers (AC), the Data Centers (DC), and the Combination Center (CC).

2.1 Governing Board

On GB's request, a Working Group was formed on September 2010 to review and update the IDS Terms of Reference. The main evolutions of the text are:

- Revision of the election process of the GB members; the members at large are elected by the Associates Members, and not by the GB.
- Addition of a representative for the Combination Center.
- Addition of a DORIS system representative appointed by CNES
- Appointment of the network representative by IGN

The new Terms of Reference have been applied for the renewal of the GB whose term was ending in December 2012. Elections were held in Fall 2012. Because of the set up of the GB partial renewal process with election every two years, only 3 elected positions were renewed this time for the 4-year term 2013-2016: Analysis Center representative, Data Center representative, 1 member at large. The terms of Frank Lemoine (Analysis Coordinator) and John Ries (Member at large) have been extended for two additional years. Elections were organized in Fall 2014 to renew these two positions. The new members elected by the IDS Associates will serve four years from January 2015 to December 2018. For the first time, a tandem was chosen to occupy the seat of Analysis Coordinator. Hugues Capdeville and Jean-Michel Lemoine share together the responsibility and the work of the Analysis Coordination. From January 1st 2015, they can be contact at ids.analysis.coordination@ids-doris.org

Table 2.1 presents the evolution of the composition of the IDS Governing Board over 2009-2015. Note that since 2013, the GB is composed of eleven members instead of nine previously.

Table 2.1: Composition of the IDS Governing Board (2009 to 2015). Current members are indicated in bold.

Position	Term	Status	Name	Affiliation	Country
Analysis coordinator	**2015-2018**	Elected	**Hugues Capdeville** **Jean-Michel Lemoine**	CLS CNES/GRGS	France
	2013-2014	Ext'd	*Frank Lemoine*	NASA/GSFC	USA
	2009-2012	E.b.GB			
Data Centers' representative	**2013-2016**	Elected	**Carey Noll**	NASA/GSFC	USA
	2009-2012	Elected			
Analysis Centers' representative	**2013-2016**	Elected	**Pascal Willis (chair)**	IGN+IPGP	France
	2009-2012	Elected			
Member at large	**2015-2018**	Elected	**Marek Ziebart**	UCL	UK
	2013-2014	Ext'd	*John Ries*	U. Texas/CSR	USA
	2009-2012	E.b.GB			
Member at large	**2013-2016**	Elected	**Richard Biancale**	CNES/GRGS	France
	2009-2012	E.b.GB	*Pascale Ferrage*	CNES	France
Director of the Central Bureau	**since 2003**	Appointed	**Laurent Soudarin**	CLS	France
Combination Center representative	**since 2013**	Appointed	**Guilhem Moreaux**	CLS	France
Network representative	**2013-2016**	Appointed	**Jérôme Saunier**	IGN	France
	2010-2012	E.b.GB	*Bruno Garayt*	IGN	France
	2009	E.b.GB	*Hervé Fagard*	IGN	France
System representative	**2013-2016**	Appointed	**Pascale Ferrage**	CNES	France
IAG representative	**2013-2016**	Appointed	**Michiel Otten**	ESOC	Germany
	2009-2012	Appointed			
IERS representative	**2013-2016**	Appointed	**Brian Luzum**	USNO	USA
	2009-2012	Appointed	*Chopo Ma*	NASA/GSFC	USA

Elected = Elected by IDS Associates

E.b.GB = Elected by the previous Governing Board

Ext'd = Extended term for two years linked to the set up of the partial renewal process

2.2 Central Bureau

During the last four years, the Central has continued to improve the IDS information system. One of the main events is the launch of the IDS web service (http://ids-doris.org/webservice) named DOR-O-T for DORis Online Tools (pronounced like the French given name Dorothée) in 2014. The current version provides tools to browse time series in an interactive and intuitive way. It includes a network viewer to select sites and a family of plot tools to visualize the following time series: (1) station position differences at observation epochs relative to a reference position; (2) DORIS data residuals and the amount of available station observations as deduced from the CNES Precise Orbit Ephemeris processing, (3) outputs of the IDS Combination Center analysis, such as the Helmert parameters, and the WRMS. In addition to visualizing DORIS station coordinate time series, the web service also incorporates the time evolution of GNSS stations that are in co-location with DORIS, thanks to collaboration with the IGS Terrestrial Reference Frame Combination Center.

The website has been also improved. The content management system was upgraded. The updating of the web pages including station information is now easier since these data are now directly loaded from the database initially installed for the web service.

In 2012, then in 2014, the DORIS users were solicited to give their satisfaction level concerning the services provided by the IDS CB. They were invited to fill in a survey form on the IDS web site. These surveys helped the Central Bureau to improve the web site and the web service.

2.3 Data Centers

Since the beginning of the IDS, two data centers have provided open access to IDS data and products: the CDDIS, located in the U.S. and funded by NASA/GSFC (ftp://cddis.gsfc.nasa.gov) and IGN in France using two mirroring sites (ftp://doris.ign.fr and ftp://doris.ensg.ign.fr). They are both exact mirrors of each other, and so, are able to continue on an operational basis, even if one of them is inaccessible due to a temporary failure.

2.4 Analysis Centers and Analysis Coordination

In the last four years, the number of Analysis Centers slightly changed due to the cessation of the activities of Geoscience Australia as an IDS Analysis Center in December 2012.
There are currently six active Analysis Centers, using five different software packages, as displayed in Table 2.3.

Table 2.3: IDS Analysis centers. As of May 2015.

Acronym	Analysis Center	Country	Software Package
ESA	European Space Operation Center	Germany	NAPEOS
GOP	Geodetic Observatory Pecny	Czech Rep.	Bernese
GSC	Goddard Space Flight Center	USA	GEODYN
IGN	Institut Geographique National	France	GIPSY/OASIS
INA	INASAN	Russia	GIPSY/OASIS
GRG (formerly LCA)	Centre National d'Etudes Spatiales + Collecte Localisation Satellite	France	GINS/DYNAMO

Three other institutions contribute to IDS analysis too: GFZ, TU/Delft, the University College/London. It should also be mentionned that the Norwegian Mapping Authority (NMA) expressed in an interest in analysis of DORIS data, and also in multi-technique analyses. In the future, the participation of the NMA and other potential IDS ACs should continue to be encouraged.

The Analysis Centers and the associate groups works together within the Analysis Working Group (AWG), under the initiative of the IDS Analysis Coordinator (Frank Lemoine, NASA/GSFC), discussed their analysis strategy and provided tests solutions to IDS, as well as operational solutions in view of the ITRF2008 realization.

All the Analysis Centers have a very important commitment in the AWG. With the support of the Combination Center, they made sustained efforts in the last few years to implement improvements in their processing, to reprocess all the DORIS data, and to prepare weekly SINEX files from 1993 to 2014 for the development of the IDS contribution to ITRF2014.

The major changes that were validated in 2013-2014, included the following:

(1) The implementation and validation of the phase law for the DORIS antennae in the software of the different IDS Analysis Centers;
(2) The introduction of new satellites into the DORIS weekly solutions;
(3) The improvement in the troposphere modeling by some of the different IDS Analysis Centers;
(4) The testing of improved gravity models, and associated models for atmospheric and ocean de-aliasing;
(5) The identification of discrepancies in the processing for different analysis centers through comparison of the time series of empirical accelerations.

As a conclusion, we may highlight that six DORIS Analysis Centers successfully processed 20 years of data to 11 satellites and submitted SINEX files that were combined into an IDS solution for ITRF2014. The IDS Community should not rest on its laurels, as there are still many substantive issues that remain to be addressed, even with the current data already processed.

2.5 Combination Center

After the successful DORIS contribution to ITRF2008, IDS decided to extend the combination process to an operational service. Every 3 months, Analysis Centers deliver to the DCs 3 months of cumulated weekly SINEX solutions (including all the satellites) with a latency of 3 months.

In addition to its operational activities of evaluation and combination of all the individual ACs weekly solutions, the IDS Combination Center has been involved in several studies proposed by the AWG and the Analysis Coordinator:

- impact of the seven channels of the new DORIS DGXX receiver;
- impact of the properly handling of the beacon frequency offsets between the actual frequency of the transmitted signal at 2GHz by the beacons and its nominal value at 2.03625 GHZ (this correction solved copious amounts of artificial discontinuities and shifts in the vertical position time series);
- assessment of the ground antenna phase laws;
- contribution of each new satellite to the combination.

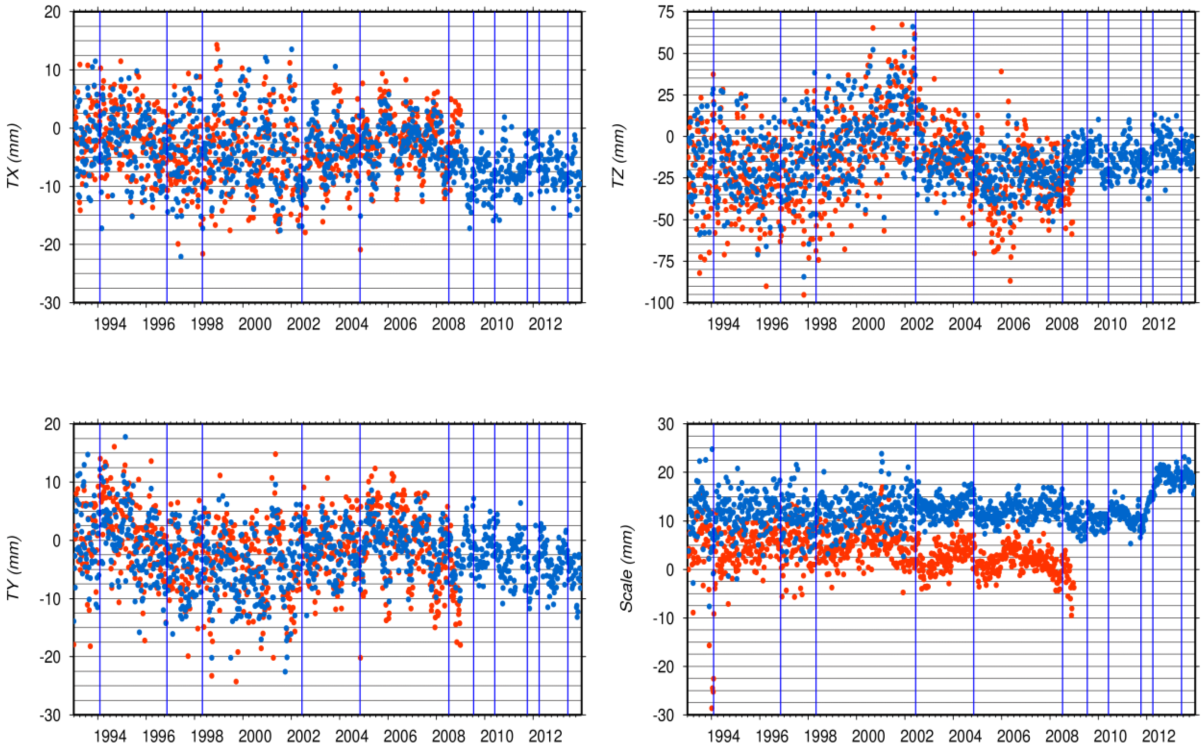


Figure 2.1 - Helmert parameters (translations and scale of the IDS contributions to ITRF2008 (red) and ITRF2014 (blue) with respect to ITRF2008.

From 2012, the activity of the Combination Center has been mainly devoted to the elaboration of the DORIS contribution to the next ITRF. In 2014, it delivered to IERS five versions of the IDS combined SINEX files. Each version is a set of eleven hundreds of weekly SINEX files including station coordinates and earth orientation parameters, covering the time period from 1993 to 2014. These IDS series are the result of the combination of weekly solutions from the six Analysis Centers (ESA, Geodetic Observatory of Pecny, NASA, IGN, INASAN, CNES/CLS). The data comes from three generations of DORIS receivers onboard of eleven satellites (Cryosat-2, Envisat, HY-2A, Jason-1,-2, Saral, SPOT-2,-3,-4,-5 and TOPEX/Poseidon) supported by a beacon network of nearly sixty stations uniformly spread across the globe. Due to Jason-1 and SPOT5 USO's sensitivity to the South Atlantic Anomaly (SAA), for these 2 missions IDS made available SAA corrected data. Evaluation of the IDS contribution to ITRF2008 (series 01) and to ITRF2014 (series 07) with respect to ITRF2008 (see Figure 2.1) showed:

- Improvements of Tx, Ty and Tz after 2002 (lower STDs, less annual signal) thanks to time variable gravity fields use in the ITRF2014 contribution.
- Scale offset (between the IDS contributions to the 2 ITRF) due to phase center's variations of the beacons in ITRF2014 processing.
- Less scale spurious values early 1994 (SPOT2 is no more included in the combined scale) in IDS series 07.
- No more scale factor discontinuity in 2002 thanks to beacon frequency offset estimations.
- Improvement of scale stability between end of TOPEX (late 2004) and Jason-2 start (mid 2008) thanks to Jason-1 including.
- Scale factor increase mid 2012.
- Better week-to-week repeatability of Helmert parameters of IDS series 07 (solution more consistent).

In addition, the evaluation process also pointed out that the IDS contribution to ITRF2013 gives higher differences of mainly X-pole estimates with the IERS C04 than the IDS contribution to ITRF2008 series. The explanation of that substantial degradation could be that the new solution uses 2 ACs less than the previous one.

3. IDS products

Table 3.1 presents the current IDS products available through the two IDS data centers. All Analysis Centers provided at a least a long-term weekly solution of SINEX files.

Table 3.1: IDS Product Types and Contributing Analysis Centers. As of December 2014

Type of Product	ACs/Products										
	ESA	**GAU***	**GOP**	**GRG ****	**GSC**	**IDS**	**IGN**	**INA**	**LCA ****	**SOD***	**SSA**
Time series of SINEX solutions (*sinex_series*)	X	X	X	X	X	X	X	X	X	X	X
Global SINEX solutions (*sinex_global*)				X			X		X		
Geocenter time series (*geoc*)							X	X	X		
Orbits/satellite (*orbits*)				X	X				X		X
Ionosphere products/satellite (*iono*)											X
Time series of EOP (*eop*)							X	X			
Time series of station coordinates (*stcd*)	X				X	X	X	X	X		X
Time series of SINEX solutions (2010campaign)		X	X		X		X	X	X		

*Note: GAU and SOD historic solutions

**Note: CNES/CLS transitioned their AC acronym from LCA to GRG in 2014.

4. IDS meetings and publications

4.1 Meetings

IDS organizes two types of meetings:

- IDS Workshops (every two years), opened to a large public and related to scientific aspects or applications of the DORIS systems
- Analysis Working Group Meetings (AWG) (when needed), more focussed on technical issues, and usually attended by representatives of Analysis Centers.

Table 4.1 summarizes all the IDS meetings held during the last four years.

Table 4.1: IDS meetings (June 2011 – May 2015).

Meeting	Location	Country	Dates
DORIS AWG Meeting	Prague	Czech Republic	31 May-1 June 2012
DORIS AWG Meeting	Venice	Italy	26 September 2012
IDS Workshop	Venice	Italy	25-26 September 2012
DORIS AWG Meeting	Toulouse	France	4-5 April 2013
DORIS AWG Meeting	Washington	USA	15-16 October 2013
DORIS AWG Meeting	Paris	France	26-27 March 2014
IDS Workshop	Konstanz	Germany	27-28 October 2014
DORIS AWG Meeting	Toulouse	France	28-29 May 2014

4.2 Publications

During the last four years, IDS published several annual reports (by chronological order) :

Willis, P., International DORIS Service (IDS), Report of the International Association of Geodesy 2007-2011, Travaux de l'Association Internationale de Geodesie, 2011. http://ids-doris.org/documents/report/IDS_Report_2007_2011_for_IAG.pdf

Ferrage, P., Garayt, B., Govind, R., Kuzin, S., Lemoine, F., Ma, F., Moreaux, G., Noll, C., Otten, M., Ries, J.C., Saunier, J., Soudarin, L., Stepanek, P., Willis, P. International DORIS Service Activity report 2011, 85 pages, 2012. http://ids-doris.org/documents/report/IDS_Report_2011.pdf

Ferrage, P., Garayt, B., Kuzin, S., Lemoine, F., Ma, F., Moreaux, G., Noll, C., Otten, M., Ries, J.C., Saunier, J., Soudarin, L., Stepanek, P., Willis, P. International DORIS Service Activity report 2012, 96 pages, 2013. http://ids-doris.org/documents/report/IDS_Report_2012.pdf

Biancale, B., Capdeville, H., Ferrage, P., Garayt, B., Kuzin, S., Lemoine, F., Luzum, B., Moreaux, G., Noll, C., Otten, M., Ries, J.C., Saunier, J., Soudarin, L., Stepanek, P., Willis, P. International DORIS Service Activity report 2013, 98 pages, 2014. http://ids-doris.org/documents/report/IDS_Report_2013.pdf

Capdeville, H., Couhert, A., Ferrage, P., Kuzin, S., Lemoine, F., Moreaux, G., Noll, C., Otten, M., Rudenko, S., Saunier, J., Schrama, E., Soudarin, L., Stepanek, P., Willis, P., International DORIS Service Activity report 2014, 120 pages, 2015. (in preparation)

4.3 Peer-reviewed publications related to DORIS

Following two DORIS Special Issues published in Journal of Geodesy in 2006-2007, and Advances in Space Research (ASR) in 2010, a call for participation was issued by the Guest Editors (Frank Lemoine and Ernst Schrama) for a new DORIS Special Issue in ASR entitled "Scientific Applications of DORIS data in preparation of ITRF2014". The submission deadline for the papers is May 31, 2015.

IDS also maintains on its Web site a complete list of DORIS-related peer-reviewed articles published in international Journals (http://ids-doris.org/report/publications/peer-reviewed-journals.html). In the last five years, the following articles were published (by year):

In press

Jayles, C.; Chauveau, J.P.; Auriol, A., in press. DORIS/DIODE : Real-Time Orbit Determination Performance on Board SARAL/AltiKa, Marine Geodesy, DOI: 10.1080/01490419.2015.1015695

Willis, P.; Lemoine, F.G.; Moreaux, G.; Soudarin, L.; Ferrage, P.; Ries, J.; Otten, M.; Saunier, J.; Noll, C.; Biancale, R.; Luzum, B., in press. The International DORIS Service (IDS), recent developments in preparation for ITRF2013, IAG SYMPOSIA SERIES, 143

Willis, P.; Zelensky, N.P.; Ries, J.; Soudarin, L.; Cerri, L.; Moreaux, G.; Lemoine, F.G.; Otten, M.; Argus, D.F.; Heflin, M.B., in press. DPOD2008, a DORIS-oriented Terrestrial Reference Frame for Precise Orbit Determination, IAG SYMPOSIA SERIES,143

2015

Couhert, A.; Cerri, L.; Legeais, J.F.; Ablain, M.; Zelensky, N.P.; Haines, B.J.; Lemoine, F.G.; Bertiger, W.I.; Desai, S.D.; Otten, M., 2015. Towards the 1 mm/y Stability of the Radial Orbit Error at Regional Scales, ADVANCES IN SPACE RESEARCH, 55(1), 2-3, DOI : 10.1016/j.asr.2014.06.041 1-year OPEN ACCESS

Gao, F.; Peng, B.; Zhang, Y.; Evariste, N.H.; Liu, J.; Wang, X.; Zhong, M.; Lin, M.; Wang, N.; Chen, R.; Xu H., 2015. Analysis of HY2A Precise Orbit Determination Using DORIS, ADVANCES IN SPACE RESEARCH, 55(5), 1394-1404, DOI : 10.1016/j.asr.2014.11.032

Zishen, L. ; Yunbin, Y.; Ningbo, W.; Hernandez-Pajares, M.; Xingliang, H., 2015. SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions, JOURNAL OF GEODESY, 89(4), 331-345, DOI: 10.1007/s00190-014-0778-9

2014

Bock, O.; Willis, P.; Wang, J.; Mears, C., 2014. A high-quality, homogenized, global, long-term (1993-2008) DORIS precipitable water dataset for climate monitoring and model verification, JOURNAL OF GEOPHYSICAL RESEARCH - ATMOSPHERES, DOI: 10.1002/2013JD021124

Dettmering, D.; Limberger, M.; Schmidt, M., 2014. Using DORIS measurements for modeling the vertical total electron content of the Earth's ionosphere, JOURNAL OF GEODESY, 48(12), 1131-1143, DOI : 10.1007/s00190-014-0748-2

Guo, J.; Zhao, Q.; Guo, X.; Liu, X.L.; Liu, J.N.; Zhou, Q., 2014. Quality assessment of onboard GPS receiver and its combination with DORIS and SLR for Haiyang 2A precise orbit determination, SCIENCE CHINA-EARTH SCIENCES, 58(1), 138-150, DOI: 10.1007/s11430-014-4943-z

Kong, Q.; Guo, J.; Hwang, C.; Gao, F.; Lin, H.; Zhao, C., 2014. Precise orbit determination and accuracy analysis of HY-2A satellite using DORIS Doppler data, ACTA GEODAETICA ET GEOPHYSICA, 49(4), 455-470, DOI : 10.1007/s40328-014-0066-4

Kosek, W.; Wnęk, A.; Zbylut-Górska,M.; Popiński, W., 2014. Wavelet analysis of the Earth center of mass time series determined by satellite techniques, JOURNAL OF GEODYNAMICS, DOI: 10.1016/j.jog.2014.02.005

Palanisamy, H.; Cazenave, A.; Meyssignac, B.; Soudarin, L.; Wöppelmann, G.; Becker, M., 2014. Regional sea level variability, total relative sea level rise and its impacts on islands and coastal zones of Indian Ocean over the last sixty years, GLOBAL AND PLANETARY CHANGE, 116:54-67, DOI: 10.1016/j.gloplacha.2014.02.001

Rudenko, S.; Dettmering, D.; Esselborn, S.; Schöne, T.; Förste, C.; Lemoine, J.M.; Ablain, M.; Alexandre, D., Neumayer, K.H., 2014. Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trend, ADVANCES IN SPACE RESEARCH, 54(1): 92-118, DOI: 10.1016/j.asr.2014.03.010

Stepanek, P.; Rodriguez-Solano, C.J.; Hugentobler, U.; Filler, V., 2014. Impact of orbit modeling on DORIS station position and Earth rotation estimates, ADVANCES IN SPACE RESEARCH, 53(7):1058-1070, DOI: 10.1016/j.asr.2014.01.007

Willis, P.; Bock, O.; Bar-Sever, Y.E., 2014. DORIS Tropospheric Estimation at IGN, Current Strategies, GPS Intercomparisons and Perspectives, IAG SYMPOSIA SERIES, 139:11-18, DOI: 10.1007/978-3-642-37222-3_2

Zhou, Q.; Guo, J.; Zhao, Q., 2014. Precise orbit determination for Haiyang 2A satellite using un-differenced DORIS code and phase measurements, LECTURE NOTES IN ELECTRICAL ENGINEERING, 305(3), 31-39. DOI: 10.1007/978-3-642-54740-9_3

2013

Cerri, L.; Lemoine, J.M.; Mercier, F.; Zelensky, N.P.; Lemoine, F.G., 2013. DORIS-based point mascons for the long term stability of precise orbit solutions, ADVANCES IN SPACE RESEARCH, 52(3):466-476, DOI: 10.1016/j.asr.2013.03.023

Guo, J.; Kong, Q.; Qin, J.; Sun, Y., 2013. On precise orbit determination of HY-2 with space geodetic techniques, ACTA GEOPHYSICA, 61(3):752-772, DOI: 10.2478/s11600-012-0095-8

Khelifa, S.; Kalhouche, S.; Belbachir, M.F., 2013. Analysis of position time series of GPS-DORIS co-located stations, INTERNATIONAL JOURNAL OF APPLIED EARTH OBERVATION AND GEOINFORMATION, 20:67-76, DOI: 10.1016/j.jag.2011.12.011

Melachroinos, S.A.; Lemoine, F.G.; Zelensky, N.P.; Rowlands, D.D.; Luthcke, S.B.; Bordyugov, O., 2013. The effect of geocenter motion on Jason-2 orbits and the mean sea level, ADVANCES IN SPACE RESEARCH, 51(8):1323-1334, DOI: 10.1016/j.asr.2012.06.004

Saria, E.; Calais, E.; Altamimi, Z.; Willis, P.; Farah, H., 2013. A new velocity field for Africa from combined GPS and DORIS space geodetic solutions: Contribution to the definition of the African reference frame (AFREF), JOURNAL OF GEOPHYSICAL RESEARCH - SOLID EARTH, 118(4):1677-1697, DOI: 10.1002/jgrb.50137

Stepanek, P.; Dousa, J.; Filler, V., 2013. SPOT-5 DORIS oscillator instability due to South Atlantic Anomaly: mapping the effect and application of data corrective model, ADVANCES IN SPACE RESEARCH, 52(7):1355–1365, DOI: 10.1016/j.asr.2013.07.010

Willis, P.; Mertikas, S.; Argus, D.F.; Bock, O., 2013. DORIS and GPS Monitoring of the Gavdos Calibration Site in Crete, ADVANCES IN SPACE RESEARCH, 51(8):1438-1447, DOI: 10.1016/j.asr.2012.08.006

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Khelifa, S.; Kalhouche, S.; Belbachir, M.F., 2012. Signal and noise separation in time series of DORIS station coordinates using wavelet and singular spectrum analysis, COMPTES RENDUS GEOSCIENCE, 344(6-7):319-376, DOI: 10.1016/j.crte.2012.05.003.

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Seitz, M.; Angermann, D.; Blossfeld, M.; Drewes, H.; Gerstl, M., 2012. The 2008 DGFI realization of the ITRS: DTRF2008, JOURNAL OF GEODESY, 86(12):1097-1123, DOI: 10.1007/s00190-012-0567-2

Tatevian, S.; Kluykov, A.; Kuzin S., 2012. On the role of space geodetic measurements for global changes monitoring, RUSSIAN JOURNAL OF EARTH SCIENCES VOL. 12, ES3002, DOI: 10.2205/2012ES000511

Willis, P.; Bar-Sever, Y.E; Bock, O., 2012. Estimating horizontal tropospheric gradients in DORIS data processing, Preliminary results, IAG SYMPOSIA SERIES, 136:1013-1019, DOI: 10.1007/978-3-642-20338-1_127

Willis, P.; Gobinddass, M.L.; Garayt, B.; Fagard, H., 2012. Recent improvements in DORIS data processing in view of ITRF2008, the ignwd08 solution, IAG SYMPOSIA SERIES, 136:43-49, DOI: 10.1007/978-3-642-20338-1_6

2011

Altamimi, Z.: Collilieux, X.; Métivier, L., 2011. ITRF2008: An improved solution of the International Terrestrial Reference Frame, JOURNAL OF GEODESY, 85(8):457-473, DOI: 10.1007/s00190-011-0444-4 OPEN ACCESS

Dettmering, D.; Heinkelmann, R.; Schmidt, M., 2011. Systematic differences between VTEC obtained by different space-geodetic techniques during CONT08, JOURNAL OF GEODESY, 85(7):443-451, DOI: 10.1007/s00190-011-0473-z

Fadil, A.; Sichoix, L.; Barriot, J.P.; Ortéga, P.; Willis, P., 2011. Evidence for a slow subsidence of the Tahiti Island from GPS, DORIS, and combined satellite altimetry and tide gauge sea level records, COMPTES RENDUS GEOSCIENCES, 343(5):331-341, DOI: 10.1016/j.crte.2011.02.002

Flohrer, C.; Otten, M.; Springer, T.; Dow, J., 2011. Generating precise and homogeneous orbits for Jason-1 and Jason-2, ADVANCES IN SPACE RESEARCH, 48(1):152-172, DOI: 10.1016/j.asr.2011.02.017

Siefring, Carl L.; Bernhardt, Paul A.; Koch, Douglas E.; Galysh, Ivan J., 2011. Using TEC and radio scintillation data from the CITRIS radio beacon receiver to study low and midlatitude ionospheric irregularities, RADIO SCIENCE, 46, Art. RS0D19, DOI: 10.1029/2010RS004585

Teke, K.; Böhm, J.; Nilsson, T.; Schuh, H.; Steigenberger, P.; Dach, R.; Heinkelmann, R.; Willis, P.; Haas, R.; Garcia-Espada, S.; Hobiger, T.; Ichikawa, R.; Shimizu, S., 2011. Multi-technique comparison of troposphere zenith delays and gradients during CONT08, JOURNAL OF GEODESY, 85(7), 395-413, DOI: 10.1007/s00190-010-0434-y

Yin, P.; Mitchell, C.N., 2011. Demonstration of the use of the Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) measurements to validate GPS ionospheric, ADVANCES IN SPACE RESEARCH, 48(3):500-506, DOI: 10.1016/j.asr.2011.04.010

International Earth Rotation and Reference Systems Service (IERS)

http://www.iers.org

Chair of the Directing Board: Chopo Ma (USA) (until 31 December 2012), Brian Luzum (USA) (since 1 January 2013)
Director of the Central Bureau: Bernd Richter (Germany) (until 31 March 2013), Daniela Thaller (since 1 April 2013)

Overview

The International Earth Rotation and Reference Systems Service marked its 25th anniversary of operations on 1 January 2013. It continues to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other operationally oriented communities.

Earth orientation data have been issued on a daily (and since 2012 also 4 times per day), weekly, and monthly basis, and new global geophysical fluids data were added. Work on new realizations of the International Terrestrial Reference System (ITRF2014) and of the International Celestial Reference System (ICRF3) was started. The IERS Conventions (i.e. standards etc.) have been updated regularly. New Working Groups on SINEX Format and on Site Coordinate Time Series Format were established in 2011 and 2012, respectively.

The IERS continued to issue Technical Notes, Annual Reports, Bulletins, and electronic newsletters. It held a GGFC Workshop (April 2012), a Workshop on Local Surveys and Co-locations (May 2013), a Retreat (May 2013), and organized two Unified Analysis Workshops (September 2011 and June 2014).

The IERS Data and Information System (DIS) at the web site www.iers.org, maintained by the Central Bureau, has been updated, improved and enlarged continually. It presents information related to the IERS and the topics of Earth rotation and reference systems. As the central access point to all IERS products it provides tools for searching within the products (data and publications), to work with the products and to download them. The DIS provides links to other servers, among these to about 10 web sites run by other IERS components.

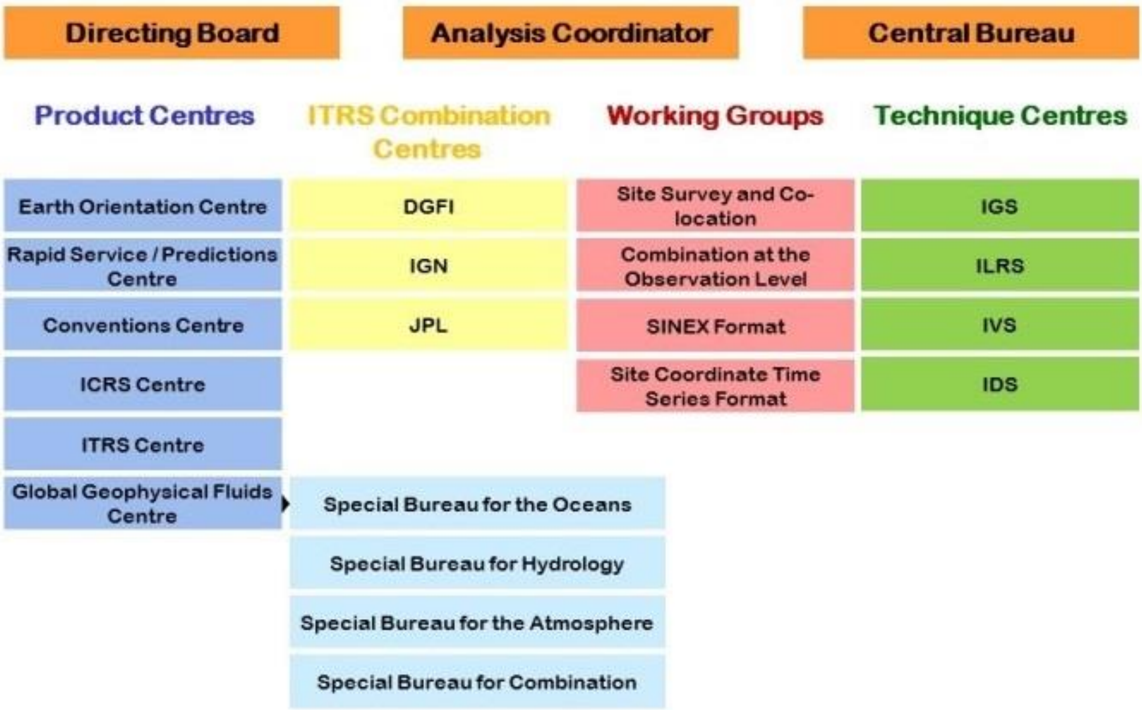
In 2013, changes in key positions of IERS occurred with a new Chair of the Directing Board and a new Director of the Central Bureau.

Structure

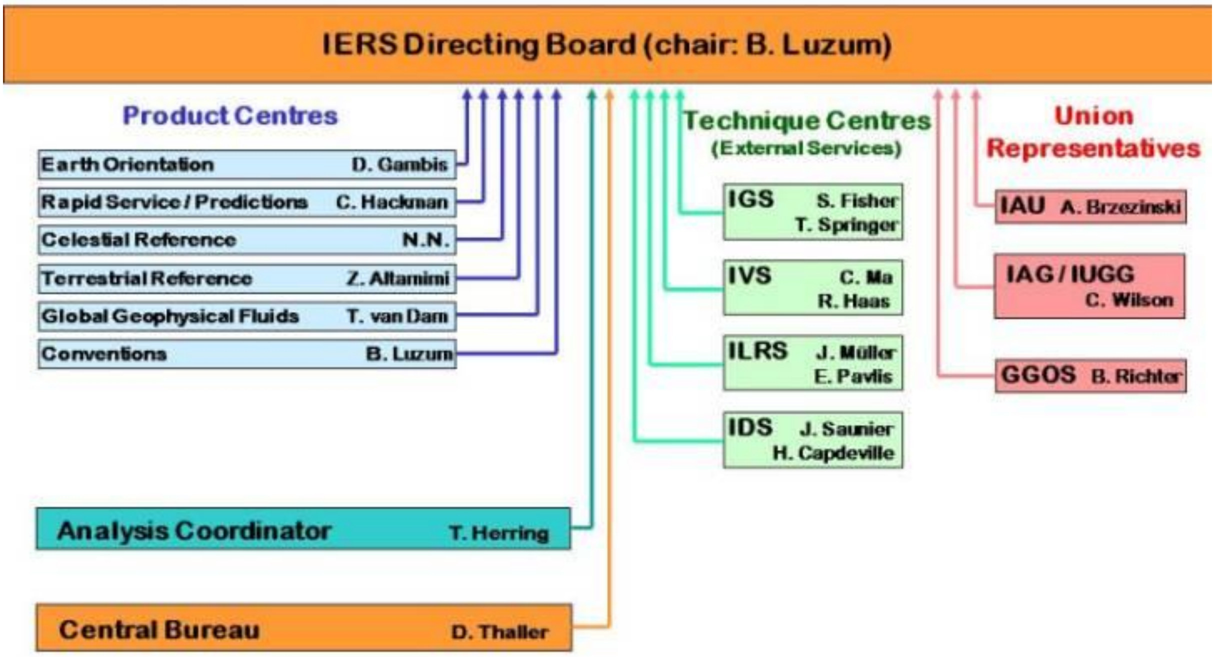
According to the Terms of Reference, the IERS consists of the following components:
- Technique Centres
- Product Centres
- ITRS Combination Centre(s)
- Analysis Coordinator
- Central Bureau
- Directing Board
- Working Groups

The Technique Centres are autonomous operations, structurally independent from the IERS, but which cooperate with the IERS.

As of May 2015, the IERS consists of the following components:



The current members of the Directing Board (representatives of scientific unions and of IERS' components) are:



Activities

Publications

The following IERS publications and newsletters appeared between mid-2011 and May 2015:

- IERS Technical Note No. 37: Z. Altamimi, X. Collilieux and L. Métivier: Analysis and results of ITRF2008
- IERS Annual Reports 2008-09, 2010, 2011, 2012, and 2013
- IERS Bulletins A, B, C, and D (weekly to half-yearly)
- IERS Messages Nos. 191 to 269

Workshops

The IERS organized the following workshops and a retreat:

- *Third GGOS Unified Analysis Workshop (Zürich, Switzerland, 16 – 17 September 2011)*. The workshop was intended to be a forum for the exchange of information and results concerning both problems common to more than one service and problems specific to an individual service. It was aimed at increasing the common understanding of the individual techniques as they contribute to GGOS. The following sessions were held: Session 1: Products by the Services, Filling the GGOS Portal; Session 2: Modelling Based on External Data (Atmosphere, Ocean, ...), Modelling Deficiencies and Standards; Session 3: ITRF 20xx and Other Combined Products; Session 4: Co-location on Ground and in Space, GGOS Core Sites.
- *GGFC Workshop (Vienna, Austria, 20 April 2012)*. The meeting focused on assessing the errors in current environmental models and proposals for overcoming these limitations for use in geodetic and geophysical data analysis. 10 recommendations were formulated (combining the various products for atmospheric and hydrologic models).
- *IERS Workshop on Local Surveys and Co-locations (Paris, France, 21 – 22 May 2013)*. This second workshop on local ties, tie vectors, co-location sites and their use in the combination of space geodetic solutions provided a platform for discussion and diffusion of the most recent results. Particular emphasis was put on the systematic errors that affect both the space geodetic and the tie vector solutions, these latter being key elements to improve ITRF accuracy. A list of recommendations has been drafted, e.g. a local survey archive is planned.
- *IERS Retreat (Paris, France, 23 – 24 May 2013)*. The aim of the retreat was to establish directions for the IERS over next decade that will ensure its core role is met. The overall theme was to maintain the quality and regularity of the IERS' products and to ensure that the service continues to meet the needs of all of its users. The retreat covered the following sessions: Session 1: Towards "real-time" products; Session 2: Rigorous combined products; Session 3: Long-term stability and parameterization of the reference frame; Session 5: EOP predictions improvements; Session 6: Unification of product formats; Sessions 4+7: New products and mechanisms for IERS evolution.
- *4th Unified Analysis Workshop (Pasadena, California, USA, 27 - 28 June 2014)*. For this workshop, papers were invited that addressed the following areas: VLBI/SLR/ DORIS scale differences; Assessment of models of geophysical fluids on EOP variations; Development of loading models; Analysis methods; Monument stability. Several recommendations for these topics were developed.

Abstracts, presentations, and recommendations of these meetings are available at the IERS web site.

Activities of the IERS components

Central components

The *IERS Directing Board* (DB) met twice each year to decide on important matters of the Service like structural changes, overall strategy, creating working groups, launching projects, changing Terms of Reference, etc:

- Meeting No. 53 in San Francisco, December 3, 2011;
- No. 54 in Vienna, April 22, 2012;
- No. 55 in San Francisco, December 1, 2012;
- No. 56 in Paris, May 25, 2013;
- No. 57 in San Francisco, December 8, 2013;
- No. 58 in Vienna, April 27, 2014;
- No. 59 in San Francisco, December 14, 2014;
- No. 60 in Vienna, April 12, 2015.

Among the most important decisions made by the DB in 2011–2015 were the following:

- Accepted the provisional geophysical fluids products as operational ones.
- Approved the activity to establish a "survey operational entity" within the ITRS Centre.
- Agreed to establish IERS Working Groups on SINEX Format and on Site Coordinate Time Series Format.
- Accepted JPL as new ITRS Combination Centre.
- Elected a new Chair of the Directing Board.
- Changed the Terms of Reference to specify the role of the IERS Associate Members.

The *Central Bureau* coordinated the work of the Directing Board and the IERS in general, organized meetings and issued publications. It replied to questions of users regarding IERS products and general topics of Earth rotation and reference systems. It further developed the IERS Data and Information System based on modern technologies for internet-based exchange of data and information like the application of the Extensible Markup Language (XML) and the generation and administration of ISO standardised metadata. The system provides general information on the structure and the components of the IERS and gives access to all products. For most IERS products, metadata according to ISO 19115 were produced. The move to a new data management system of retrieval, check, metadata extraction, format conversions, storage, and presentation was finished in May 2013. At the end of 2014, a new IERS User and Address Management System was introduced. Users and members of the IERS may log in to the private user area of the IERS website and may update their contact data and subscribe to newsletters and printed publications. New users can register directly on the IERS website.

The work of the *Analysis Coordinator* focused on preparing the Unified Analysis Workshops and the IERS Retreat (see above). He analysed the current state of EOP products, proposed to establish a unified EOP data format, and developed recommendations from the Unified Analysis Workshops.

Technique Centres

The Technique Centres (TC) are autonomous independent services, which cooperate with the IERS:

- *International GNSS Service* (IGS)
- *International Laser Ranging Service* (ILRS)
- *International VLBI Service for Geodesy and Astrometry* (IVS)
- *International DORIS Service* (IDS)

By the end of February 2015, all TCs submitted their solutions for the ITRF2014. For details about the work of the TCs, see their individual reports to IAG.

Product Centres

The *Earth Orientation Centre* is responsible for monitoring of long-term Earth orientation parameters, publications for time dissemination and leap second announcements. It issues IERS Bulletins B, C, and D and corresponding data files. Since December 2011, only final values of the C04 EOP series values are provided. The generation of C04 series has been made fully automated with daily quality checks and comparisons. EOPs are now available also in XML format. The centre is working on the format for an authoritative file with leap second information.

The *Rapid Service/Prediction Centre* is responsible for providing Earth orientation parameters on a rapid turnaround basis, primarily for real-time-users and others needing the highest quality EOP information before the IERS final values are available. It issues IERS Bulletin A and corresponding data files. Further work has been dedicated to improvement of the centre's products. Since 2012, a new solution of ultra rapids is available 4 times per day. The short-term UT1−UTC predictions improved by nearly 25% since 2010 because of the reduced latency of VLBI intensive operations due to the electronic transfer of VLBI data. A backup of the EOP Combination and Prediction procedure, including web site for disseminating data, has been established at an offsite location. The centre studied the possibility of using the Network Time Protocol for distributing UT1.

The *Conventions Centre* started work on technical updates to the IERS Conventions (2010), with updates of existing content, expansion of models, and introducing new topics (non-tidal loading, SINEX format for modelling, ...). The Centre maintains a web site including pages for the Conventions updates.

Involvement by *ICRS Centre* personnel in the celestial reference frame VLBI program has continued, participating in extensive observing programmes. The ICRS Centre has continued the various tasks devoted to the monitoring of ICRF sources, the link with the dynamical system (through LLR, pulsar timing, and observations of asteroids), the construction of the LQAC (Large Quasar Astrometric Catalogue) and of the LQRF (Large Quasar Reference Frame). Together with the new IAU Division 1 Working Group on ICRF3, the ICRS Centre started work to prepare the next ICRF, which is expected to be finished by 2018. The IERS wrote a letter of support for the VLBA, the closure of which would be detrimental to the completion of ICRF3.

The *ITRS Centre* participated in complete surveys of some co-location sites, contributed to specifications for ITRF densification, developed the tools and methodology for generating the ITRF from SINEX inputs from the various space geodesy techniques (in cooperation with the ITRS Combination Centres), and maintained the IERS network. In March 2013, the ITRS Centre issued a Call for Participation in ITRF2013. In 2014 it was decided to expand the time span of data used until the end of 2014 and to create an ITRF2014. The IERS Directing Board approved the activity to establish a "Survey operational entity" within the ITRS Centre; its mission would be to supply local tie data and products as well as recommendations to surveyors and users. The ITRF web site has been newly designed and improved.

The *Global Geophysical Fluids Centre* (GGFC) has been re-organized since 2010. It consists now of four Special Bureaus for Oceans, Hydrology, Atmosphere, and Combination. The first product centres were recognized. The IERS Directing Board accepted the provisional geophysical fluids products as operational. An additional call for new products and for the Chair of Science Support Component was distributed in 2012. Several new products have been proposed and evaluated for latency and reliability. Together with the ITRS Centre, the GGFC issued a call for participation concerning tidal and non-tidal loading studies in 2012. It organized a GGFC workshop in April 2012 in Vienna (see above).

ITRS Combination Centres and Working Groups

Three *ITRS Combination Centres* are responsible for providing ITRF products by combining ITRF inputs. The ITRS Combination Centre at DGFI focused on research regarding a common realization of the ITRS and ICRS. It realized for the first time the ITRS and the ICRS consistently in one common adjustment. The IERS Directing Board accepted JPL as new ITRS Combination Centre in December 2012. The ITRS Combination Centres started to work on their new realizations of the ITRS by analysing the contributions of the Technique Centres to the ITRF2014.

Areas of work of the *Working Group on Site Survey and Co-location* are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation. It was re-organized in 2012. The WG held a workshop in May 2013 (see above). In 2014 it issued a resolution on the nomenclature of space-geodetic reference points and local tie measurements.

The major task of the *Working Group on Combination at the Observation Level* is to study methods and advantages of combining techniques at the observation level, searching for an optimal strategy to solve for geodetic parameters. The first action of the WG was to organize an inter-comparison campaign in order to homogenize the software packages used. The period chosen was the one corresponding to the three weeks of the CONT08 VLBI campaign. The combination has been performed for common parameters: station coordinates, Earth orientation parameters, orbit parameters and troposphere parameters. The multi-technique approach provides the opportunity to compare in a coherent way the solutions obtained from various techniques. This was demonstrated for the case of ZTD. Homogenized processing of CONT08 and CONT11 campaigns solving all parameters together are in progress; a long-term combination is expected to be submitted in the ITRF2014 framework. The working group maintains an online "Forum Multi-technique Combinations".

The *Working Group on SINEX Format*, established in 2011, has been working on modifications in the SATELLITE/ID block and revision of Appendix II (mathematical background), as well as on other topics.

The objectives of the new *Working Group on Site Coordinate Time Series Format*, a joint WG of IERS and IAG, are a user-friendly format with data and metadata by definition of a common exchange format for coordinate time series for all geodetic techniques (DORIS, GNSS, SLR, VLBI) with all necessary information (data and metadata). The goal is to access products via web interfaces.

All working groups held several meetings, summaries and presentations of which are available at the IERS web site.

International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it

President: Riccardo Barzaghi (Italy, 2011-2013) - Mirko Reguzzoni (Italy, 2014-2015)
Director: Riccardo Barzaghi (Italy, 2011-2013) - Giovanna Sona (Italy, 2014-2015)

Overview

The International Geoid Service (IGeS) formally changed the name to International Service for the Geoid (ISG) on April 26th, 2014, during the IAG Executive Committee in Vienna. The service governance was changed too, nominating Mirko Reguzzoni as president and Giovanna Sona as director of the service.

In the period 2011-2015, the main scientific activities of ISG have been related to the following research lines:
- methods for merging local geoid estimates;
- methods for defining a global/regional unified height datum;
- GOCE data processing and merging with existing global gravity models;
- support to research centres and national institutions on geoid estimation;
- organization of schools on geoid and height datum estimation;
- ISG web site update and Newton's Bulletin publications.

High accuracy and reliable satellite-only global geopotential models can be used both to merge local geoid solutions and to properly define a unified global height datum. This second issue is particularly relevant and is one of the GGOS themes (i.e. Theme 1: Unified Height System). Both problems are strictly related to the ISG mission that is focussed on local/regional geoid estimation and evaluation.

The new methodologies that have been developed for merging local geoids and for defining a global/regional height datum are based on GOCE global geopotential models and in particular on the space-wise solutions which are computed with the support of ISG.

The procedure for merging geoids assumes that a bias (or more generally a systematic effect) exists between local estimates due to inconsistencies in defining the local height datum. It can be proved that this bias can be estimated and removed by comparing the local solutions with the GOCE derived model, since a satellite-only model is not affected by these height datum biases. The devised method for global/regional height datum unification relies on GOCE geopotential models too. Numerical tests have been performed on both methodologies with positive results. In the same line of research, a procedure to merge GOCE and EGM2008 global geoid models has been studied too.

Furthermore, the support activity on geoid computation continued. ISG has cooperated with the Centre for Geodesy and Geodynamics of Nigeria. Four researchers of this Centre were hosted at ISG in 2011 for two weeks. They attended a dedicated training course on geoid estimation theory and geoid estimation software. Similar training courses will be organized in the next months for researchers from Peru, Cameroun, Nigeria and Algeria. A delegation from the Republic Geodetic Authority of Serbia visited ISG in 2015 for three days in the framework of an EU Commission Programme. ISG also supported the computation of the geoid in the

San Paolo State in Brazil by hosting for one year (September 2011 to August 2012) a USP PhD student. ISG is currently involved in the computation of a geoid in the Jeddah area, Saudi Arabia, and it is supporting, together with BGI, the IGFS proposal for the computation of a new high resolution geoid model for the Mediterranean Sea (GEOMED-2 project). Moreover the computation of the new version of the Italian geoid has started in 2015.

An ISG school devoted to geoid estimation and height datum definition was organized during 2012 and held in October 7th-11th, 2013 at the Universidad Tecnica Particular de Loja in Loja, Ecuador. Contacts are now ongoing to organize a new geoid school in 2016.

ISG website has been totally renewed, updating information and improving the local geoid database by adding new models and by providing bibliographic references for any of the available models. Finally ISG is supporting the publication of a special issue of Newton's Bulletin 5 dedicated on the assessment of GOCE geopotential models.

Activities

1. A method for merging local geoid estimates

Local geoids estimated in neighbouring countries often display inconsistencies that can be mainly described by biases between local solutions. Sometimes, it is required to define a unique solution merging two different geoid estimates, thus removing the local biases. This can be properly done by using satellite-only models that are not perturbed by local datum effects entering in the local geoid estimates. A two-step procedure has been devised based on a GOCE geopotential model, assuming that the residuals in geoid after removing the GOCE model can be expressed as

$$N_{res} = N - N_L = b + N_H + e_{GOCE} + \nu$$

where b is the bias related to the local solution, N_L is the low frequency geoid component (the one that is assumed to be described by the GOCE model), N_H is the high frequency geoid component, e_{GOCE} is the GOCE model error and ν is the noise implied by the local geoid estimate. In the first step, by least squares adjustment, one can get the bias estimate as

$$b = \left(D^T Q^{-1} D\right)^{-1} D^T Q^{-1} N_{res}$$

with D the design matrix and

$$Q = C_{N_H} + C_{e_{GOCE}} + C_\nu \ .$$

This bias is then removed from N, thus obtaining an unbiased geoid, i.e.

$$N'_{res} = N - N_L - b \ .$$

This is done for the two geoid estimates to be merged. Then the two unbiased residual estimates can be combined via a standard collocation procedure to get a common geoid over the computation area. The final merged solution is then obtained by adding back the N_L component implied by the GOCE model. This procedure has been tested by merging the Swiss and the Italian geoids. In Figure 1 a North-South section is plotted: the effectiveness of the procedure is clearly visible.

This method has been described in the paper "A least-squares collocation procedure to merge local geoids with the aid of satellite-only gravity models: the Italian/Swiss geoids case study", by Gilardoni, Reguzzoni and Sampietro, which has been published on Bollettino di Geofisica Teorica ed Applicata,Vol. 54, n. 4, in 2013.

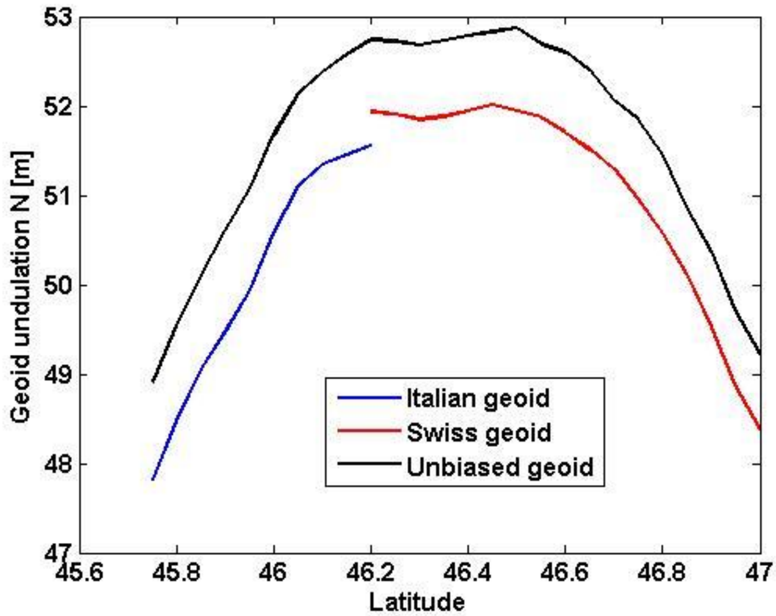


Figure 1: Merging the Italian and the Swiss geoid

The procedure has been generalized by considering not only a bias between two local geoids, but also a systematic effect due to a different reference ellipsoid. Furthermore, more than two regional geoids can be now merged together. This strategy has been tested for merging the geoid models of Spain, Portugal, France, Italy, Switzerland and part of the Mediterranean Sea. This study has been described in the paper "Using GOCE to straighten and sew European local geoids: preliminary study and first results" by Gilardoni, Reguzzoni and Sampietro, which has been published on IAG Symposia Series, Vol. 141, in 2014.

2. A method for global and local height datum estimation

The height datum problem has been revised in terms of the scalar Molodensky approach. It has been assumed that different height systems refer to their own benchmarks. So, the Earth surface can be patched into domains having different reference height systems. For each patch, a bias in the gravity potential is assumed, so that it holds

$$W(P_0^j) = W_0^j = W_0 + \delta W^j = U_0 + \delta W^j$$

where the patch S^j is referred to the benchmark point P_0^j. By developing this equation, one can get

$$\bar{\zeta}^j = -\frac{\delta W^j}{\gamma} = \tilde{\zeta}(P_l^j) - \frac{T(P_l^j)}{\gamma} = \tilde{\zeta}(P_l^j) - \frac{T_L(P_l^j)}{\gamma} - \frac{T_H(P_l^j)}{\gamma} \qquad l = 1,\ldots,M \qquad j = 1,\ldots,J$$

In this equation, the height anomaly biases $\bar{\zeta}^j$ of the different patches can be estimated using the observed (biased) height anomalies (P_l^j Earth surface point, $\tilde{P}_l^j$ point on the biased telluroids)

$$\tilde{\zeta}(P_l^j) = h(P_l^j) - h(\tilde{P}_l^j) \qquad l = 1,\dots,M$$

and the anomalous potential estimate

$$T(P) = T_L(P) + T_H(P) = \sum_{n=2}^{200} \sum_{m=-n}^{n} T_{nm} Y_{nm}(P) + \sum_{n=201}^{+\infty} \sum_{m=-n}^{n} T_{nm} Y_{nm}(P) \ .$$

Here the T_L component (the low frequency part) is given by the unbiased GOCE-only model, while the T_L component (the high frequency part) is assumed to be accounted for by the EGM2008 model up to *n=2190* (indeed this component is biased by the height datum but it can be proved that the induced error is of few millimetres).

Using this approach, an error budget has been performed. The Earth surface has been divided into 158 patches and a data distribution has been assumed in order to have at least one point per patch. Furthermore, different precisions for ellipsoidal and normal heights have been considered on the different patches. Assuming to estimate the δW^j by least squares, their standard deviation can be obtained. In Figure 2, the bias standard deviations are plotted.

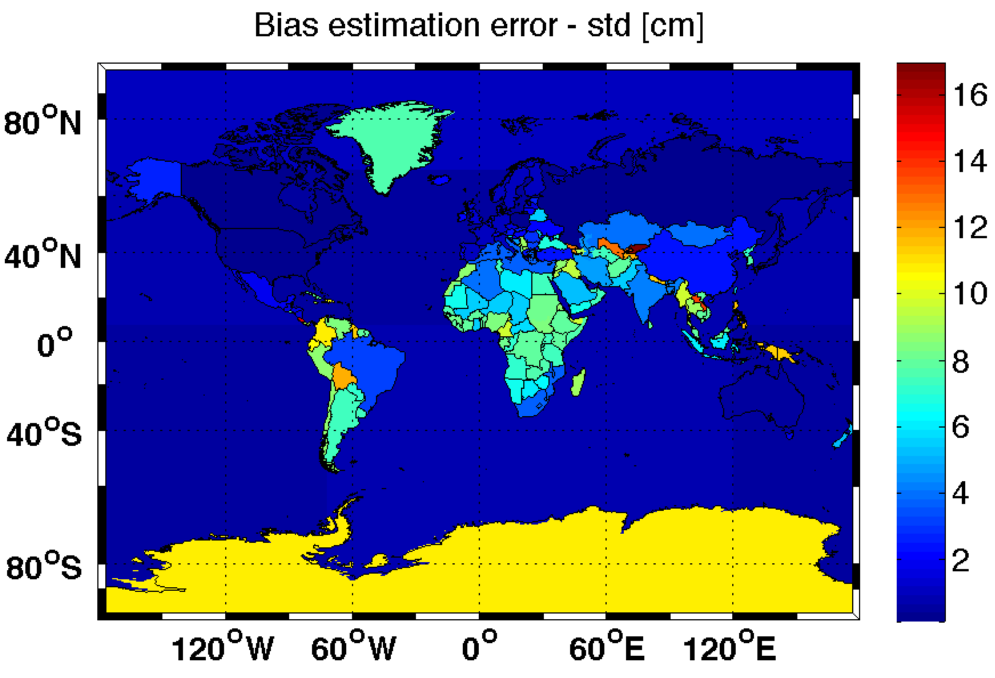


Figure 2: The δW^j standard deviations

The standard deviation values range from 1-2 cm up to 15 cm in limited areas of the Earth. This procedure seems to be feasible and, therefore, it has been initially applied to local areas, such as Italy to estimate a unified height system among mainland and Sicily and Sardinia islands, and it will be applied in the next future on EUVN data to estimate a unified European height system.

The theoretical base of the method has been described in the paper “The height datum problem and the role of satellite gravity models” by Gatti, Reguzzoni and Venuti, which has been published on Journal of Geodesy, Vol. 87, n. 1, in 2013. The simulation has been presented at EGU in Vienna in 2012 with a presentation entitled “A solution to the global height datum problem based on satellite derived global models and the corresponding error budget” by Barzaghi, Gatti, Reguzzoni and Venuti. Finally the application to the Italian case has been described in the paper “A feasibility study on the unification of the Italian height systems using GNSS-leveling data and global satellite gravity models” by Barzaghi, Carrion, Reguzzoni and Venuti, which will be published on IAG Symposia Series, Vol. 143.

3. GOCE data processing and a method to merge GOCE-only and EGM2008 models

Since the launch of the GOCE satellite (March 17th, 2009), ISG has been actively involved in estimating a global geopotential model based on GOCE data by supporting the implementation of the space-wise approach. Recently the space-wise processing scheme has been revised to produce global grids of gravity gradients at satellite altitude instead of spherical harmonic coefficients as the main product. Both SST and SGG GOCE data are used into the solution. The core of the processing scheme consists of:

- data filtering along the orbit by a successive application of a Wiener filter and a whitening filter with the aim of reducing noise variance and correlation.
- data gridding by collocation after subdividing data into local geographical patches.

From the estimated grids, spherical harmonic coefficients can be easily derived by numerical integration and by applying a global regularization. The error description of all products is based on Monte Carlo simulations.

The space-wise approach has been initially tested on a dataset based on a limited time span (from November 2009 to June 2010 corresponding to GOCE release 2 spherical harmonic global models). The method has been then applied to the full data set at nominal satellite altitude (corresponding to GOCE release 4 global models). A new solution, also including data of the GOCE altitude lowering phase (corresponding to GOCE release 5 global models) is currently under computation. Release 4 space-wise global grids and spherical harmonic coefficients have been presented at the 5th International GOCE User Workshop in Paris in 2014, with a presentation entitled “Space-wise grids of gravity gradients from GOCE data at nominal satellite altitude” by Gatti, Reguzzoni, Migliaccio and Sansò. A comparison among release 4 space-wise grids and other solutions has been presented at EGU in Vienna in 2015, with a poster entitled “Comparison of the GOCE space-wise grids and other GOCE solutions” by Gatti and Reguzzoni.

Apart from processing GOCE data, a method to merge the satellite-only GOCE global model with the ultra-high resolution EGM2008 global model has been also studied and implemented.

Particular attention has been paid to the EGM2008 error modelling into the combination. EGM2008 is in fact delivered with two, not fully consistent, sources of information on its error: spherical harmonic coefficient variances and a geographical map of error variances, e.g. in terms of geoid undulation.

A GOCE-only global gravity model can be used to improve EGM2008 in the low-medium frequencies, especially in areas where no data were available at the time of EGM2008 computation. The easiest way to combine a GOCE-only model with EGM2008 is to set up a least-squares adjustment considering the spherical harmonic coefficients of the two global gravity models

$$\underline{T}_{GECO-CC} = \left[\Sigma_E^{-1} + \Sigma_G^{-1}\right]^{-1}\left[\Sigma_E^{-1} \cdot \underline{T}_E + \Sigma_G^{-1} \cdot \underline{T}_G\right]$$

where $\underline{T}_{GECO-CC}$ is the spherical harmonic coefficient vector of the combined model, called GECO-CC (GOCE and EGM2008 combination using Coefficient Covariances), Σ_E is the diagonal covariance matrix of EGM2008, Σ_G is the block-diagonal covariance matrix of the GOCE-only model, $\underline{T}_E$ and $\underline{T}_G$ are the spherical harmonic coefficient vector of EGM2008 and of the GOCE-only model respectively (see Figure 3).

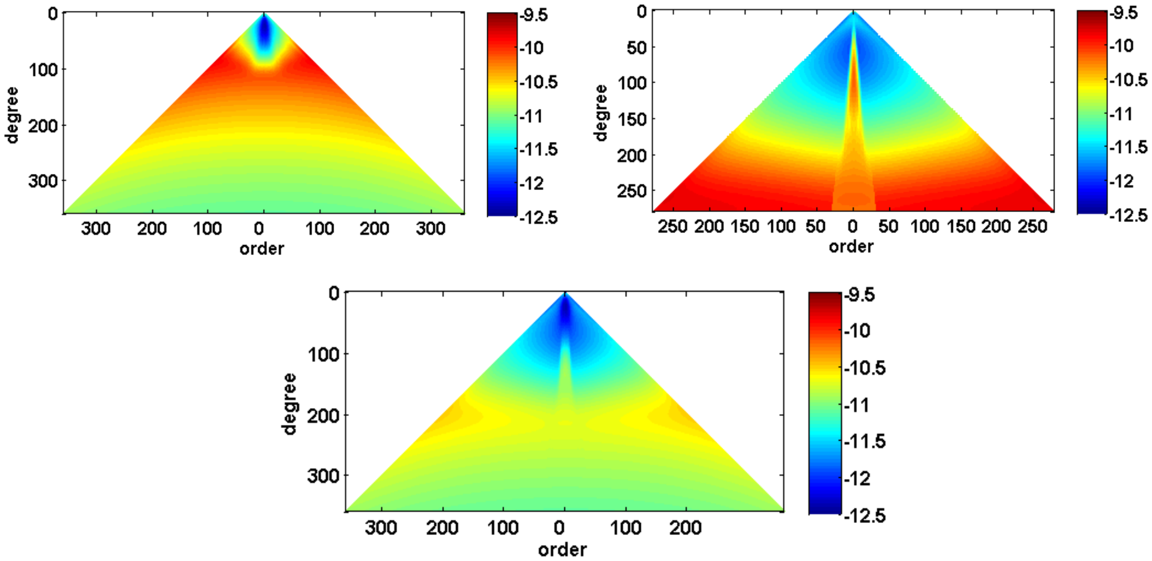


Figure 3. EGM2008 error coefficient standard deviation, GRACE contribution below degree 100 (upper-left). GOCE-only coefficient error standard deviation, polar gaps effect at low order (upper-right). GECO-CC coefficient error standard deviation, GOCE correction to EGM2008 up to about degree 200 (lower-center). All plots are in log10 scale.

A more refined way to combine GOCE and EGM2008 is to improve the EGM2008 error modelling by adding local information given by the freely available EGM2008 geographic map of error variances in terms of geoid undulations. In this locally adapted optimal combination, called GECO, the full error covariance matrix of the GOCE spherical harmonic coefficients is approximated by an order-wise block-diagonal matrix (as in GECO-CC), while for EGM2008, the error spatial correlations are taken from spherical harmonic coefficients while the point-wise error variances are taken from the provided geoid error map:

$$L_E^{NN} = S_E \cdot \left(D_E\right)^{-1} \cdot C_E^{NN} \cdot D_E^{-1} \cdot S_E$$

where L_E^{NN} is the localized covariance of $\underline{T}_E$, S_E is a diagonal matrix such that the elements of its diagonal are just the standard deviations of the geoid error map, D_E is a diagonal matrix containing the square root of the values of the main diagonal of C_E^{NN}, where C_E^{NN} is the covariance matrix obtained propagating the error coefficient variances to the geoid.

Due to computational limits, the combination is performed in terms of geoid undulation values over a regular grid on local areas. Repeating the combination for overlapping areas all over the world and then performing a harmonic analysis, the spherical harmonic coefficients of the new model are obtained. To be precise the combination is done till maximum degree 359 corresponding to 0.5° x 0.5° resolution and then the model is extended till degree 2159 using EGM2008.

The theoretical base of the combination is described in the paper "Combining EGM2008 with GOCE gravity models" by Gilardoni, Reguzzoni, Sampietro and Sansò, which has been published on Bollettino di Geofisica Teorica ed Applicata, Vol. 54, n. 4, in 2013. The practical application of the combination to produce a new global model has been described in the paper: ''GECO: a global gravity model by locally combining GOCE data and EGM2008'' by Gilardoni, Reguzzoni and Sampietro, which has been submitted to Studia Geophysica et Geodaetica in 2015.

4. The support to researches and activities on geoid estimation

In spring 2011, from May 30th to June 14th, four researchers of the Centre of Geodesy and Geodynamics (National Space Resource and Development Agency, Nigeria) attended at ISG a Special Course on Determination and Use of the Geoid. Every day, there were lectures for two or three hours. The rest of the day was devoted to individual learning with tutoring and to practice on geoid computation software using the computer facilities at ISG. The detailed program is listed below:

- May 30th — Basic concepts in geodesy and geoid computation
- May 31st — Study of Lecture Notes with tutoring
- June 1st — Global Models
- June 6th, morning: — Terrain effect in geoid computation
- June 6th, afternoon: — Residual Terrain Correction
- June 7th — Practical examples on Terrain Effect computation
- June 8th, morning: — The core solution: theory of Collocation
- June 8th, afternoon: — The core solution: Stokes and FFT
- June 9th — Practical examples on core solution computation
- June 10th — Local geoid computation: review of all the steps
- June 13th — Comparison of residual undulation computation methods
- June 14th — Practical examples on geoid computation

The aim of this special course was, as requested from the researchers of the Centre of Geodesy and Geodynamics, to have an intensive training on geoid estimation allowing them to have the basic notions for estimating their own national geoid based on the available data in Nigeria. After this course, contacts between them and ISG have been maintained.

In 2012, one PhD student from USP, San Paulo, Brazil, was hosted at ISG in the framework of a cooperation between the two Institutions. He was involved in a project aiming at estimating the geoid in the San Paulo State. During his stay at ISG, he was trained in geoid estimation procedure based on collocation and the "remove-restore" method. In order to estimate the RTC effect, a detailed DTM/bathymetry model was set up. This has been accomplished by merging the SRTM DTM with the available NOAA bathymetry of the Atlantic Ocean in the computation area. A check for possible outliers both in the gravity and in the GPS/levelling databases to be used in the geoid estimation process was also performed.

Different global geopotential models (including those based on GOCE data) were tested to check for their impact on the estimate. The final geoid estimate based on collocation has been then compared to GPS/levelling data and previous geoid computations obtained with different methods (i.e. Helmert-Stokes). The collocation estimated geoid proved to be equivalent to the existing ones and close to the GPS/levelling independent data. Statistics related to this comparison are detailed in Table 1.

Table 1: San Paulo geoid statistics. Residuals between geoid estimates and GPS/levelling (363 points)

Geoid Model	E(m)	R.m.s. (m)	Max. (m)	Min. (m)
FFT(EGM2008-360)	0.13	0.23	0.58	-0.41
LSC(EGM2008-360)	0.16	0.25	0.72	-0.47
FFT(GOCE-DIR_R3)	0.11	0.21	0.49	-0.44
LSC(GOCE-DIR_R3)	0.09	0.20	0.56	-0.50
FFT(GOCE-TIM_R3)	0.11	0.22	0.51	-0.43
LSC(GOCE-TIM_R3)	0.09	0.20	0.58	-0.47
FFT(GOCO03S)	0.12	0.22	0.51	-0.43
LSC(GOCO03S)	0.09	0.20	0.54	-0.47
FFT(EIGEN-6C)	0.11	0.22	0.51	-0.45
LSC(EIGEN-6C)	0.09	0.20	0.51	-0.49

The geoid estimate based on Least Squares Collocation is displayed in Figure 4.

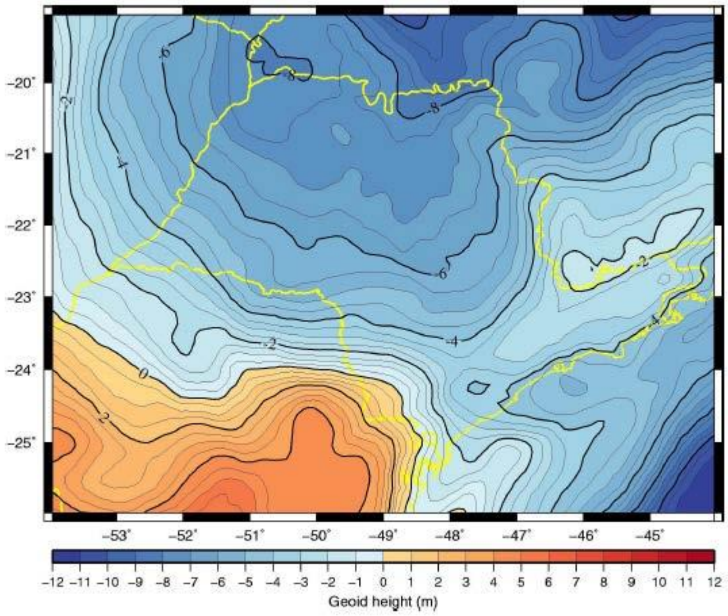


Figure 4: San Paulo geoid estimate using LSC

The student got a joint PhD between USP and Politecnico di Milano, discussing a PhD thesis entitled "A geoid model in the State of Sao Paulo: An attempt for the evaluation of different methodologies" (Brazilian tutor Prof. Denizar Blitzkow, Italian tutor Prof. Riccardo Barzaghi). In spring 2015, from April 22nd to April 24th, three officers of the Republic Geodetic Authority of Serbia visited ISG in the framework of the TAIEX (Technical Assistance and

Information Exchange) programme supported by the European Commission. The aim of this study visit was to present the activities performed by ISG on local and global geoid computation and on the use of the computed geoid. The study visit agenda was the following:

- April 22nd, morning: Local geoid computation by using remove-restore technique
- April 22nd, afternoon: The use of DTMs for RTC computation
- April 23rd, morning: Global model computation from satellite missions
- April 23rd, afternoon: The importance of preprocessing and orthometric corrections in the geoid computation - the Italian case
- April 24th, morning: The use of geoid models for ocean circulation modelling
- April 24th, afternoon: Presentation of the ISG website and activities

In 2015, training activities are planned for supporting researchers coming from developing countries. In particular, a Special Course on Determination and Use of the Geoid (similar to the one given in Spring 2011 to the Nigerian researchers) will be given to two researches of the Coodinacion Tecnica de Aerodromos and Coodinacion Tecnica de Navegacion Aerea (Peru) and from 13rd to 28th November, 2015 (date to be fixed) to three or four researchers of the Institut National de Cartographie (Cameroun). Furthermore study visits are foreseen for a researcher from the Nigerian College of Aviation Technology (from 8th to 12th June, 2015), for an Algerian researcher (from 1st to 30th September, 2015). Finally three officers of BGI will attend an advance training course on the software for geoid computation at ISG.

As for the projects dedicated to geoid estimation ISG has been involved in the computation of a high resolution geoid in the Jeddah area, Saudi Arabia, which is currently under evaluation process. ISG is also supporting, together with BGI, the IGFS proposal for the computation of a high resolution geoid of the Mediterranean Sea (GEOMED-2 project) submitted to ESA. Apart from the IGFS/BGI/ISG services, the proposal partners are:

- Politecnico di Milano (Italy)
- GET, OCA/Geoazur and SHOM (France)
- University of Thessaloniki (Greece)
- DTU Space (Denmark)
- General Command of Mapping (Turkey)
- University of Zagreb (Croatia)
- University of Jaén (Spain)

A two years project is planned to estimate the geoid and the DOT of the Mediterranean Sea.
In 2015 the computation of the new version of the Italian geoid has started. For this purpose, the Italian gravity database has been validated: the database has been formed by merging different sources on the sea and on the land, the data have been cross-checked to look for outliers. The database has also been purged from double points. The database improvement, in addition to a refinement in the collocation estimation of the residuals, led to a reduction of 2 cm in the standard deviation of the residuals of the gravimetric geoid with respect to the GPS/levelling (from 11 cm to 9 cm). A refinement of the adaptation of the gravimetric geoid to the GPS/levelling data is still ongoing.

In cooperation with the IGM (Istituto Geografico Militare) the impact of the orthometric correction to the Italian network levelling loops misclosure is being evaluated. It has been verified that the Italian geoid gravity database can be used to fill the existing gaps in the gravity measures corresponding to the levelling lines. This will allow to obtain orthometric, normal and dynamic heights for the Italian levelling network. The computation of the corrections is still ongoing. The feasibility of the method has been described in the paper "Orthometric correction and normal heights for Italian levelling network: a case study", by Barzaghi, Betti, Carrion, Gentile, Maseroli, Sacerdote, which has been published on Applied Geomatics, Vol. 6, in 2014. A further discussion about the correction equations can be found in the paper "The observation equation of spirit leveling in Molodensky's context" by Betti, Carrion, Sacerdote and Venuti, which will be published in IAG Symposia Series (Proceedings of the VIII Hotine Marussi Symnposium).

5. The organization of schools on geoid and height datum estimation

The XI International IGS School was held in Ecuador from 7th to 11th October, 2013, at the Universidad Tecnica Particular de Loja in Loja. The title of the school was "heights and datum height" and, differently from the previous ISG schools, it was not dedicated only to the standard methods on geoid computation, but also to new items on height systems. More specifically, the school program was the following:

Geodetic Heights (October 7th, 2015)

Definition of ellipsoidal, dynamical and orthometric heights and their observation equations; geoid and telluroid; the GBVP, reduction to the ellipsoid, mapping to the sphere, spherical harmonics.

The Global Gravitational Model EGM2008 (October 8th, 2015)

Creation of a Global Geopotential Model and in particular of EGM2008; computation of different functionals.

Modelling the topographic effect (October 9th, 2015)

Terrain Correction, Helmert reduction; from TC to Residual TC.

Local improvements of the geoid (October 9th, 2015)

Remove-Restore method; collocation; geoid computation using FFT.

Exercises (October 10th, 2015)

Exercises on the use of global geopotential models and on the computation of local geoid models.

Vertical Datum Standardization (October 11th, 2015)

Vertical datum establishment, standardization and unification: the South American case.

The total number of participant was 15. They come from Brazil, Colombia, Dominic Republic, Ecuador, Egypt, Greece, Mexico, United States of America and Venezuela. Students had some printed lectures notes, and the ISG CD-rom with software and data for exercises. At the end of the School, the Local Committee gave to the students also a CD-rom with all the lectures presented in the School, photos and Loja city video. Each student and professor received a Participation Certificate. The teachers of this school were F. Sansò, N. Pavlis, D. Blitzkow, R. Barzaghi and L. Sánchez.

A new ISG School is going to be held next year. There are many candidates to organize the school (e.g. Universities of the Dominican Republic, Mexico, Jordan, etc.); a final decision on the location will be taken in the next months. Furthermore, different formats will be studied and proposed in order to have schools on a broader set of possible topics in physical geodesy.

6. The new ISG website and Newton's Bulletin publications

During 2012, the ISG website has been completely revised and improved. The geoid repository has been enriched with new local solutions, namely the Switzerland, the French, the new European EGG2008 and the US geoids. In the last two years, the number of available geoid models has been further increased, e.g. adding the Ukrainian and the Hungarian geoids, see Figure 5, and two models in the Antarctica.

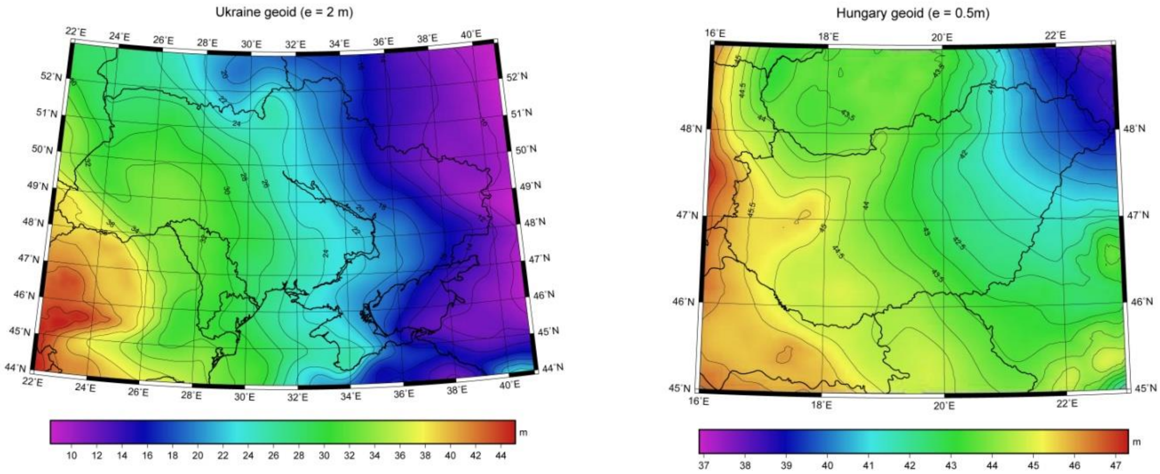


Figure 5: Ukrainian geoid (on the left) and Hungarian geoid (on the right).

A total number of 41 regional models in GRD format are currently stored in the repository and retrievable by users according to the defined distribution policy. Geoids can be freely downloaded if coded as public, available on demand in case the authors asked to be informed before made them available, private if the geoid owners decided not to distribute them. The geoid model to retrieve can be selected from a complete list of available geoids or by clicking on a geographical map. As for the global geoid models, a link to ICGEM is provided. A new regional model can be submitted to ISG via website (sending an email with proper information); in addition, email requests for acquiring new regional models are directly and quite frequently sent by ISG secretariat to the geoid authors/owners. Finally, at least a bibliographic reference for any regional model is now given.

As for the software section, a free and open source program for synthesizing different gravity field functional from ultra-high degree spherical harmonic models has been made available. This software is supported by the Italian Space Agency (ASI) through the GOCE-Italy project (rif. dr. tec-001-GOCEI-1.0).

As for the ISG publications, in the new website the IGeS Bulletins' archive has been made available. Any single issue can be downloaded directly from the webpage (note that IGeS Bulletin is not published anymore since 2003). Moreover, Newton's Bulletin issues are now available online. In this case, either the full issue or single papers (online first) can be downloaded by readers. The new ISG main webpage is shown in Figure 6.

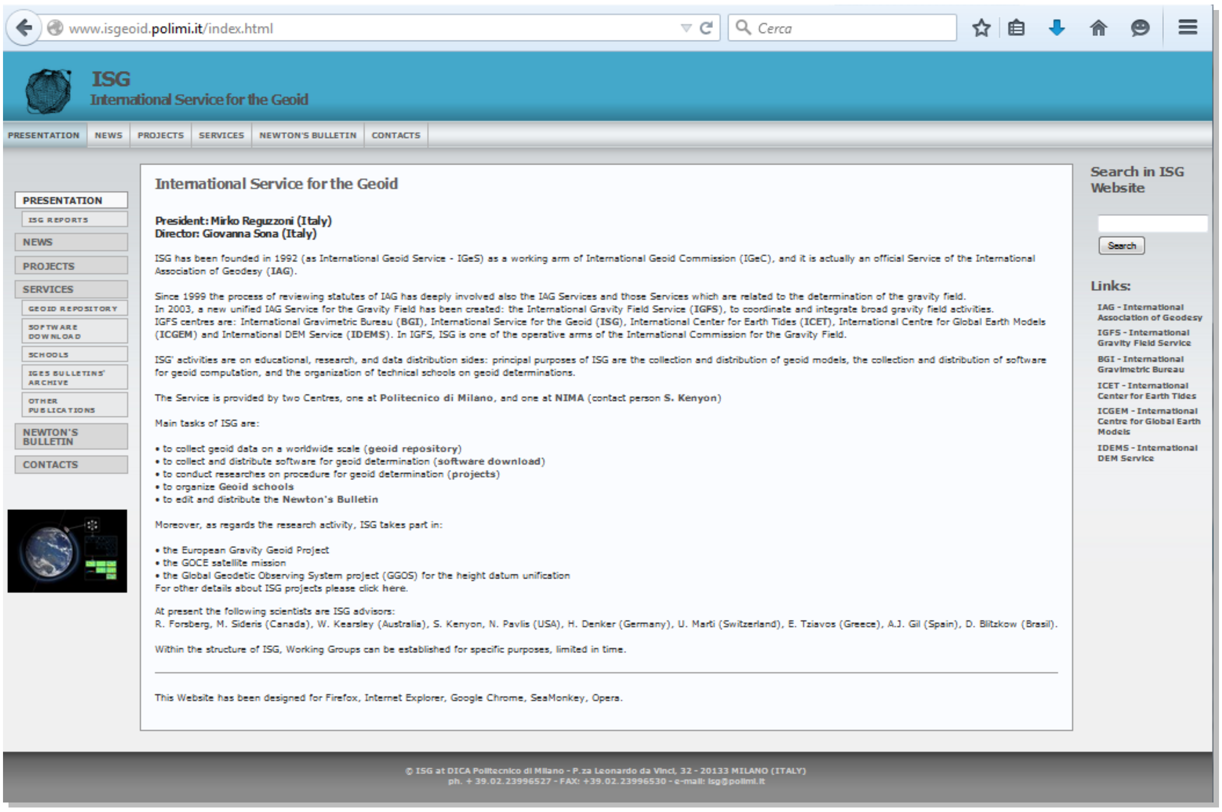


Figure 6: The new ISG webpage

In the last years two peer-reviewed papers have been accepted for publication on Newton's Bulletin and they are now published "online first". During a JWG2.3 splinter meeting in Shanghai, China, in the occasion of the last IGFS general assembly (June 30th - July 6th, 2014), it was decided to collect contributions for a special issue of Newton's Bulletin 5 dedicated on the assessment of GOCE geopotential models, and in particular HPF release R5 model (TIM05 and DIR05). Jianliang Huang is editor of this issue, supported by Mirko Reguzzoni and Thomas Gruber as associated editors. A total number of 13 submissions have been received. The plan is to complete the whole review process and published the accepted manuscripts for the IUGG2015 general assembly in Prague.

International Gravimetric Bureau (Bureau Gravimétrique International, BGI)

http://bgi.obs-mip.fr

Director: Sylvain Bonvalot (France)

Overview

The International Gravimetric Bureau (BGI) has been created in 1951 by the IUGG (International Union in Geophysics and Geodesy) with the aim to collect on a world-wide basis, all gravity measurements to generate a global digital database of gravity data for any public or private user. The technological and scientific evolutions which occurred over the last 50 years in the area of gravimetry (improvements in field, airborne and seaborne gravity meters, development of absolute gravity meters, space gravity missions, etc.) provided significant increases of the number, diversity and accuracy of the gravity field observables. Following these evolutions, BGI has contributed to provide original databases and services for a wide international community concerned by the studies of the Earth gravity field.

The BGI is an official service of the International Association of Geodesy (IAG) and since 2003 it is coordinated with others IAG services (IGeS, ICET, ICGEM, IDEMS) by the International Gravity Field Service (IGFS). It also directly contributes to the activities of the IAG Commission 2 "Gravity Field" and of the IAG Global Geodetic Observing System (GGOS). It is recognized by the International Council for Science (ICSU) successively as one of the services of the Federation of Astronomical and Geophysical Services (FAGS) and of the World Data System (WDS) created in 2008.

For more information:

- The International Gravimetric Bureau. In: "The Geodesist's Handbook, 2012", H. Drewes, H. Hornik, J. Adam, S. Rozsa Eds. (International Association of Geodesy). Journal of Geodesy, Volume 86, Number 10, October 2012, pp. 946-949.
- BGI website : http://bgi.obs-mip.fr/

Mission and objectives

As a service of IAG/IGFS, BGI aims ensuring the data inventory and the long term availability of the gravity measurements acquired on Earth. Hence, one of the main task of BGI is to collect all gravity measurements (relative or absolute) and pertinent information about the Earth's gravity field, to compile them and store them in a computerized data base in order to redistribute them on request to a large variety of users for scientific purposes.

The database of relative measurements contains over 12 million of observations compiled and computerized from land, marine and airborne gravity surveys. For several decades, it has been extensively used for the definition of Earth gravity field models and for many applications in geodesy, geophysics, oceanography, metrology, satellite orbit computation, etc.

A database for absolute gravity measurements was also set up and put into operation in joint cooperation between BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany). This global database initiated in 2008, now displays and makes accessible data and information on available absolute gravity measurements.

In addition, BGI provides other additional services in the area of gravimetry (validation for regional or global projects, online access to reference gravity stations, expertise, bibliography database, etc.). It also contributes to R&D activities (global gravity modeling, data interpretation, software developments, etc.), to data acquisition (relative or absolute gravity surveys), and to educational activities (teaching and summer schools on gravity data acquisition and processing, tutorials and educational materials in gravimetry, etc.).

BGI activities are mostly carried out in the frame of national and international collaborations with many institutions involved in the acquisition or in the use of gravity measurements. Collaborations within IAG Services and Commissions and within IGFS activities are also very active in areas such as absolute gravimetry, global gravity modeling, combination of satellite & surface data, etc.

Most of services provided by BGI (consultations and requests of gravity database, products, documentations, etc.) are accessible through the BGI website (http://bgi.obs-mip.fr/). Data, products or software available at BGI are mostly dedicated to support scientific and academic activities.

Structure and membership

National support

BGI has had its offices located in France (Paris, then Toulouse) since its creation. Since 1979, it has been housed in the premises of the Centre National d'Etudes Spatiales (CNES) / Groupe de Recherche en Géodésie Spatiale (GRGS) and of the Observatoire Midi-Pyrénées (OMP). Today, BGI is also recognized as a permanent service accredited by french Institut National des Sciences de l'Univers (INSU). In 2013, all BGI offices and staff moved in a new building within the OMP Toulouse. The address and contacts are unchanged.

The activities of BGI in France are supported by most of the national Institutions / Agencies and Universities involved in the acquisition or use of gravity data for a wide range of applications (research, education, exploration, reference system, metrology…). This comprises : Centre National d'Etudes Spatiales (CNES) / Groupe de Recherche en Géodésie Spatiale (GRGS), Institut National des Sciences de l'Univers (INSU), Institut Géographique National (IGN), Bureau de Recherches Géologiques et Minières (BRGM), Institut de Physique du Globe de Paris (IPGP), Institut de Recherche pour le Développement (IRD), Service Hydrographique et Océanographique de la Marine (SHOM), Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Ecole Supérieure des Géomètres et Topographes (ESGT) and several laboratories of the Universities of Toulouse (GET), Montpellier (GM), and Strasbourg (EOST/IPGS). The contribution of each supporting institution is defined and updated each four years in a general agreement / MOU approved by all respective Directors.

International collaborations

International collaborations are mostly carried out with other IAG services or commissions in the frame of IGFS activities as well as directly with BGI users.

A new partnership has been established in 2008 between BGI and the Bundesamt für Kartographie und Geodäsie (BKG) Germany for the realization and the maintenance of the global database of absolute gravity measurements now operated jointly by BGI and BKG. This database will provide the support for the new International Reference Gravity Network that will replace the old IGSN71.

In the last few years, active collaborations also tool place with NGA (USA), DTU (Denmark) or Curtin University (Australia) for the computation or the validation of the gravity anomalies performed for the World Gravity Map project led by BGI.

The figure 1 summarizes the main structure and collaboration of BGI.

Figure 1: International and national structure of BGI and main recent international collaborations

Permanent staff (full time or part time)

Central Bureau, Toulouse (CNES-GRGS, IRD, CNRS-INSU, OMP)

- S. Bonvalot *Geophysics – Absolute & relative gravimetry (Director)*
- G. Balmino , *Geodesist - Space geodesy*
- A. Briais, *Geologist / Geophysicist – marine gravimetry*
- R. Biancale, *Geodesist - Space geodesy*
- S. Bruinsma, *Geodesist - Space geodesy*
- G. Gabalda, *Geophysicist – Absolute & relative gravimetry*
- N. Lestieu, *Secretary*
- F. Reinquin, *Geodesist - Database manager / software developer*
- L. Seoane, *Geodesist - Satellite gravimetry*

Others teams and contributors (France)

Paris (IPGP - IGN-LAREG: M. Diament, I. Panet, G. Pajot); Orléans (BRGM: G. Martelet); Strasbourg (EOST: J. Hinderer, S. Rozat, JP. Boy, JB. Daniel); Montpellier (Géosciences: N. Le Moigne, C. Champollion, S. Mazzotti); Brest (IFREMER: E. Moussat, L. Petit de la Villeon); Brest (SHOM: M.F. Lalancette; D. Rouxel); Le Mans (ESGT: J. Cali, J. Verdun).

Associated contributors (Germany)

Frankfurt / Leipzig (BKG : H. Wilmes, H. Wziontek)

Activities

According to the 2011-2015 project plan, the main BGI activities aimed (i) at consolidating the terrestrial gravity database (relative and absolute) and encouraging the collection and compilation of incoming datasets, (ii) at developing new products and services for the Earth's science community, and (iii) at making easier the consultation and diffusion of gravity data and products for end-users, through user-friendly Internet interfaces.

In the same time, BGI also continued operating with its supporting organizations other activities in gravimetry (research, software development, teaching, expertise, field surveys, etc.) with the aim to maintain a high level of competence and to improve the efficiency and the quality of its services.

We have thus contributed to the following activities:

- Processing and assistance to users regarding data requests
- Maintenance and modernization of the databases (absolute gravity data for instance)
- Maintenance and modernization of the website and development of new web-services
- Update of the data validation procedures for land gravity surveys
- Finalization of the World Gravity Map project realized for the Commission for the Geological Map of the World and UNESCO.
- Participation to IAG activities and scientific assemblies
- Contribution to outreach / educational activities
- Contribution to gravity surveys

Global gravity databases and related web services

Most of the databases and services provided by BGI are available from the BGI website (http://bgi.obs-mip.fr). An updated version has been realized in 2012. It gives access to four main global database of gravity observations: 1) Relative measurements from land surveys; 2) Relative measurements from marine surveys; 3) Reference gravity stations related to the former IGSN71 and Potsdam 1930 networks, 4) Absolute measurements.

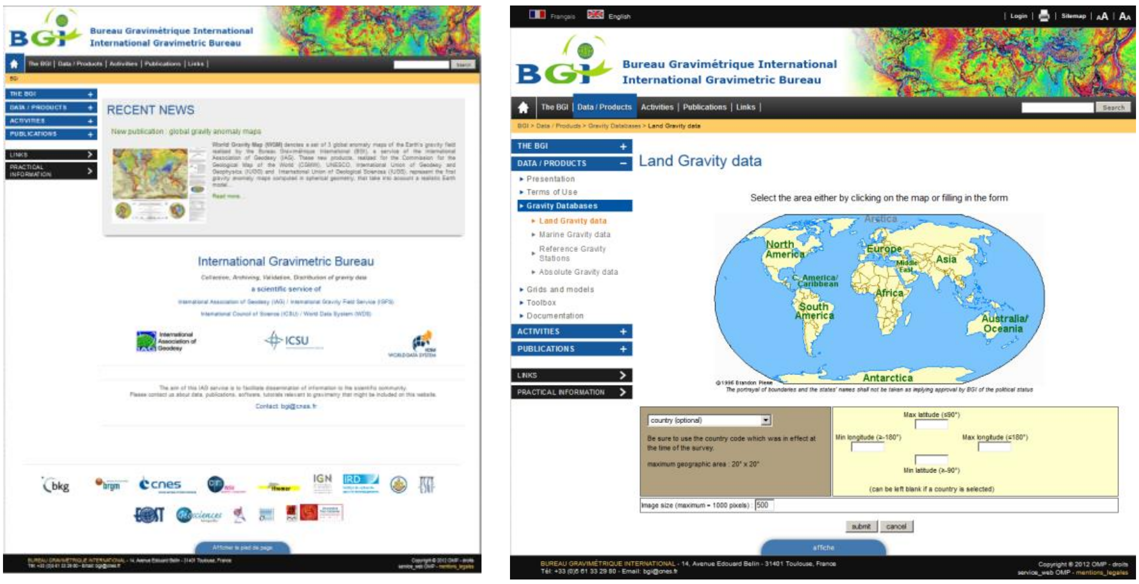


Figure 2: Left: Main page of the BGI website. Right: Data consultation/request page (http://bgi.obs-mip.fr)

Overview of the BGI gravity database

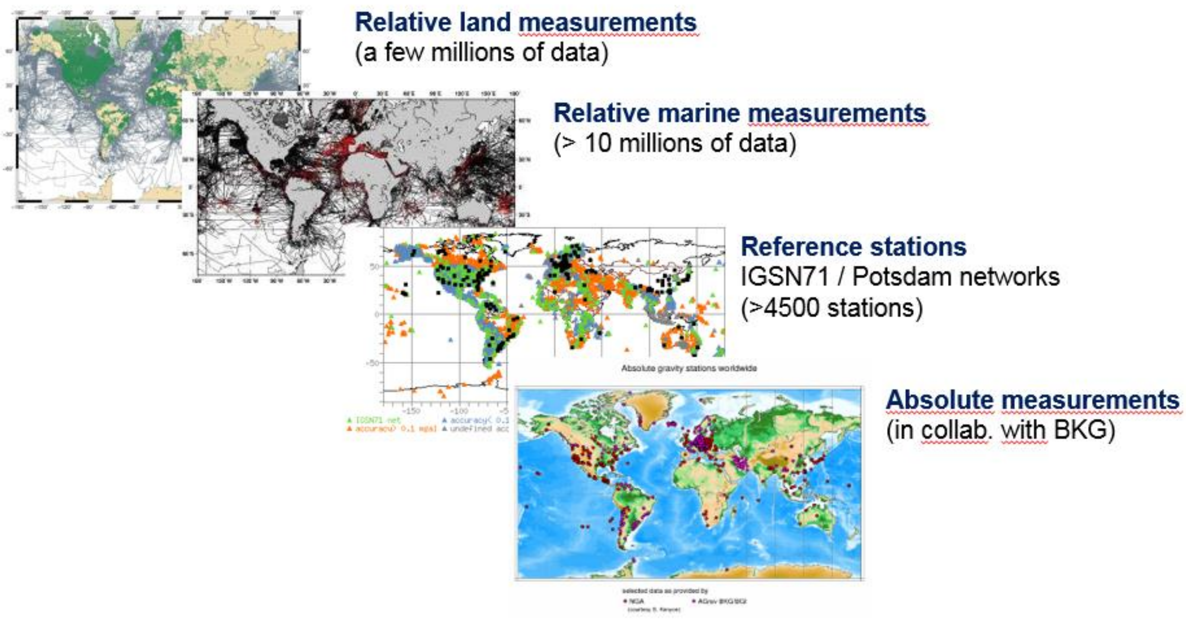


Figure 3: Overview of the global gravity database maintained at BGI (http://bgi.obs-mip.fr)

Relative gravity database

The most frequent service BGI can provide is the consultation and retrieval of gravity data and information over local or regional areas. Data requests are issued through the BGI website and are processed electronically (email, ftp transfer or direct download). Few millions of relative data are currently distributed each year to scientific users.

Absolute gravity database

The global database for absolute gravity measurements was set up and put into operation in 2008 in joint cooperation between BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany). This relational absolute gravity database (AGrav) is capable of storing information about stations, instruments, observations and involved institutions. By this, it allows the exchange of meta-data and the provision of contact details of the responsible institutions on the one hand and the storage and long term availability of gravity data and processing details on the other hand.

The database can be accessed by a web based interface (based on a Google map interface) at two mirrored sites at BGI (http://bgi.obs-mip.fr) and BKG http://agrav.bkg.bund.de/agrav-meta/). It provides publicly available meta-data as well as complete datasets for community of users contributing to the archive. A simple exchange format (project files) was selected which includes all relevant information and is known by the majority of users, avoiding additional effort. In this way the upload of data to the database is possible, using a web based upload form. The provided information ranges from meta-data (localization of stations) up to full information on the absolute determination of the gravity field on a given site (raw or processed data, description of measurement sites, etc.). The collection and archiving of absolute gravity data is in progress. Scientists involved in the acquisition of absolute gravity measurements are invited to contribute with their own observations to this new global database.

The database is expected to become the foundation for a future international gravity reference system (replacing the obsolete IGSN71) and will serve as a pool for geophysical interpretation of absolute gravity observations on a global scale. More information can be found in Wziontek et al. (2011).

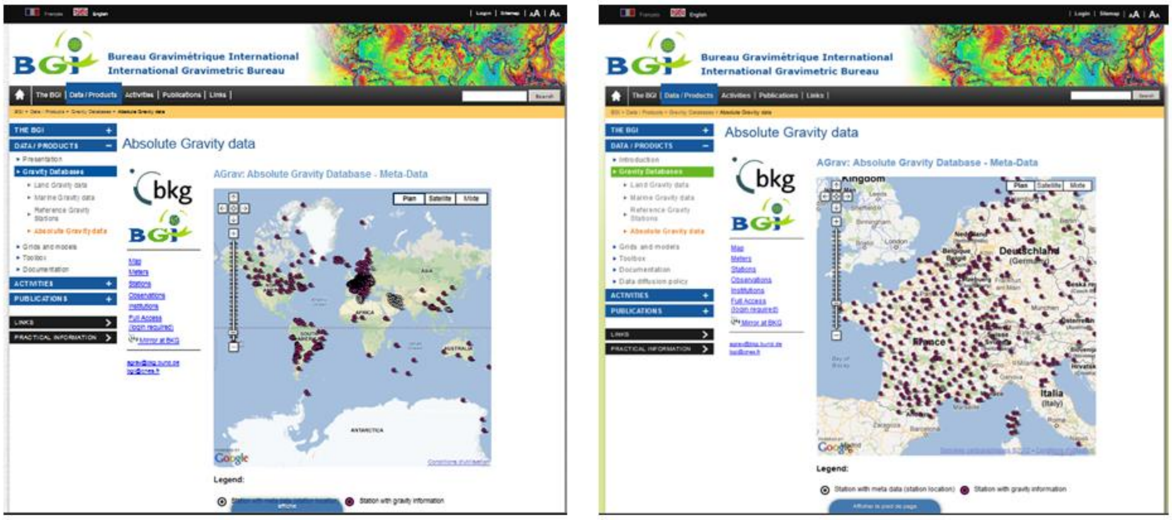


Figure 4: Internet Interface of the Absolute Gravity database (BGI-BKG). Current status (30/5/2015) : 1121 stations / 3344 observations / 51 instruments / 44 institutions (http://bgi.obs-mip.fr - http://agrav.bkg.bund.de/agrav-meta)

The database includes (summer 2015): 1121 Stations, 3344 Observations from 51 Gravimeters provided by 44 Institutions from more than 25 countries.

An improved database is currently in development at BKG. This new database, now based on open-source software (OpenStreetMap), keeps a similar structure but will provide new functionalities and a link to the superconducting gravity times series (interactive maps, plot of time series, link to SG observations from GGP network, etc.).

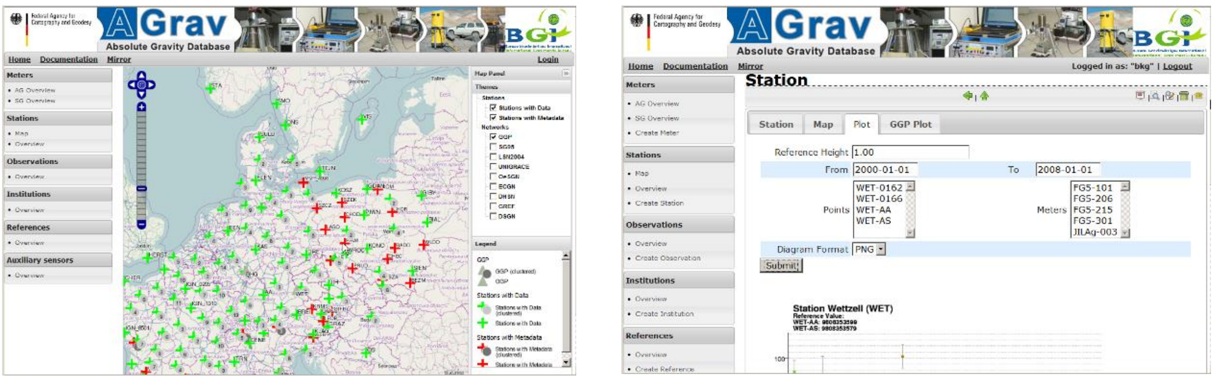


Figure 5: Snapshots of interface of the 2nd generation of the Absolute Gravity database (BGI-BKG)

New on-line services (data and products)

Prediction of gravity value from the BGI database

BGI also receive requests from users who need to know the expected gravity value at a given site for metrology purposes. A new application has thus been developed to predict the gravity value at any point on Earth for given geographic coordinates and altitude. The theoretical gravity is calculated in GRS80 system using the Somigliana formula. If enough gravity data are available from the relative BGI database in the surrounding area, a prediction of the expected gravity value is also computed at the same location from the interpolation of the available surface data. Both theoretical and predicted gravity values are computed at the geoid level and at the given elevation (see example of resulting plot provided to users on fig. 6).

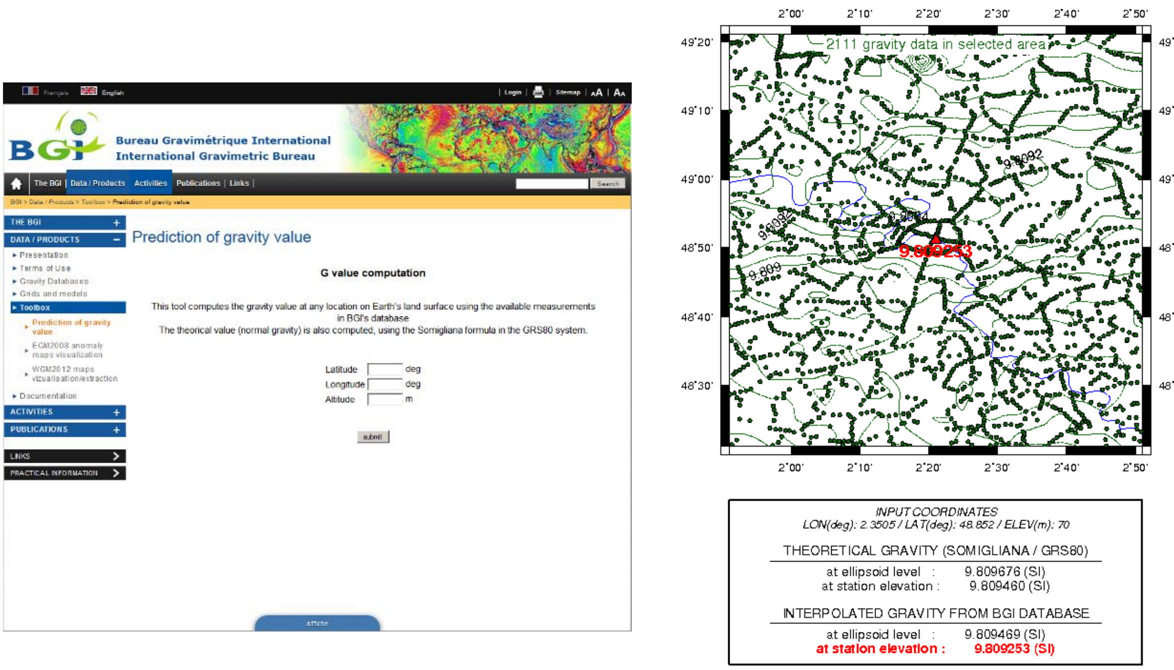


Figure 6: Web page and resulting plot for the prediction of the gravity value at a given point http://bgi.omp.obs-mip.fr/index.php/eng/Data-Products/Toolbox/Prediction-of-gravity-value

On-line availability of the BGI Bulletins collection (1959 – 2003)

For several decades (1959 to 2003), the BGI has edited a biennial publication of the BGI Bulletin containing both internal matters on BGI activities and contributing research papers in the area of gravimetry. We carried out the digitalization of the full series of the BGI Bulletins and summaries in order to provide on-line access (downloadable PDF files) on the BGI web-site (http://bgi.obs-mip.fr/publications/bgi_bulletin). This task has been achieved in August 2013.

The publication of the BGI Bulletins ended in 2003 and was replaced by the Newton's Bulletin published in collaboration with the International Geoid Service (IGeS) and distributed electronically. On-line versions of the issues of the Newton's Bulletins are available on both websites of IGeS (http://www.iges.polimi.it/Newton/newton.html) and BGI (http://bgi.obs-mip.fr/publications/newton_bulletin).

Global grids of Bouguer, Isostatic and free-air gravity anomalies (WGM2012 release)

We recently put an on-line access to any users the 2012 release of the Earth's gravity anomalies computed in spherical geometry at BGI for the WGM (World Gravity Map) project (see details below). The WGM2012 release includes digital grids of the complete Bouguer anomaly and isostatic anomalies (including terrain corrections up to 1 min resolution) and surface free-air anomaly.

The global digital grids (2'x2' resolution) are available to download. An interactive tool is also available to make regional extraction and plots of the gravity anomalies for a given region (http://bgi.obs-mip.fr/data-products/Grids-and-models/wgm2012).

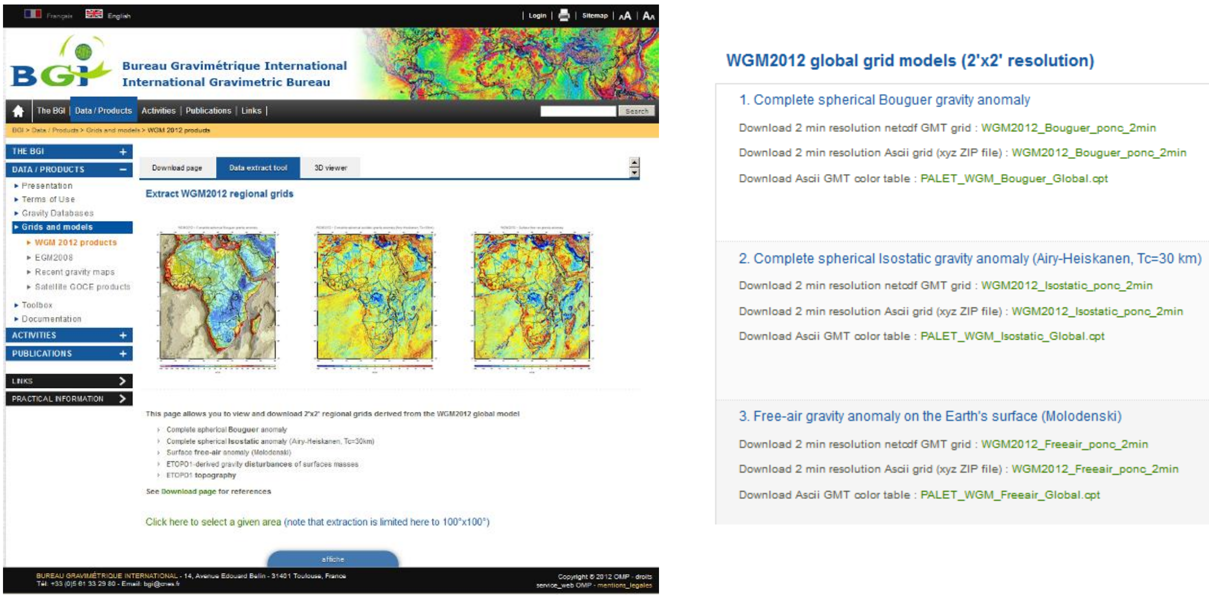


Figure 7: Web page for the download and extraction of the WGM2012 Earth's gravity anomalies. http://bgi.obs-mip.fr/data-products/Grids-and-models/wgm2012).

World Gravity Map (WGM)

The WGM project, launched in early 2008 by BGI in collaboration with Commission for the Geological Map of the World (CGMW) and UNESCO, has been finalized in 2012 with its first release (WGM2012). The aim of the WGM project is to provide to the scientific community high-resolution digital maps and grids of the Earth's gravity anomalies (Bouguer, isostatic, free-air) using the best available gravity information and based on rigorous computations that are consistent with geodetic and geophysical definitions of gravity anomalies. This project, supported by the International Association of Geodesy (IAG/IGFS), the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS), also aims to complement a set of global geological and geophysical digital maps published by CGMW and UNESCO for educative and research purposes.

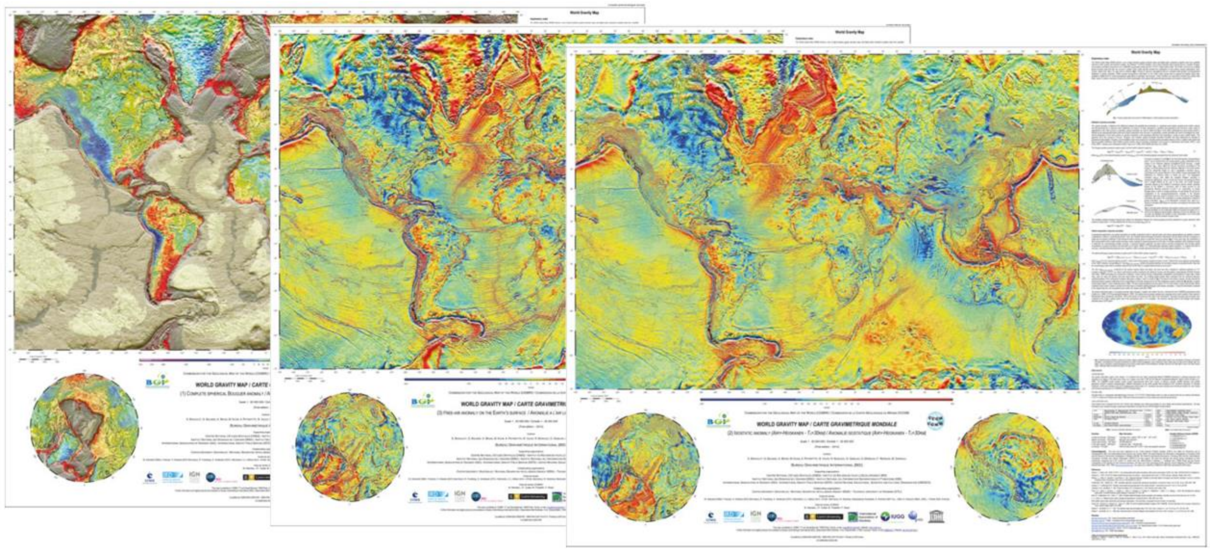


Figure 8: World Gravity Maps (Bonvalot et al., 2012). The 1:50 000 000 maps include Complete Spherical Bouguer anomaly, Complete spherical isostatic anomaly, Free-air anomaly on the Earth's surface (Molodenski).

In 2012, we published the first release of the World Gravity Map (Bonvalot et al., 2012). This set of 3 global maps represents the first anomaly maps of the Earth's gravity field computed in spherical geometry, that take into account a realistic Earth model. The anomaly maps (Bouguer, isostatic and surface free-air) were derived from the most recent reference Earth gravity models (EGM2008, DTU10). They include 1'x1' resolution terrain corrections derived from the ETOPO1 relief model that consider the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps and ice shelves).

Here, the complete spherical Bouguer anomaly is determined over the whole Earth by computing in a single step the gravity contribution of all mentioned surface masses above or below the mean sea surface. In the same way, the contribution of their compensation at the crustal-mantle boundary is also computed in spherical geometry on the base of isostatic equilibrium (Airy-Heiskanen model) to determine the corresponding isostatic anomaly. A spherical harmonic approach has been used to provide homogeneous and accurate global computations of gravity corrections and anomalies up to degree 10800 (1'x1' half-wavelength equivalent spatial resolution). To achieve this level of accuracy, new theoretical developments were achieved to handle spherical harmonics to ultra-high degrees (Balmino et al., 2011).

These new products, providing useful and homogeneous information on the Earth's static gravity field anomalies at regional and global scales for many applications, have been made available on the BGI website. An interactive tool also enables users to perform their own extraction and plot of gravity anomalies derived from the WGM2012 model (see previous section "New on-line services"). Further releases will be done to include more surface data (field, marine or airborne surveys) as well as satellite data.

Software

Spherical Harmonic analysis and synthesis to ultra-high resolution (d/o 32400)

A specific algorithm was developed to enable the computation of associated Legendre functions to any degree (and order); it was successfully tested up to degree 32400. All analysis and synthesis were performed with it, in 64 bits arithmetic and with semi-empirical control of the significant terms in order to prevent from calculus underflows and overflows (according to IEEE limitations), also in preserving the efficiency of a specific regular grid processing scheme. See Balmino et al. (2011) for more details.

Contribution to relative and absolute gravity surveys

Scientific teams associated to BGI have also contributed during the last years to various field surveys for absolute or relative gravity measurements in South America (Chile, Argentina, Peru, French Guiana), Africa (Niger, Benin, Djibouti), Asia (Bouthan) and Europe.

Participation to scientific conferences and workshops

- IAG/IGFS Int. Symposium (Shanghai, China - 07/2014)
- AGU 2014 (San Francisco, USA, 12/2014)
- ESA GOCE Users Workshop (Paris, France -11/2014)
- EGU 2014 (Vienne, Austria, 04/2014)
- AGU 2013 (San Francisco, USA, 12/2013)
- ESA Living Planet Symposium 2013 (Edinburgh, UK - 09/ 2013)
- IAG Scientific Assembly 2013 – 150 years of IAG (Potsdam, Germany - 09/2013)
- TGSMM Terrestrial Gravimetry (St. Petersburg, Russia - 09/2013)
- International Symposium on Earth Tides (Varsaw, Poland – 04/2013)
- EGU 2013 (Vienne, Austria, 04/2013)
- IAG/IGFS Int. Symposium on Gravity, Geoid, Height Systems (Venice, Italy, 10/2012)
- Workshop on Absolute Gravimetry (Boulder Co, USA, 09/2012)
- IUGG General Assembly (Melbourne, 08/2012)
- EGU 2012 (Vienne, Austria, 04/2012)
- AGU Fall Meeting, (San Francisco, USA, 12/2011)
- 4th International GOCE User Workshop (Munich, Germany, 03/2011)

Contribution to Scientific Organizing Committees

- IGFS 3rd Scientific Assembly (Shanghaï, China, 2014)
- IAG Scientific Assembly 2013 – 150 years of IAG (Potsdam, Germany - 09/2013)
- TGSMM Terrestrial Gravimetry (St. Petersburg, Russia - 09/2013)

Perspectives

BGI will benefit of the continuing support (long term financial and personal support) from the French research Authorities. Activities of the service will thus be ensured according to the BGI missions and objectives and to the positive evaluation resulting from the IAG Service Assessment. Some evolutions in the service and its organization will be also proposed according to the recent recommendations made the IAG Service Assessment team. Here are listed the main perspectives for the next years.

Improvement of the global gravity databases and services

BGI will continue in collaboration with BKG Germany the development and set up of the new version of the of the Absolute Gravity database AGrav. In the same time, BGI will continue the integration of incoming dataset from relative or absolute gravity surveys. We encourage any user or institution to contribute to the IAG databases. Products derived from airborne gravity surveys (grids for instance) are also very welcome to be included in the BGI database for improving the global data coverage.

Contribution to new global gravity models

BGI will strength within IAG/IGFS activities its collaboration with other groups also involved in the determination or analysis of global gravity field models as for instance with NGA (USA), ISG Polimi (Milan), DTU (Denmark), Curtin Univ (Australia), IGN/IPG Paris (France). The contribution of the BGI surface gravity database for the determination and evaluation of the future Earth Gravity Model is expected.

Establishment of the new global absolute gravity reference system

BGI will contribute, within IAG Commission 2 and IAG/IGFS activities, to the working group for the Establishment of the future global absolute gravity reference system. The main contributions will concern : (i) the establishment of a global network of reference stations linked to the international comparisons of absolute gravimeters ; (ii) the initiation of the replacement of the International Gravimetric Standardization Network 1971 (IGSN71) by the new Global Absolute Gravity Reference System ; (iii) the archiving and distribution of the absolute measurements through the existing AGrav database jointly with BKG. BGI may also provide its recent expertise in absolute gravity measurements using cold-atom gravimeters.

Publications by BGI team (2011-2015)

2015

Balmino, G. et S. Bonvalot. Gravity anomalies. In*: Encyclopedy of Geodesy*, Springer (submitted).

Rigo, A., C. Adam, M. Grégoire, M. Gerbault, R. Meyer, M. Rabinowicz, F. Fontaine, S. Bonvalot. Insights for the melt migration, the volcanic activity and the ultra-fast delamination of lithosphere related to the Yellowstone plume (Western USA). *Geophys. Journal Int.* (in press).

Driussi, O., Briais A., Maillard A., Evidence for transform motion along the South Balearic margin and implications for the kinematics of opening of the Algerian Basin, 2015. *Bull. Soc. Géol.,Fr.* Volume 186 Number 4-5, 2015.

Pallero, J.L.G., Fernandez-Martınez, J.L., Bonvalot, S., Fudym, O. 2015. Gravity inversion and uncertainty assessment of basement relief via Particle Swarm Optimization. *Journal of Applied Geophysics*. Doi: 10.1016/j.jappgeo.2015.03.008

Perrouty, S., Moussirou, B., Martinod, J., Bonvalot, S., Carretier, S., Gabalda, G., Monod, B., Herail, G., Regard, V., Remy, D. Geometry of two glacial valleys in northern Pyrenees estimated using gravity data. *Comptes Rendus Geosciences*. Doi: 10.1016/j.crte.2015.01.002

2014

Bruinsma S., Förste C., Abrikosov O., Lemoine, J-M., Marty J-C., Mulet S., Rio M-H., Bonvalot S. ESA's satellite-only gravity field model via the direct approach based on all GOCE data". *Geophysical Research Letters*. 2014GL062045R.

Panet, I., Pajot-Metivier, G., Lefftz, M., Metivier, L., Diament, M., Mioara, 2014. Mapping the mass distribution of Earth's mantle using satellite-derived gravity gradients. Nature Geosciences, 7, 2, 131-135, http://dx.doi.org/10.1038/ngeo2063

Mikhailov, V.O, Panet, I., Hayn, M. Timoshkina, E.P., Bonvalot, S., Lyakhovsky, V., Diament, M. Viron, O.de. Comparative study of temporal variations in the earth's gravity field using GRACE gravity models in the regions of three recent giant earthquakes, 2014. J Izvestiya, Physics of the Solid Earth, March 2014, Volume 50, Issue 2, pp 177-191. doi:10.1134/S1069351314020062

2013

Bruinsma S., Förste C., Abrikosov O., Marty J-C., Rio M-H., Mulet S., Bonvalot S. (2013). The new ESA satellite-only gravity field model via the direct approach: Confrontation with the GOCE mission objectives *Geophys. Res. Letters*, 40,1-6, DOI:10.1002/grl.50716, 2013.

Martin, M., Monteiller, V., Komatitsch, D., Perrouty, S., Jessell, M., Bonvalot, S., Lindsay, M. (2013). Gravity inversion using wavelet-based compression on parallel hybrid CPU/GPU systems: application to SW Ghana region. *Geophysical Journal International*. Volume 195, Issue 3, pp. 1594-1619, doi:10.1093/gji/ggt334, 2013.

Frappart F., Seoane L., Ramillien G. (2013). Validation of GRACE-derived Terrestrial Water Storage from a regional approach over South America. *Remote Sensing of Environment*. Volume 137, October 2013, Pages 69–83. doi:10.1016/j.rse.2013.06.008

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International Gravity Field Service (IGFS)

http://www.gravityfield.org

Chairman: Renè Forsberg (Denmark, 2011-2013) - Riccardo Barzaghi (Italy, 2013-2015)
Director of the Technical Centre: Steve Kenyon (USA)
Director of the Central Bureau: Iginio Marson (Italy)

Overview

IGFS activities in the period 2011-2015 have been focussed on the main institutional IGFS lines that are: the collection, validation, archiving and testing of gravity field related data; the distribution of software for gravity field estimation; the organization of courses on geoid estimation; the distribution of information materials related to the Earth's gravity field. These activities were mainly performed by the related Gravity Services in the framework of IGFS that acted in order to harmonize and merge them into a common view.

IGFS has established active links with GGOS. IGFS representatives participated to GGOS meetings (particularly those of the Bureau for Network and Communications) to present some developments on gravity field that are of relevance for GGOS.

Particularly, in this context, the activities carried out in connection with IAG Commission 2 (Gravity Field) were highlighted. Three Joint Study Groups (JWG2.1, JWG2.2, JWG2.3) have been actively operating in assessing the precision of the GOCE global geopotential models, in defining methods for comparing absolute gravimeter observations and in establishing a new global absolute gravity reference system. These researches are of particular relevance for the geodetic community. The realization of the Absolute Gravity Reference System is a key issue in Geodesy. The IGNS71 is the current realization that strictly needs for an update due also to the relevant improvements in absolute gravimeters that occurred in the last decades. The same holds for the assessment of GOCE global geopotential models. As it was done for EGM2008, comparisons with existing ground-based data set are extremely important in order to assess the precision of the different GOCE models, obtained following different approaches. This also in relationship to new planned missions aimed at improving the present day GOCE models precision.

Another action that has been developed in coordination with GGOS is the one on the researches aiming at establishing a global vertical datum. The activities of the Working Group on Vertical datum Standardization are in the framework of GGOS Theme 1 – Global Vertical Datum. Also, IGFS has been involved in the activities of the Group on International Height Reference System (IHRS) that was established during the IAG Executive Committee in San Francisco with the objective to define a resolution on the definition of an IHRS to be presented at the IAG/IUGG General Assembly in Prague (June 2015).

It has also to be mentioned that IGFS has co-organized two scientific meetings on gravity field related topics:

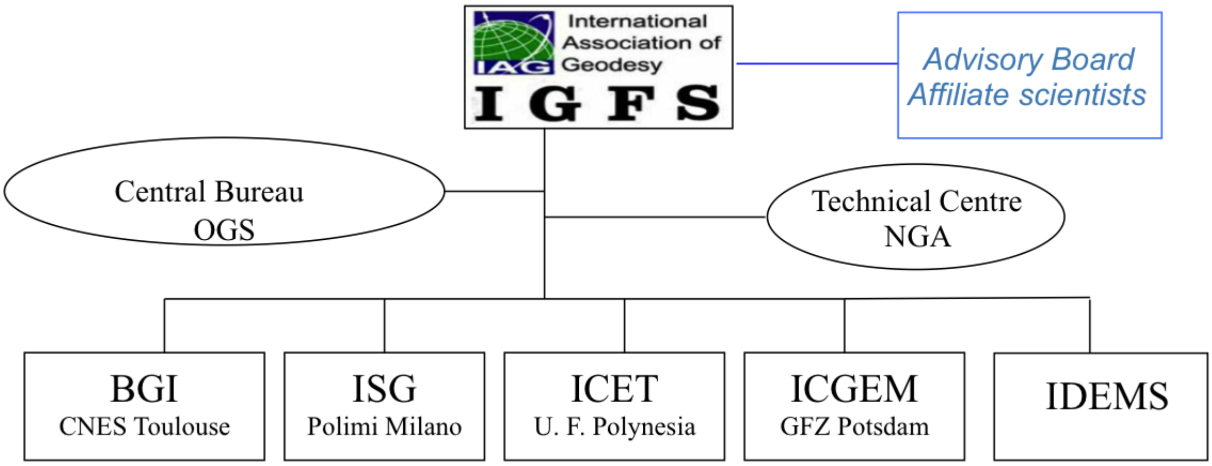
- the International Symposium on Gravity, Geoid and Height System GGHS2012, organized by IAG-Commission 2 and IGFS (via its Central Bureau) in San Servolo, Venice (October 9th-12th, 2012);

- the 3rd IGFS General Assembly, organized by IGFS, the Shanghai Astronomical Observatory and IAG Commission 2 in Shanghai (June 30th - July 6th, 2014).

Finally, the IGFS Central Bureau has realized the new IGFS web page that will be a tool for better informing the geodetic community on gravity field related topics.

Structure

The IGFS structure is described in Figure 1.



BGI=Bureau Gravimetrique International
ISG=International Service for the Geoid (formerly IGeS)
ICET=International Centre for Earth Tides
ICGEM=International Centre for Global Earth Models
IDEMS=International DEM Services
OGS=Istituto Nazionale di Oceanografia e Geofisica Sperimentale
NGA=National Geospatial-Intelligence Agency

Figure 1: The IGFS structure

IGFS coordinates the activities of the related Services via the Advisory Board, its Central Bureau at OGS and the Technical Centre at NGA. This structure allows an effective relationship among the different Services working on gravity field. IGFS also provide a common interface towards other IAG bodies such as GGOS, in order e.g. to come to a standardization of the gravity "products". Within IGFS, Joint Working Groups are coordinated with Commission 2, namely JWG2.1 (International and Regional Comparison Campaigns of Absolute Gravimeters), JWG2.2 (Absolute Gravimeters and Absolute Gravity Reference System), JWG2.3 (Assessment of GOCE Geopotential Models). Furthermore, a Working Group on Vertical Datum Standardization was established jointly with GGOS Theme 1- Global Vertical Datum. This WG is also involved, through IGFS, in the activities of the Group on IHRS.

It must be mentioned that the IGFS structure has changed in the 2011-2015 period and that there will be further changes in the near future.

Since mid 2013, IDMES is not fully operational. Contacts between Curtin University and ESRI Company have been established by IGFS in order to reactivate this important service for the geodetic community.

At the IAG Executive Committee in Vienna (April 26th, 2014), the International Geoid Service (IGeS) changed its name into International Service for the Geoid (ISG) due to internal organization problems. On April 1st, 2013, a new chairman, Riccardo Barzaghi from Politecnico di Milano (Italy), started managing IGFS thus substituting Rene Forsberg from the National Space Institute (Denmark). Finally, there is a proposal for evolving the ICET Service into a new IAG/IGFS Service related to the Global Geodynamic Project (GGP). This proposal will be presented at the General IAG/IUGG Assembly in Prague (June 2015).

Activities

IGFS has directly promoted the GEOMED2 project aiming at estimating a detailed geoid in the Mediterranean area. This project (that will last at the end of 2016) is based on the co-operation of a large number of institutions, namely:

- BGI/ISG
- Politecnico di Milano (Italy)
- University of Thessaloniki (Greece)
- University of Jaén (Spain)
- GET/OCA/Geoazur and SHOM (France)
- DTU Space (Denmark)
- General Command of Mapping (Turkey)
- University of Zagreb (Croatia)

By comparison with existing altimeter data, an accurate estimate of the DOT and of the circulation in the Mediterranean Sea will be also obtained. Furthermore, as previously mentioned, the Gravity Services have developed many activities that have been coordinated and documented by IGFS. BGI has developed and finalized the World Gravity Map project. Bouguer, Isostatic and free-air gravity anomalies are available, either as spherical harmonic expansions or 1’× 1’ digital grids (Figure 2).

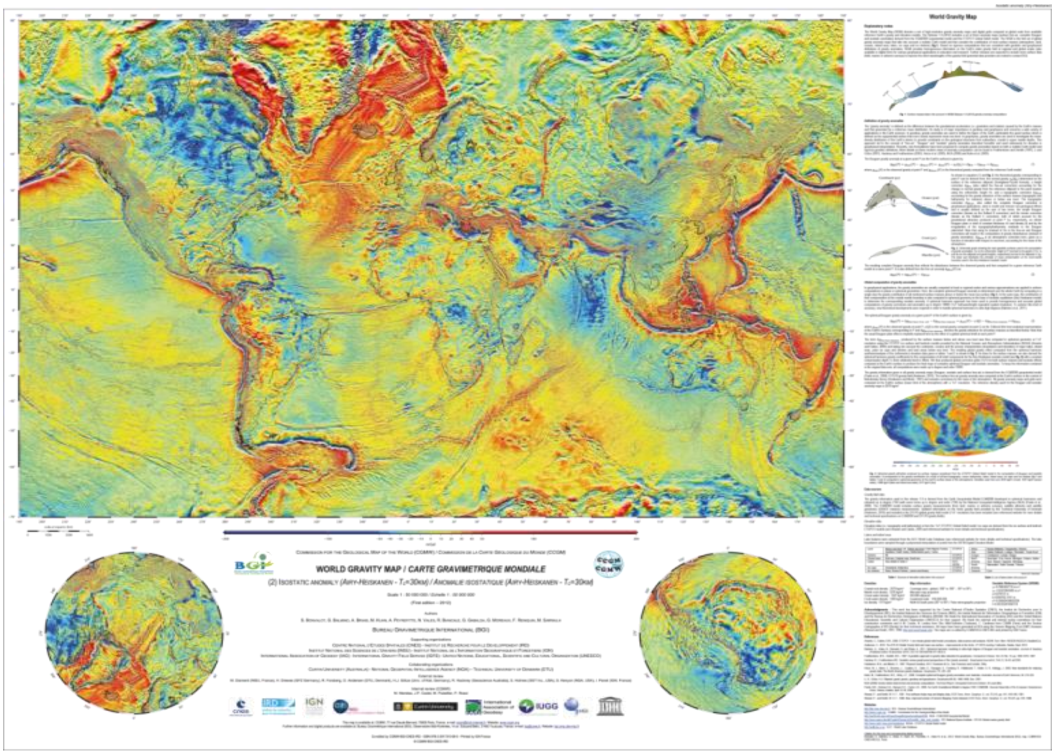


Figure 2: The World Gravity Map by BGI

Furthermore, BGI supports the African Geoid Project (Figure 3) and, as already mentioned, the GEOMED2 project supplying gravity data and co-operating in processing the gravity data.

GOCE data were also processed at BGI (DIR-5 is the last computed solution) and global GOCE gradients have been estimated in a Local North-Oriented Frame (LNOF) and in the Instrument Frame (GRF frame).

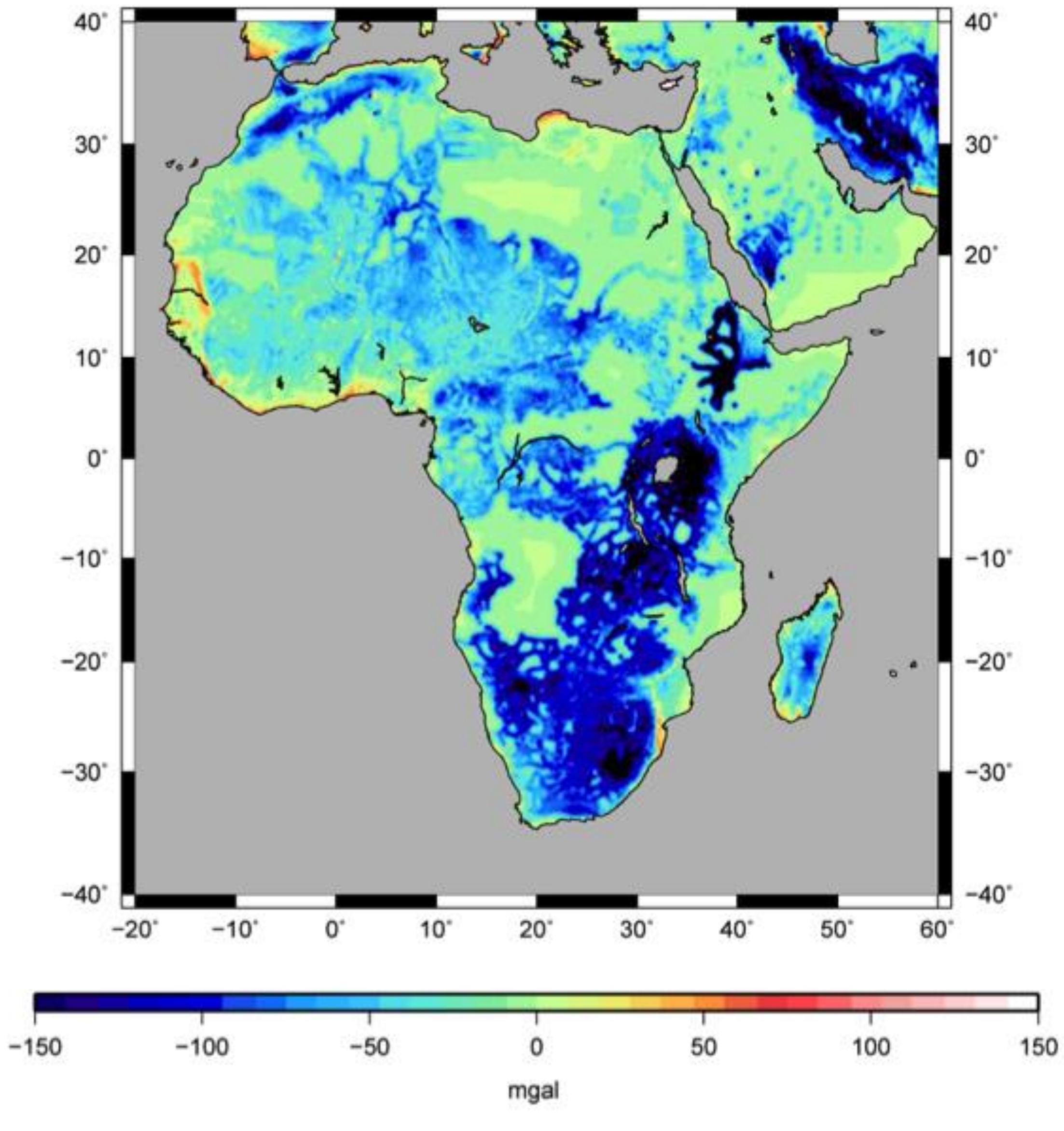


Figure 3: The Bouguer Anomaly Map in Africa

Furthermore BGI is developing in co-operation with BKG an absolute gravity database that contains data from 1121 stations, from 44 different institutions (at June 2015). The information contained in these data is of strong interest in many geodetic/geophysical investigations and could contribute to the project aiming at establishing the new global gravity reference system.

ICGEM and ISG have collected both global geopotential models and local geoid solutions which are available through their web pages that are linked to the IGFS web page.

ICGEM collected and documented 150 global geopotential models that can be downloaded via the ICGEM web page. Validation of global models is provided both in the spectral domain and by direct comparison with GPS/levelling data.

On line interactive visualization tools can be used and evaluation of global model effects can be obtained via web interface. Particularly, the new G3-Browser has been developed for visualizing gravity field variations based on GRACE observations (see Figure 4).

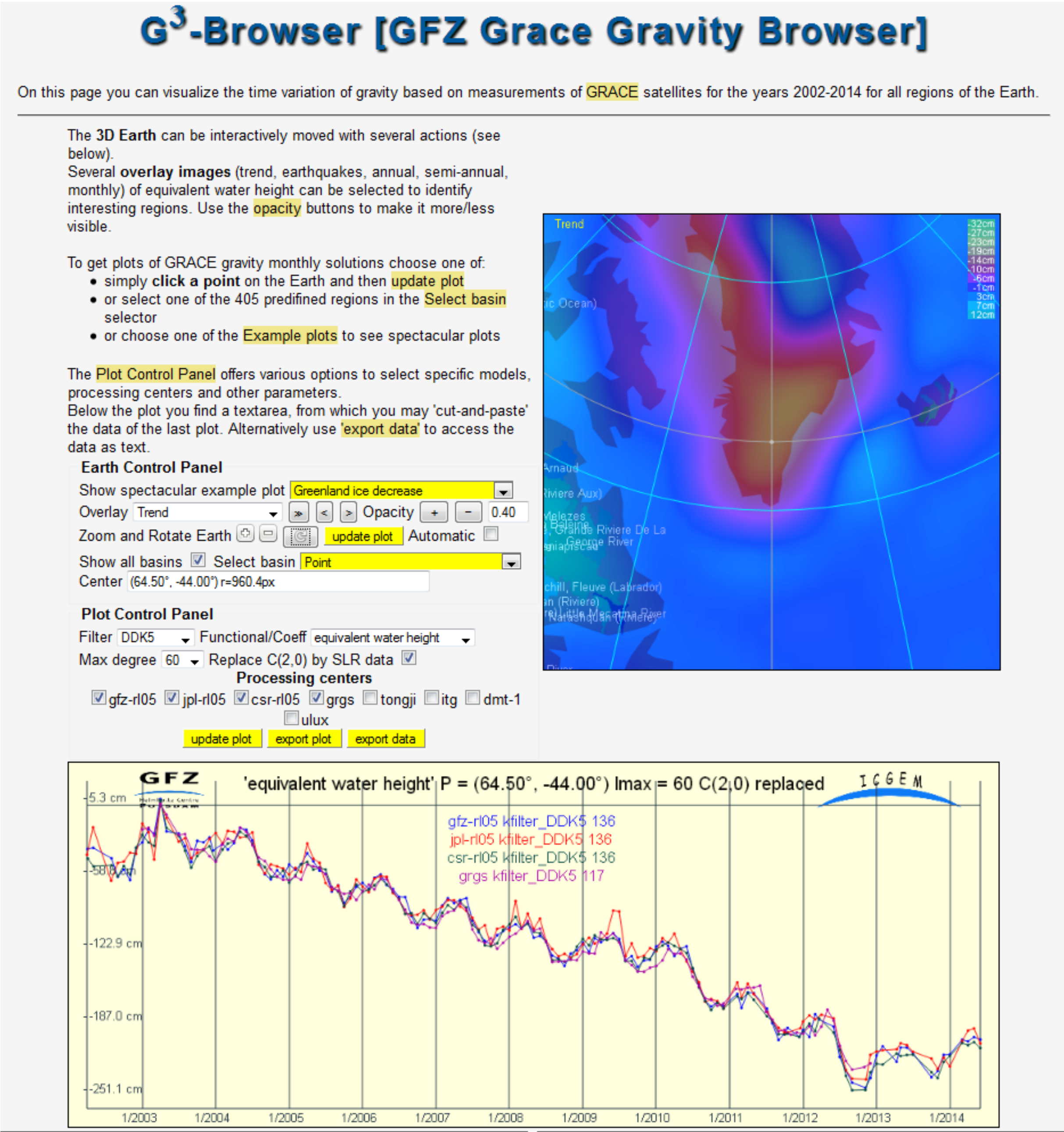


Figure 4: The gravity data variation in the area of Greenland

The ISG web page has been totally renewed in order to provide a better service to the users. At present (June 2015), 41 estimated geoids are stored in ISG database and can be downloaded, either freely or on demand, through the web page (see Figure 5). They are frequently requested by users that are interested in detailed geoid solutions, basically for mapping and GIS applications.

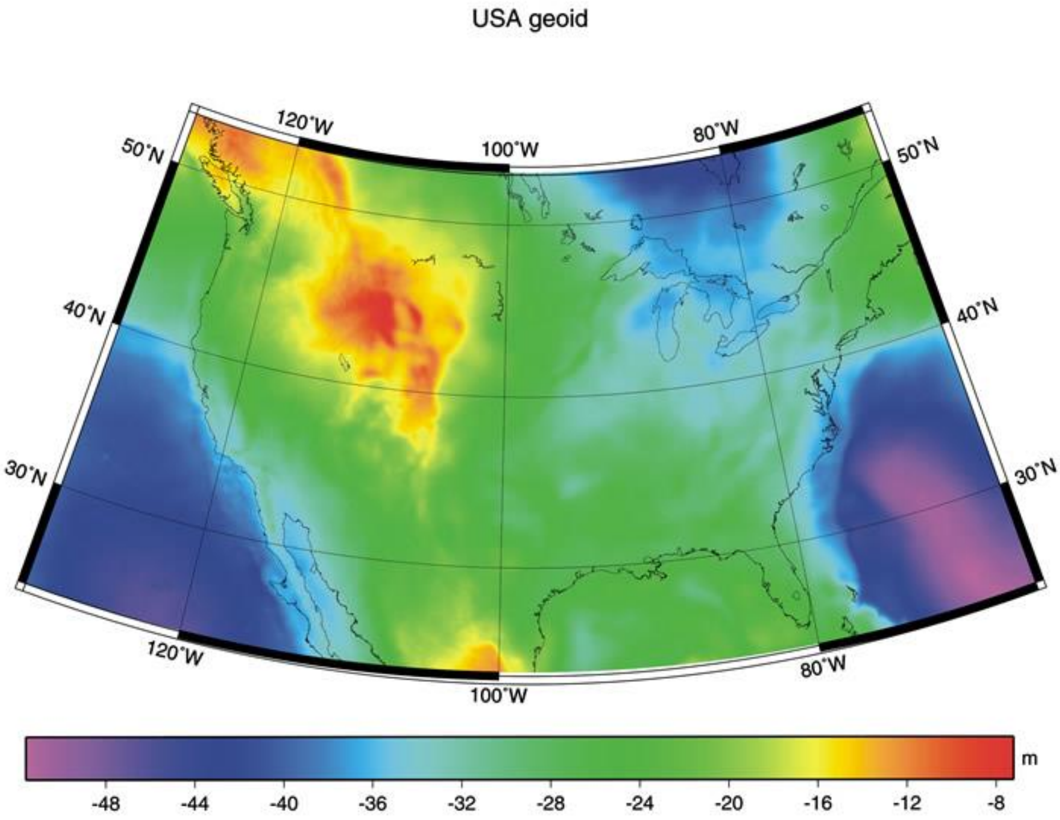


Figure 5: The USA gravimetric geoid available at ISG

Furthermore, ISG contributed to the estimation of a GOCE global geopotential model based on the space-wise approach.

ICET participated to the Global Geodynamics Project (GGP) by processing the gravity data uploaded to the ICET and GFZ database for earth tides.

As an example, in Figure 6, the gravity variation in time in one of the station is displayed.

As mentioned previously, a proposal for merging the ICET Service into a new IAG/IGFS Service related to the GGP will be presented at the General IAG/IUGG Assembly in Prague (June 2015).

Finally, despite some recent inefficiencies in its activity, it must be considered the important role of IDEMS that distributes and validates global DEM models. They are extremely important for removing/restoring the terrain effect in e.g. geoid estimation. IGFS is currently having contacts with Curtin University and ESRI Company in order to set a new proposal aiming at renewing and improving this important service.

Other important activities that have been documented by IGFS during the GGOS Bureau for Network and Communications meetings in San Francisco (end of 2014) and Vienna (Spring 2015) were related to the European geoid computation, the Artic Gravity Project and the project aiming at coordinating the activities of the Consultative Committee for Mass and Related Quantities-Working Group on Gravity (CCM-WGG) and IAG Commission 2. As for this last point, it must be mentioned that a common strategy document of IAG and CCM for metrology in absolute gravimetry have been prepared by the cooperation of IAG JWGs (2.1 and 2.2) and CCM-WGG. The IAG Executive Committee accepted the current document “CCM-IAG Strategy for Metrology in Absolute Gravity” as relevant and important for IAG in the establishment of a global gravity reference system and a contribution to the Global Geodetic Observing System (GGOS).

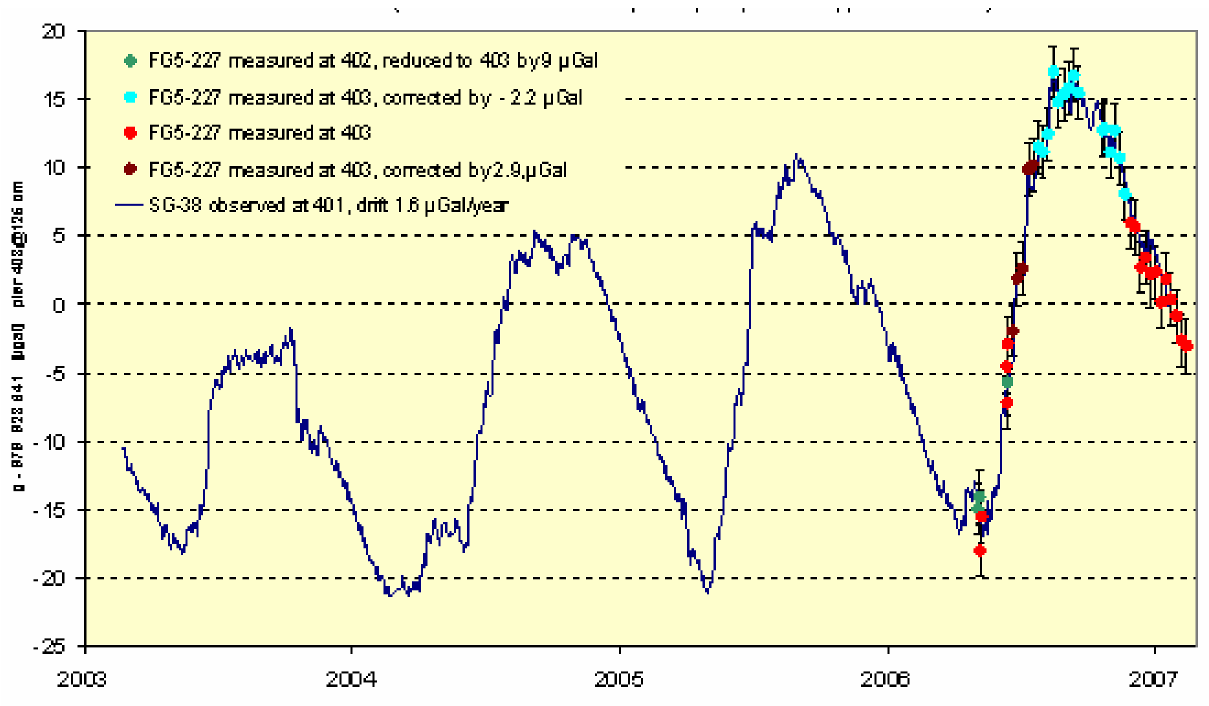


Figure 6: The gravity field variations at Conception

The publication of technical papers is also one of the activities that are coordinated and sponsored by IGFS.

ISG and BGI are issuing via their web pages the Newton’s Bulletin which contains technical papers on geoid computation, gravity data handling and gravity campaigns. Within mid June 2015, a Special Issue of the Newton’s Bulletin will be published. This issue contains reports on the validation of the GOCE global geopotential models carried out in the framework of the JWG2.3 activities.

Another publication related to the gravity field services is issued by ICET which regularly publishes the Bulletin International des Marées Terrestres (BIM) in electronic form through its web page.

All these activities are documented in the IGFS web page at the address: *http://www.gravityfield.org/*.

Another important activity that is performed by IGFS in cooperation with IAG Commission 2 is to organize Symposia and Schools on geoid computation.

On October 9th-12th 2012, the International Symposium on Gravity, Geoid and Height System GGHS2012 has been organized in Venice (San Servolo island) with the following session scheme:

- Session 1: Gravimetry and gravity networks
- Session 2: Global gravity field modelling, assessments and applications
- Session 3: Future gravity field missions

- Session 4: Advances in precise local and regional high-resolution geoid modeling
- Session 5: Establishment and unification of vertical reference systems
- Session 6: Gravity field and mass transport modelling
- Session 7: Modelling and inversion of gravity-solid earth coupling
- Session 8: Gravity field of planetary bodies

As it can be seen, the most relevant topics related to the gravity field analysis and estimation have been discussed. Most of the presented papers have been submitted for publication (after peer review) on IAG Symposia Series published by Springer.
Furthermore, IGFS has organized in Shanghai the 3rd IGFS General Assembly, together with the Shanghai Astronomical Observatory and IAG Commission 2 (June 30th - July 6th, 2014).
The focus of this Assembly was on methods for observing, estimating and interpreting the Earth gravity field as well as on applications. The scientific sessions were:

- Session 1: Gravimetry (aerograv, absolute/relative gravity observations, gravity network)
- Session 2: Global geopotential models and vertical datum unification
- Session 3: Local geoid/gravity modelling
- Session 4: Satellite gravity
- Session 5: Mass movements in the Earth system
- Session 6: Solid Earth Investigations

Also in this case, paper will be published on a dedicated volume of the IAG Symposia Series.
Finally, a new school was organized in 2013. It was held at the Universidad Tecnica Particular de Loja, Loja (Ecuador) in October 7th-11th, 2013. It was the eleventh Geoid School that continued the ISG schools tradition. Besides geoid estimation, a new important topic has been added, namely the one related to the definition of a global height datum. The program of this school and the teachers were the following:

- Heights, height datum and Boundary Value Problems (Sansò)
- Global geopotential models and their use (Pavlis)
- Modelling the topographic effect (Blitzkow)
- Local improvements of the geoid (Barzaghi)
- Vertical Datum Standardization (Sanchez)

15 participants attended this school: they were coming from Brazil, Colombia, Dominic Republic, Ecuador, Egypt, Greece, Mexico, USA and Venezuela. As usual, software and lecture notes were distributed them.

In the end, it has to be mentioned that IGFS meetings were held during the IAG Scientific assembly in Potsdam (September, 2013) and the 3rd IGFS General Assembly in Shanghai (June, 2014). In these meetings, IGFS structure, projects and perspectives were discussed among the participants.

International Laser Ranging Service (ILRS)

http://ilrs.gsfc.nasa.gov

E. C. Pavlis[1], M. R. Pearlman[2], C. E. Noll[3], G. Appleby[4], J. Müller[5], G. Bianco[6]

Overview

The ILRS is the international source that provides Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data and data products for scientific and engineering programs with the main focus on Earth and Lunar applications. The basic observables are the precise two-way time-of-flight of ultra short laser pulses from ground stations to retroreflector arrays on satellites and the Moon and the one-way time-of-flight measurements to spaceborne receivers (transponders). These data sets are made available to the community through the CDDIS and the EDC archives, and are also used by the ILRS to generate fundamental data products, including: accurate satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters.

SLR is one of the four space geodetic techniques (along with VLBI, GNSS, and DORIS) whose observations are the basis for the development of the International Terrestrial Reference Frame (ITRF), which is maintained by the IERS. SLR defines the origin of the reference frame, the Earth center-of-mass and, along with VLBI, its scale. The ILRS generates daily a standard product of station positions and Earth orientation based on the analysis of the data collected over the previous seven days, for submission to the IERS, and produces LAGEOS/Etalon combination solutions for maintenance and improvement of the International Terrestrial Reference Frame. The latest requirement is to improve the reference frame to an accuracy of 1 mm accuracy and 0.1 mm/year stability, a factor of 10–20 improvement over the current product. To address this requirement, the SLR community will need to significantly improve the quantity and quality of ranging to the geodetic constellation (LAGEOS-1, LAGEOS-2, and LARES) to support the definition of the reference frame, and to the GNSS constellations to support the global distribution of the reference frame.

The ILRS participates in the Global Geodetic Observing System (GGOS) organized under the IAG to integrate and help coordinate the Service activities and plans.

ILRS Structure

The ILRS Organization (see Figure 1) includes the following permanent components:

- Tracking Stations organized into Sub-networks
- Operations Centers

[1] *[1] Goddard Earth Science and Technology Center, UMBC and NASA GSFC, Baltimore, MD 21250, USA*
[2] Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA USA 02138, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4] NERC Space Geodesy Facility, Herstmonceux Castle, Hailsham, East Sussex, BN27 1RN, UK
[5] University of Hannover/Institut für Erdmessung, Hannover, GERMANY
[6] Agenzia Spaziale Italiana, CGS, Matera, ITALY

- Global and Regional Data Centers
- Analysis and Associate Analysis Centers
- Central Bureau
- Working Groups

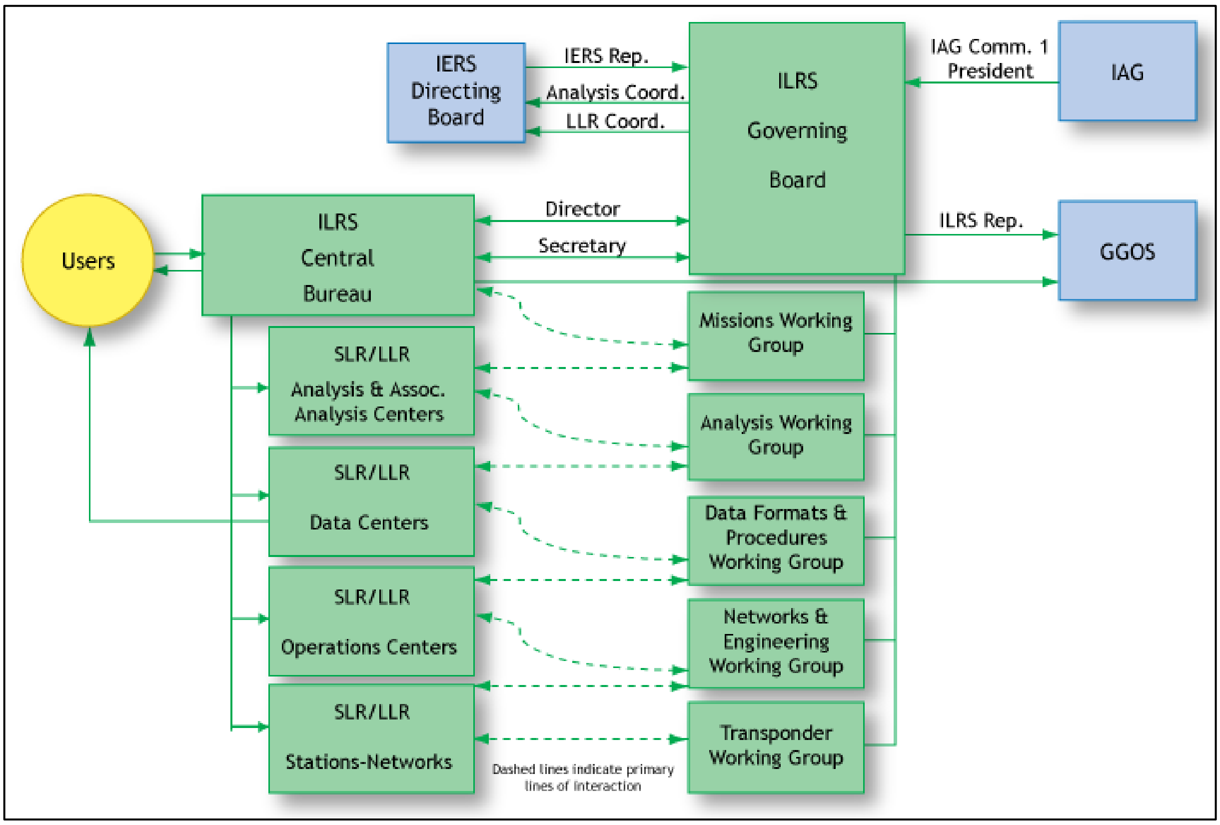


Figure 1. The organization of the International Laser Ranging Service (ILRS).

The role of these components and their inter-relationship is presented on the ILRS website (*http://ilrs.gsfc.nasa.gov/about/organization/index.html*).

The Governing Board (GB) is responsible for the general direction of the service. It defines official ILRS policy and products, determines satellite-tracking priorities, develops standards and procedures, and interacts with other services and organizations. The members of the current Governing Board, selected and elected for a two-year term, are listed in Table 1.

Within the GB, permanent (standing) or temporary (ad-hoc) Working Groups (WGs) carry out policy formulation for the ILRS. The WGs are intended to provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the five WGs, led by a Chair and Co-Chair (see Table 1). The WGs continue to attract talented people from the general ILRS membership who contributed greatly to the success of these efforts.

Table 1. ILRS Governing Board (as of May 2015)

Tonie van Dam	Ex-Officio, President of IAG Commission 1	Luxembourg
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Bob Schutz	Appointed, IERS Representative to ILRS	USA
Giuseppe Bianco	Appointed, EUROLAS, Governing Board Chair	Italy
Georg Kirchner	Appointed, EUROLAS, Networks and Engineering Working Group Co-Chair	Austria
David McCormick	Appointed, NASA	USA
Jan McGarry	Appointed, NASA, Transponder Working Group Co-Chair	USA
Wu Bin	Appointed, WPLTN	China
Toshimichi Otsubo	Appointed, WPLTN, Missions Working Group Chair	Japan
Vincenza Luceri	Elected, Analysis Representative, Analysis Working Group Deputy Chair	Italy
Erricos C. Pavlis	Elected, Analysis Representative, Analysis Working Group Chair	USA
Horst Mueller	Elected, Data Centers Representative, Data Formats and Procedures Working Group Chair	Germany
Jürgen Müller	Elected, Lunar Representative	Germany
Ulrich Schreiber	Elected, At-Large, Transponder Working Group Chair	Germany
Matt Wilkinson	Elected, At-Large, Networks and Engineering Working Group Chair	UK
Former Governing Board Members during 2011-2015		
Graham Appleby	Elected, At-Large, Former Governing Board Chair	UK
David Carter	Appointed, NASA	USA
Ramesh Govind	Appointed, WPLTN	Australia
Hiroo Kunimori	Appointed, WPLTN	Japan
Francis Pierron	Appointed, EUROLAS	France

Data Products

The main ILRS analysis products consist of SINEX files of weekly-averaged station coordinates and daily Earth Orientation Parameters (x-pole, y-pole and excess length-of-day, LOD) estimated from 7-day arcs of SLR tracking of the two LAGEOS and two Etalon satellites. As of May 1, 2012, the weekly analysis product is no longer the official ILRS Analysis product (thence reserved for Pilot Project use only), replaced by the same type of analysis performed on a DAILY basis by sliding the 7-day period covered by the arc by one day forward every day. This allows the ILRS to respond to two main users of its products: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single analysis per week, the latter however requires as "fresh" EOP estimates as possible, that the "sliding" daily analysis readily provides. Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous one and constrained to an ITRF, currently ITRF2008. Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate these products with individual and combined solutions respectively. Both the individual and combined solutions follow strict standards agreed upon within the ILRS Analysis Working Group (AWG) to provide high quality products consistent with the IERS Conventions. This description refers to the status as of May 2015. Each official ILRS solution is obtained through the combination of solutions submitted by the official ILRS Analysis Centers:

- ASI, Agenzia Spaziale Italiana
- BKG, Bundesamt für Kartographie und Geodäsie
- DGFI, Deutsches Geodätisches ForschungsInstitut
- ESA, European Space Agency
- *GA, Geosciences Australia (up until the end of 2012)*
- GFZ, GeoForschungsZentrum Potsdam
- GRGS, Observatoire de Cote d'Azur
- JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
- NSGF, NERC Space Geodesy Facility

These ACs have been certified through a benchmark process developed and adopted by the AWG. The official Primary Combination Center (ASI) and the official Backup Combination Center (JCET) follow strict timelines for these routinely provided products.

In addition to operational products, solutions obtained from re-analysis have been provided covering the period back to 1983 in support of ITRF development. The ILRS products are available, via ftp from the official ILRS Data Centers CDDIS/NASA Goddard Space Flight Center (*ftp://cddis.gsfc.nasa.gov/*) and EDC/DGFI (*ftp://ftp.dgfi.badw-muenchen.de*).

The individual ILRS AC and CC contributions as well as the combinations are monitored on a daily basis in graphical and statistical presentation of these time series through a dedicated website hosted by the JCET AC at: *http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*

The main focus of the Analysis WG activities over the past two years was the improvement of modeling used in the reduction of the SLR data and generation of the official products in preparation for the development of the next ITRF model, ITRF2014, Luceri et al., 2014). In particular, all ACs made major efforts to comply with the adopted analysis standards and the IERS Conventions 2010, the consistent modeling of low degree time-varying gravitation and the realistic modeling of the mean pole in computing the pole tide effects (Pavlis et al., 2014). Since the delivery of the ILRS contribution to ITRF2014, the AWG has focused on a set of Pilot Projects to test, evaluate and adopt new models and practices that will limit or mitigate the effect of systematic errors in the ILRS data, improve the final products through realistic description of geophysical processes, and strengthen the quality of the products by including an additional accurate target: LARES (Pavlis et al., 2015). As far as the LLR analysis activities, a new service has been instituted via a web application, where one can obtain predictions for LLR observations at a specific site and they can also have their LLR data checked for validity, prior to submitting them to the Data Centers for archival. Currently, the LLR group is in the process of developing a unique data set of all available LLR data in the newly adopted CRD format, in order to better serve the community and to conform with the ILRS standards.

Satellite Laser Ranging

ILRS Network

The present ILRS network includes over forty stations in 27 countries (see Figure 2); some of these stations are undergoing refurbishment and upgrade. During the last five years, new Russians stations joined the ILRS network in Arkhyz, Zelenchukskaya, Svetloe, Badary, Irkutsk, Baikonur (in Russia), and Brasilia (Brazil) filling-in very important geographic gaps. The Russians are planning new SLR systems in other sites including Havana (Cuba), Harteebesthoek (South Africa), and several other locations. SLR and LLR data are again flowing from the new MeO (Metrology and Optics) station at Grasse, France. A new SLR station is currently in Sejong, Korea and two new stations are under construction in India. The TIGO system, operational in Concepción Chile since 2002, has recently been closed and will be relocated to La Plata Argentina in 2015. New SLR stations are also being planned for Metsahovi (Finland) and Ny Ålesund (Norway). The NASA Space Geodesy Project (SGP) is planning for construction of up to ten new, next generation SLR systems as part of core sites; the first two systems are planned for deployment at McDonald, TX and Haleakala, HI in the 2017 time frame; several are planned to replace current legacy systems. Large gaps are still very prominent in Africa and South America and discussions are underway with several groups in the hope of addressing this shortcoming.

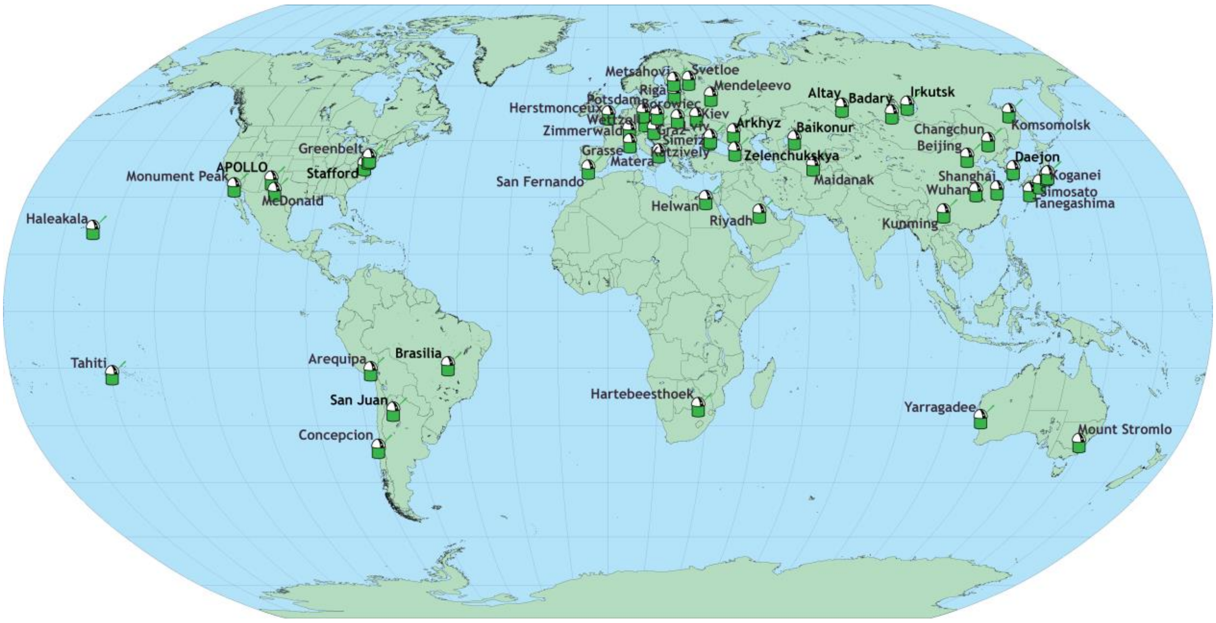


Figure 2. ILRS network (as of May 2015).

Stations designated as operational have met the minimum ILRS qualification for data quantity and quality. In general, stations continue to improve their performance. Several stations dominated the network with the Yarragadee, Changchun and Mt. Stromlo stations being the strongest performers. The next group of stations with impressive contributions included Greenbelt, Zimmerwald, Herstmonceux, Monument Peak, Graz, Matera, and Wettzell. During the twelve-month period from April 2014 to March 2015, 27 stations met the ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

Several stations are now operating with kHz lasers and fast detectors, thereby increasing data yield and allowing them to be more productive with pass interleaving, a critical step as the number of satellites being tracked with SLR is increasing dramatically. Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

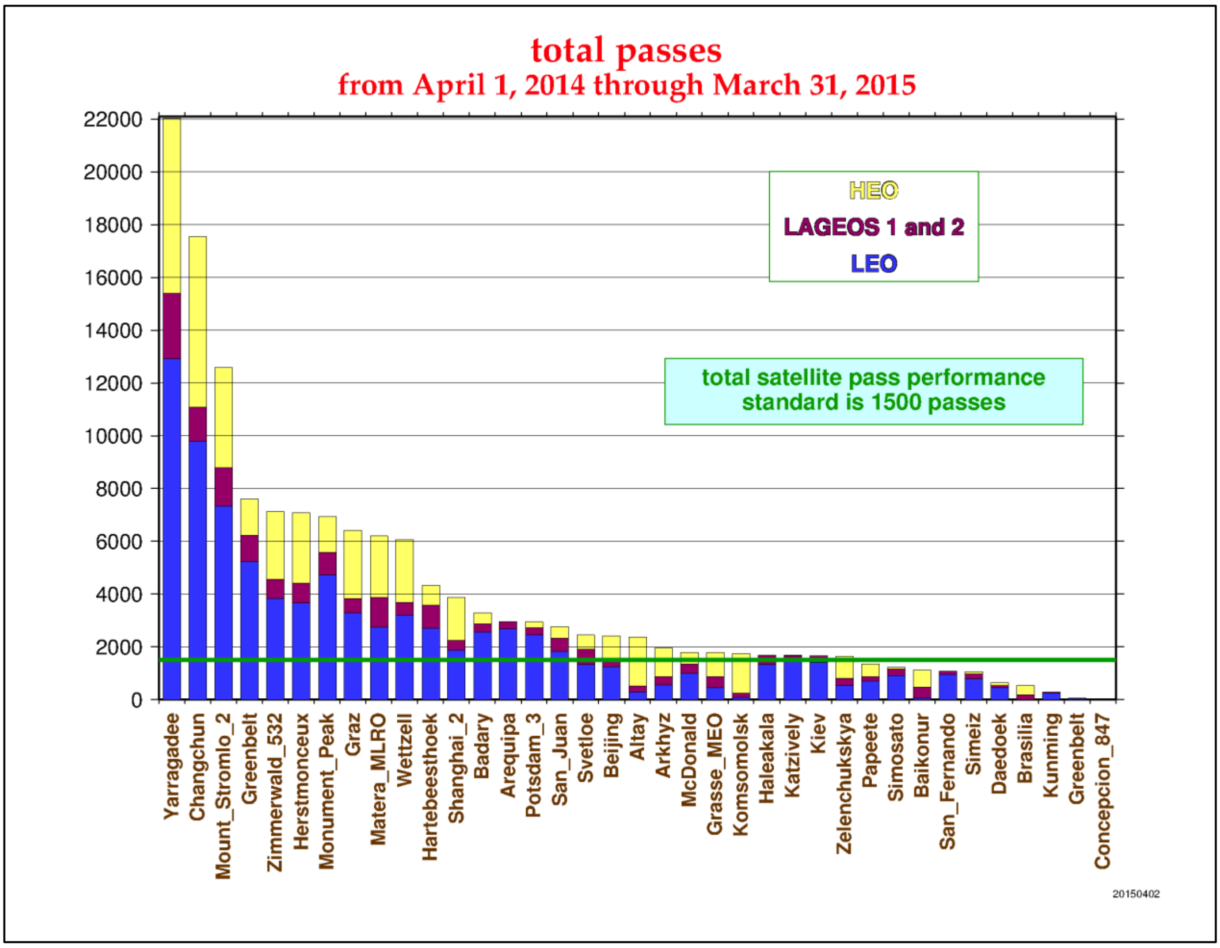


Figure 3. ILRS network performance (total passes).

Satellite Missions

The ILRS is currently tracking nearly eighty artificial satellites including passive geodetic (geodynamics) satellites, Earth remote sensing satellites, navigation satellites, and engineering missions (see Figure 4). The stations with lunar capability are also tracking the lunar reflectors. In response to tandem missions (e.g., GRACE-A/-B, TanDEM-X/TerraSAR-X) and general overlapping schedules, many stations are tracking satellites with interleaving procedures.

The ILRS assigns satellite priorities in an attempt to maximize data yield on the full satellite complex while at the same time placing greatest emphasis on the most immediate data needs. Priorities provide guidelines for the network stations, but stations may occasionally deviate from the priorities to support regional activities or national initiatives and to expand tracking coverage in regions with multiple stations. Tracking priorities are set by the Governing Board, based on application to the Central Bureau and recommendation of the Missions Working Group (see *http://ilrs.gsfc.nasa.gov/missions/mission_operations/priorities/index.html*).

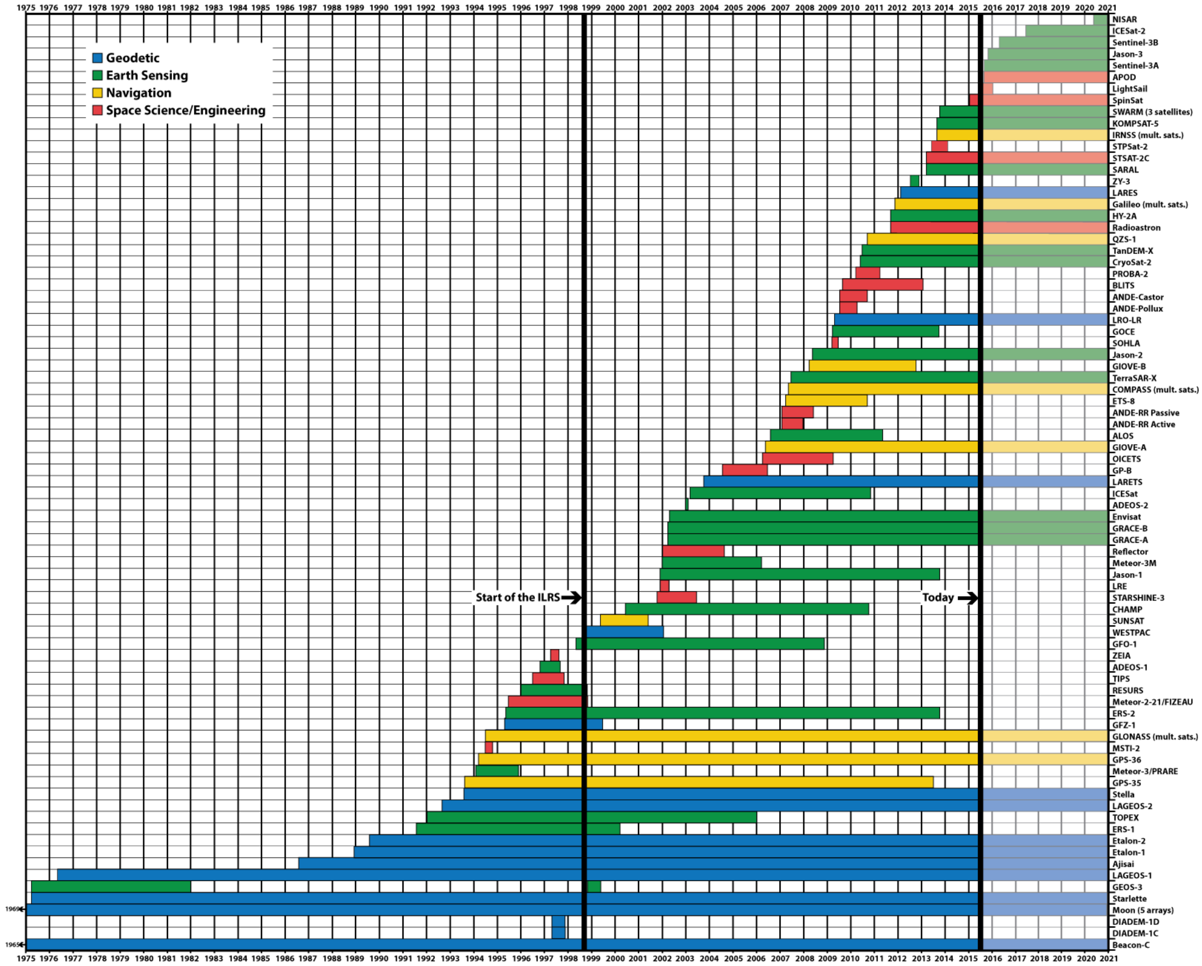


Figure 4. The past, current and future tracking roster for the ILRS network (as of May 2015).

Missions are added to the ILRS tracking roster as new satellites are launched and as new requirements are adopted. Missions for completed programs are deleted from the ILRS priority list (see Figure 4). Notable recent losses include the altimeter missions Envisat (ESA) and Jason-1 (NASA/CNES), after over ten years of ILRS support for each fully operational mission, as well as GOCE and BLITS. The ILRS continues to track Envisat to provide ephemerides and orientation data to help with trajectory/safety planning.

During this reporting period, LARES was added to the geodetic satellite constellation to support the reference frame and relativity studies. Several new satellites were added in geosynchronous and MEO orbits. The ILRS tracking roster presently includes six GLONASS satellites, four Compass, and eight Galileo satellites. Following discussions at the ILRS Technical Workshop, “Satellite, Lunar and Planetary Laser Ranging: Characterizing the Space Segment,” in Frascati, Italy in November 2012, and agreements that were approved by the ILRS and GGOS after deliberations within the “LAser Ranging to GNSS s/c Experiment (LARGE)” Study Group meeting in April 2014, several stations routinely track segments of passes of all 24 active GLONASS satellites and beyond. The newer “high” satellites are using retroreflector arrays that satisfy the ILRS standard. As a result, stations are having greater success with daylight ranging.

The tracking approval process begins with the submission of a Missions Support Request Form, which is accessible through the ILRS website (*http://ilrs.gsfc.nasa.gov/docs/2009/ilrsmsr_0901.pdf*).

The form provides the ILRS with the following information: a description of the mission objectives, mission requirements, responsible individuals and contact information, timeline, satellite subsystems, and details of the retroreflector array and its placement on the satellite. This form also outlines the early stages of intensive support that may be required during the initial orbital acquisition and stabilization and spacecraft checkout phases. A list of upcoming space missions that have requested ILRS tracking support is summarized in Table 2 along with their sponsors, intended application, and projected launch dates.

Table 2. Recently Launched and Upcoming Missions (as of May 2015)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Compass (6 satellites)	Chinese Defence Ministry	Positioning, navigation, timing	2007-2012
Galileo (8 satellites)	ESA	Positioning, navigation, timing	2011-2015
IRNSS (4 satellites)	ISRO	Positioning, navigation, timing	2013-2015
KOMPSAT-5	KARI,	Earth observation	Aug-2013
LARES	ASI/ESA	Geodesy, relativity	Feb-2012
RadioAstron	Lavochkin Association	Space science	Jul-2011
SARAL	CNES/ISRO	Earth observation	Feb-2013
SpinSat	NRL	Atmospheric density determination	Sep-2014
STPSat-2	AFRL	Spacecraft development	Nov-2010
STSAT-2C	MEST/KAIST	Spacecraft development	Jan-2013
SWARM	ESA	Earth observation	Dec-2013
Approved by ILRS for Future SLR Tracking			
APOD/PN-1A, -1B, -1C, -1D	Beijing Aerospace Control Center	Engineering	Aug-2015
LightSail-A	Planetary Society	Engineering	May-2015
NISAR	NASA	Earth sensing	2020
Future Satellites with Retroreflectors			
GPS-III	U.S. DoD, DoT	Positioning, navigation, timing	TBD
HY-2B	CNES, CNSA	Earth observation	2012
HY-2C	CNES, CNSA	Earth observation	2015
HY-2D	CNES, CNSA	Earth observation	2019
ICESat-2	NASA	Ice sheet mass balance, sea level	2016
Jason-3	NASA, CNES, Eumetsat, NOAA	Oceanography, climate change	2015
Sentinel-3A and -3B	ESA (GMES)	Oceanography	2014
SWOT	NASA, CNES	SAR altimeter	2016

Since several remote sensing missions have suffered failures in their active tracking systems or have required in-flight recalibration, the ILRS has encouraged new missions with high precision orbit requirements to include retroreflectors as a fail-safe backup tracking system, to improve or strengthen overall orbit precision, and to provide important intercomparison and calibration data with onboard microwave navigation systems.

The ILRS network has been involved in one-way ranging and time transfer programs. The first time transfer experiment T2L2 (Time Transfer by Laser Link) continues to demonstrate improved time transfer capabilities with the Jason-2 satellite; to date, time transfer to an accuracy of 100 ps has been demonstrated with potential of greater accuracy as the data analysis continues. A second time transfer proposal (European Laser Timing, ELT) utilizing a laser link for the atomic clock ensemble in space (Atomic Clock Ensemble in Space, ACES) mission on the International Space Station (ISS) has progressed to the point that it is ready to be accepted for the baseline design of ACES. The ILRS supported the Lunar Reconnaissance Orbiter (LRO), where one-way laser ranging from a subset of the ILRS network was used to improve the orbit determination for the laser altimeter and surface positioning. Approximately a dozen ground stations supported one-way ranging to LRO. The ILRS network provided nearly 4,200 hours of tracking over the five years the LRO-LR activity was funded. Ground-based hardware simulations for planning and designs for laser transponders have also been carried out by several groups looking forward to interplanetary ranging.

Lunar Laser Ranging (LLR) Network

The LLR results are considered among the most important science return of the Apollo era. Of all the active ILRS observatories very few are technically equipped to track retro-reflector arrays on the surface of the Moon or spacecraft orbiting around the Moon. In 2014, only three Lunar Laser Ranging (LLR) sites collected ranging data to the Moon: the Observatoire de la Côte d’ Azur, France (430 NPs), the APOLLO site in New Mexico, USA (212 NPs) and the Matera Laser Ranging station in Italy (6 NPs). Unfortunately, no NPs have been obtained from the McDonald Observatory in Texas, USA. This means, a time series of LLR tracking at McDonald, which has run for four decades, has been interrupted.

The LLR measurement statistics for 2014 (Figure 5) shows that about two thirds of the data have been collected at the French MeO site near Grasse and about one third of the data at APOLLO. Figure 6 illustrates the statistics for the observed retro-reflector arrays, where much better coverage of all reflectors was achieved than in previous years. Nevertheless, most of the data was obtained on the big Apollo 15 reflector array (56%). Figure 7 presents the entire LLR data set from 1970 to 2014 showing the amount of data collected by each of the active LLR sites in each year. The total data yield over this period is about 21,000 NPs, recently averaging about 600 NPs per year. At the Observatoire de Paris, an “assisting tool” has been developed to support lunar tracking by providing predictions of future LLR observations as well as a validation of past LLR normal points. This tool and further information can be accessed via the ILRS website (*http://ilrs.gsfc.nasa.gov/science/scienceContributions/lunar.html*).

LLR data analysis is carried out by a few major LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; Institute of Geodesy (IfE), University of Hannover, Germany. In the last few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. The six LLR analysis centers focus on different research topics (such as relativity, lunar interior, etc.). In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

One general objective of LLR analysis is to improve accuracy from the current cm to the mm level. The various analysis centers continue their comparison initiative to mutually improve the various reduction codes. Recent activities also include comprehensive simulations to show the potential benefit of improved tracking with additional observatories and/or to new reflectors.

Above all, LLR remains one of the best tools to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system (Müller et al. 2014). LLR analysis steadily reduces the margins for a possible violation of Einstein's theory of relativity and impressively underpins its validity – now in the 100th year of its existence.

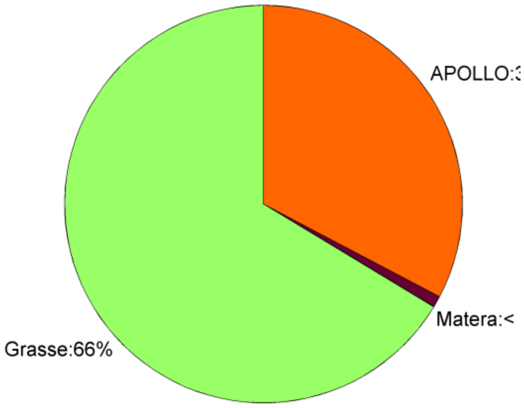


Figure 5. Observatory statistics in 2014.

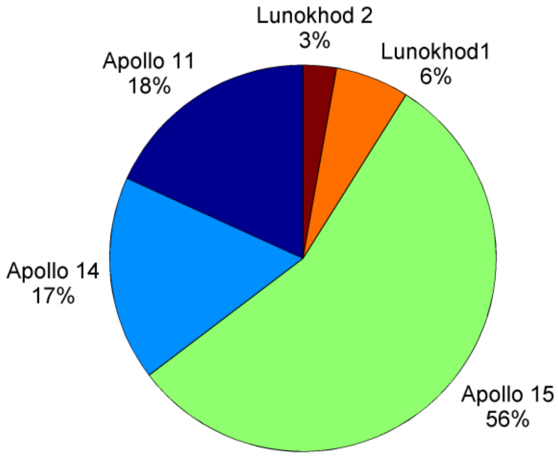


Figure 6. Reflector statistics in 2014.

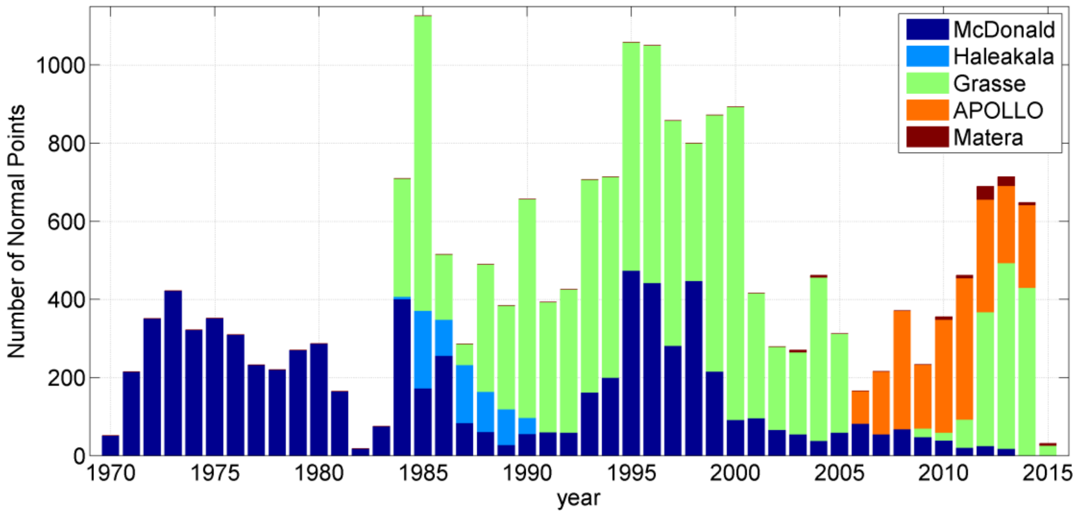


Figure 7. Data yield of the global LLR network of stations (through the end of 2014).

Recent Activities

Mission Campaigns

During the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand the ILRS network support of the various GNSS constellations. To that end, the ILRS and GGOS jointly formed a study group, the LAser Ranging to GNSS s/c Experiment (LARGE). The objectives of this study group are to define an operational GNSS tracking strategy for the ILRS that addresses all proposed requirements and to clarify outstanding ILRS and IGS issues with the GNSS satellites and ground stations. The satellite constellations of interest with retroreflector arrays include GLONASS, BeiDou (Compass), Galileo, and GPS. The GLONASS constellation is fully populated. BeiDou and Galileo (including GIOVE) constellations are in process. GPS satellites with laser retroreflector arrays will begin launching in the 2018 timeframe. When completed, the full GNSS complex should reach about 80 satellites.

Two GNSS tracking campaigns have been held thus far to determine strategies for the ILRS network to support tracking of this future large number of GNSS satellites. The first session was held in August and September 2014. Stations were asked to track as many GNSS targets as possible (24 GLONASS, 4 Beidou, and 5 Galileo satellites). Although several stations were able to accomplish this goal, few stations obtained more than one segment per pass and very few daylight passes were tracked. A second GNSS campaign was held from November 2014 through January 2015 with a reduced number of satellites (6 GLONASS, 4 Beidou, and 4 Galileo). Stations were asked to track three segments per pass and include daylight tracking.

In addition to the LARGE effort, the ILRS has supported several other tracking campaigns, including the IRNSS constellation at geosynchronous orbits.

ILRS Meetings

The ILRS organizes regular meetings of the Governing Board and working groups. These meetings are typically held in conjunction with ILRS workshops, such as the ILRS Technical Workshops (oriented toward SLR practitioners) or the biannual International Workshop on Laser Ranging. A summary of recent and planned ILRS meetings is shown in Table 3. Minutes and presentations from these meetings are available from the ILRS website (*http://ilrs.gsfc.nasa.gov/about/reports/meeting_reports.html*).

The ILRS also conducts meetings of the Central Bureau on a monthly basis. These meetings review network station operation and performance, as well as coordinate support of upcoming missions, monitoring and managing the ILRS infrastructure, and future directions and activities, such as the implementation of the new ILRS website.

In May 2011, the Bundesamt fuer Kartographie und Geodaesie/BKG (Geodetic Observatory Wettzell and TIGO), the Research Group Satellite Geodesy of the Technische Universitaet Muenchen and the ILRS sponsored the 17th International Workshop on Laser Ranging in Bad Kötzting, Germany. Over 140 attendees participated in the workshop. Various ILRS-related meetings were held in conjunction with the workshop, including the 23rd General Assembly of the ILRS, and Governing Board and working group meetings. A trip to the Geodetic Observatory Wettzell and an introduction to the TWIN VLBI project was arranged.

Table 3. Recent ILRS Meetings (as of May 2015)

Timeframe	Location	Meeting
May 2011	Bad Kötzting, Germany	17th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Working Group meetings ILRS General Assembly
September 2011	Zurich, Switzerland	ILRS Analysis Working Group meeting
December 2011	San Francisco CA, USA	ILRS Governing Board meeting
April 2012	Vienna, Austria	ILRS Governing Board meeting ILRS Working Group meetings
November 2012	Frascati, Italy	ILRS Technical Workshop "Satellite, Lunar, and Planetary Laser Ranging: Characterizing the Space Segment" ILRS Governing Board meeting ILRS Working Group meetings
April 2013	Vienna, Austria	ILRS Analysis Working Group meeting
September 2013	Potsdam, Germany	ILRS Analysis Working Group meeting
November 2013	Fujiyoshida, Japan	18th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Working Group meetings ILRS General Assembly
April 2014	Vienna, Austria	ILRS Analysis Working Group meeting
October 2014	Annapolis MD, USA	19th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Working Group meetings
April 2015	Vienna, Austria	ILRS Analysis Working Group meeting
October 2015	Matera, Italy	ILRS Technical Workshop
2016	Potsdam, Germany	20th International Workshop on Laser Ranging

The ILRS Technical Workshop 2012: "Satellite, Lunar and Planetary Laser Ranging: characterizing the space segment" was held at the Frascati National Laboratories of the INFN-LNF, Frascati, Italy on November 5-9, 2012, in conjunction with a one-day Workshop on "ASI-INFN ETRUSCO-2 Project of Technological Development and Test of SLR Payloads for GNSS Satellites." The meeting focused on the laser ranging space segment including retroreflector arrays for Earth orbiting satellites and the Moon, with special attention to the expanding role of ranging to GNSS and geosynchronous satellites. Topics also included receivers in space for time transfer experiments (T2L2), one-way ranging to lunar orbiters (LRO) and interplanetary spacecraft (MLA, MOLA), and data relay systems.

The 18th International Laser Ranging Workshop was held in Fujiyoshida Japan, November 11-15, 2013. The theme of the 18th workshop was "Pursuing Ultimate Accuracy and Creating New Synergies." An important topic for this workshop was maximizing accuracy in the network with the intent of enhancing the potential for laser ranging by including activities in relevant fields. The workshop was funded by the National Institute of Information and Communications Technology (NICT) International Exchange Program, the Support Center for Advanced Telecommunications Technology Research (SCAT), the Geodetic Society of Japan, and the Society for Promotion of Space Science, and is academically supported by the Science Council of Japan, the Geodetic Society of Japan and also by the Japan Society for Aeronautical and Space Sciences. Over 150 attendees participated in the workshop. As with most workshops, ILRS-related meetings were held in conjunction with the workshop. Attendees were also able to make a trip to the Koganei Geodetic Observatory during the week.

The 19th International Workshop on Laser Ranging was held in Annapolis, MD October 27-31, 2015. NASA, along with the Smithsonian Astrophysical Observatory (SAO) and the International Laser Ranging Service (ILRS), sponsored the workshop, with help from several corporate supporters. Over 180 attendees participated in the workshop from 23 countries. NASA Goddard Space Flight Center (GSFC) had the unique opportunity to host this event at the birthplace of SLR: October 31, 2014 marked the 50th anniversary of the first successful SLR measurement, conducted at what is now the Goddard Geophysical and Astronomical Observatory (GGAO). The theme for this workshop, "Celebrating 50 Years of SLR: Remembering the Past and Planning for the Future" allowed attendees to look back on the many accomplishments of the laser ranging community and present plans for future advances in SLR technology and science. The workshop featured sessions of invited talks by the pioneers in the field as well as science sessions highlighting SLR's positive impact on various NASA and international missions. In addition to the events in Annapolis, the participants were given a daylong tour of GSFC and GGAO. A new format for a station operations session was introduced at this workshop where ILRS experts met in small groups with station engineers and operators to provide solutions to common station problems, information to maintain station stability, and guidelines for interacting with the analysts in determining station biases. These station clinics were well attended and well received by the workshop attendees.

Publications

Detailed reports from past meetings can be found on the ILRS website. ILRS Biannual Reports summarize activities within the service over the period since the previous release. They are available as hard copy from the CB or online at the ILRS website. The ILRS published the 2009-2010 ILRS Report in late 2012. This latest volume is the fifth published report for the ILRS and concentrated on achievements and work in progress rather than ILRS organizational elements.

In October 2012, the ILRS Central Bureau implemented a new design for the ILRS website, *http://ilrs.gsfc.nasa.gov*. The redesign process allowed for a review of the organization of the site and its contents, ensuring information was made current and remained useful to the laser ranging community.

ILRS Analysis Center reports and inputs are used by the Central Bureau for review of station performance and to provide feedback to the stations when necessary. Special weekly reports on on-going campaigns are issued by email. The CB also generates monthly and quarterly Performance Report Cards and posts them on the ILRS website (*http://ilrs.gsfc.nasa.gov/network/system_performance/index.html*). These Report Cards evaluate data quantity, data quality, and operational compliance for each tracking station relative to ILRS minimum performance standards. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, and minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the ILRS website. Plots, updated frequently, of multiple satellite normal point RMS and number of full-rate points per normal point as a function of local time and range have been added to the ILRS website station pages.

Other Activities

In April 2013, the ILRS was accepted as a network member of the International Council for Science (ICSU) World Data System (WDS). The WDS strives to enable open and long-term access to multidisciplinary scientific data, data services, products and information. The WDS works to ensure long-term stewardship of data and data services to a global scientific user community. The ILRS is a network member of the WDS, representing its two data centers and coordinating their activities within the WDS.

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International VLBI Service for Geodesy and Astrometry (IVS)

http://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Axel Nothnagel (Germany)
Director of the Coordinating Center: Dirk Behrend (USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2011−2015. During a retreat in September 2011, the IVS Terms of Reference were modernized and the IVS Directing Board expanded by a second Analysis Representative to altogether 16 members. Two Directing Board elections were held, one from December 2012 to January 2013 and the other from December 2014 to January 2015. Axel Nothnagel succeeded Harald Schuh as the IVS Chair in February 2013. The first VLBI Training School was organized in March 2013; future training schools will be held in a three-year rhythm. The next-generation VLBI system was further developed and was named the VLBI Global Observing System (VGOS). The transition from the legacy S/X system to the VGOS broadband system will be undertaken in the next five years.

Activities

Introduction

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, are

- to provide a service to support geodetic, geophysical and astrometric research and operational activities,
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique, and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

The VLBI technique has been employed in geodesy for more than 40 years. Science and applications set the requirements for the realization and maintenance of global reference frames at VLBI's technical limitations. Covering intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art and providing numerous quasar positions as the best approach to an inertial reference frame, VLBI significantly contributed to the tremendous progress made in geodesy over the last decades. VLBI was a primary tool for understanding the global phenomena changing the "Solid Earth". Today VLBI continuously monitors Earth orientation parameters as well as crustal movements in order to maintain global reference frames, coordinated within the IVS.

Being tasked by IAG and IAU with the provision of timely and, highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference

Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Organization and Meetings

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability.

Taking effect in January 2013, Bill Petrachenko of Natural Resources Canada took over the position of the IVS Technology Coordinator from Alan Whitney. After 13 years of service, Axel Nothnagel handed over the responsibilities of the IVS Analysis Coordinator to John Gipson of NVI, Inc./NASA Goddard Space Flight Center on March 8, 2013.

The IVS held Directing Board elections for four representative and three at-large positions in Dec2012/Jan2013. The new sixteen Directing Board members elected Axel Nothnagel of the University of Bonn as the successor to Harald Schuh as chair of the IVS for the next four years (until spring 2017).

Table 1: Members of the IVS Directing Board during the report period (2011−2015).

a) ***Current Board members (May 2015)***			
Directing Board Member	**Institution, Country**	**Functions**	**Recent Term**
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Alessandra Bertarini	IGG, University of Bonn, Germany	Correlators and Operation Centers Representative	Feb 2015 − Feb 2019
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2013 − Feb 2017
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Alexander Ipatov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2015 − Feb 2017
Ryoji Kawabata	Geospatial Information Authority, Japan	At Large Member	Feb 2015 − Feb 2017
Jim Lovell	University of Tasmania, Hobart, Australia	Networks Representative	Feb 2013 − Feb 2017
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2015 − Feb 2019
Axel Nothnagel	IGG, University of Bonn, Germany	Analysis and Data Centers Representative, Chair	Feb 2013 − Feb 2017
Bill Petrachenko	Natural Resources Canada	Technology Coordinator	—
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 − Feb 2019
Harald Schuh	GFZ Potsdam, Germany	IAG Representative	—
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2015 − Feb 2017

b) *Previous Board members in 2011−2015*			
Jesús Gómez González	National Geographical Institute, Spain	At Large Member	Feb 2011 − Feb 2013
Hayo Hase	BKG, Germany; TIGO, Chile	Networks Representative	Feb 2011 − Feb 2015
Shinobu Kurihara	Geospatial Information Authority, Japan	At Large Member	Feb 2013 − Feb 2015
Fengchun Shu	Shanghai Astronomical Observatory, China	At Large Member	Feb 2013 − Feb 2015
Oleg Titov	Geoscience Australia	Analysis and Data Centers Representative	Feb 2009 − Feb 2013
Gino Tuccari	IRA/INAF, Italy	Networks Representative	Feb 2009 − Feb 2013
Alan Whitney	Haystack Observatory, USA	Technology Coordinator	—

In January 2013 Bill Petrachenko of Natural Resources Canada became the new IVS Technology Coordinator (succeeding Alan Whitney of MIT Haystack Observatory) and in March 2013 John Gipson of NVI, Inc./NASA Goddard Space Flight Center became the new IVS Analysis Coordinator (succeeding Axel Nothnagel).

From 21–22 September 2011, the IVS Directing Board (plus a few invited guests) held a retreat at Hohe Wand, Austria. The main goals of the retreat were a review of the IVS organization and its mandate, functions, and components as well as the definition of focus areas for future IVS work and activities. The retreat participants agreed that the IVS organization, mandate, and functions as outlined in the IVS Terms of Reference (ToR) continued to fulfill the requirements of the global geodetic/astrometric VLBI science and associated user communities. The ToR were revised to simplify and modernize the wording, to add the Global Geodetic Observing System (GGOS), and to increase the Board by the addition of a second Analysis Center representative. The revised ToR were approved by the Board in the subsequent Board meeting and then officially ratified by the IAG in December. The revised ToR can be found, for instance, on the IVS Web site at the URL http://ivscc.gsfc.nasa.gov/about/org/documents/ivsTOR.html. In terms of focus areas, the retreat participants felt that emphasis should be put on improving quality control, internal and external outreach, VLBI2010 infrastructure, real-time observation and product creation (including automation), and expanding research and research fields.

Table 2: IVS meetings during the report period (2011–2015).

Time	**Meeting**	**Location**
31 March 2011	12th IVS Analysis Workshop	Bonn, Germany
9–12 May 2011	6th IVS Technical Operations Workshop	Westford, MA, USA
13–16 November 2011	10th International e-VLBI Workshop	Broederstroom, South Africa
1–2 March 2012	VLBI2010 Workshop on Technical Specifications (TecSpec)	Bad Kötzting, Germany
4–9 March 2012	7th IVS General Meeting	Madrid, Spain
8 March 2012	13th IVS Analysis Workshop	Madrid, Spain
22–24 October 2012	1st International VLBI Technology Workshop	Westford, MA, USA
2–5 March 2013	VLBI Training School	Espoo, Finland
5 March 2013	14th IVS Analysis Workshop	Espoo, Finland
6–9 May 2013	7th IVS Technical Operations Workshop	Westford, MA, USA

10–12 October 2013	2nd International VLBI Technology Workshop	Seogwipo, Jeju Island, South Korea
2–7 March 2014	8th IVS General Meeting	Shanghai, China
7 March 2014	15th IVS Analysis Workshop	Shanghai, China
10–13 October 2014	3rd International VLBI Technology Workshop	Groningen, The Netherlands
4–7 May 2015	8th IVS Technical Operations Workshop	Westford, MA, USA
21 May 2015	16th IVS Analysis Workshop	Ponta Delgada, Azores, Portugal

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and VGOS technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 2 gives an overview of the IVS meetings during the report period.

The VLBI2010 Workshop on Technical Specifications (TecSpec), which was tailored towards the station side of VLBI2010 (now called VGOS, see below) and thus focused almost exclusively on the station specifications and hardware, covered items from fast-slewing antennas to wideband feeds and front-ends to back-ends and recorders. Additional topics included e-transfer and e-VLBI, monitor and control, as well as clock distribution. The TecSpec workshop attracted almost 100 people, testament to the very high interest in the new VLBI system. At the 7th IVS General Meeting (GM2012), a new acronym for the next generation VLBI network was introduced. From March 2012 onward the new system is called "**VGOS**" (VLBI Global Observing System).

The VLBI Training School in Espoo, Finland was the first training school organized by the IVS (through Working Group 6). Following its success, it is planned to organize such schools in a three-year rhythm (the next VLBI Training School is scheduled for March 2016 in South Africa). Over a period of four days, about 50 participants were schooled in all aspects of the VLBI technique. The school was very effective in training young researchers in the VLBI technique thus paving the way to preparing the next generation of VLBI experts in parallel to the development of the next-generation VLBI system

Working Groups

VLBI Data Structures. The Working Group 4 on VLBI Data Structures examined the data structure currently used in VLBI data processing and investigated what data structure would likely be needed in the future. Over several years the WG designed a new VLBI data structure based on the NetCDF data storage format. The resulting vgosDB format meets current and anticipated future requirements for individual VLBI sessions including a cataloguing, archiving, and distribution system. The WG prepared a final report, which is included in the 2013 Annual Report.

Space Science Applications. The Working Group 5 on Space Science Applications investigated synergies between the IVS and VLBI space science applications and looked into perspectives of future missions and the potential involvement of the IVS. The activities of the IVS in this field are not limited to providing the observations and initial data processing but also contain scientific data analysis and interpretation. The WG submitted a final report, which is posted on the IVS Web site.

VLBI Education. The Working Group 6 on VLBI Education organized a VLBI Training School (see above), compiled educational material, and established contacts to education institutions. Given the success of the WG work, the Directing Board approved the establishment of a permanent body within the IVS by creating the Committee on VLBI Education and Training.

Observing Program and Special Campaigns

Observing Program

The observing program for 2011–2015 included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 8 stations, some with 9 or 10 stations depending on station availability. These networks were designed with the goal of having comparable x_p and y_p results. Data bases are available no later than 15 days after each session. Daily 1-hour UT1 Intensive measurements on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Tsukuba (Japan).
- TRF: Bi-monthly TRF sessions with 14–16 stations using all stations at least two times per year.
- CRF: Bi-monthly sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus astrometric sessions to observe mostly southern sky sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Triennial ~two-week continuous VLBI observing campaigns to produce continuous VLBI time series and to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy. During the report period two such campaigns were observed (see below).

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. Sessions in the observing program that were recorded and correlated using K5 technology had the same accuracy and timeliness goals as those using Mark 5. On average, a total of about 1400 station days per year were used in around 180 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

CONT11

In September 2011, a 15-day continuous VLBI observation campaign called CONT11 was observed. The observing network consisted of thirteen IVS stations (see Figure 1). The actual observing was done at a rate of 512 Mbps on the basis of UT days with each CONT11 day running from 0 UT to 24 UT. UT-day observing is needed to facilitate the most accurate combination and comparison with results from other techniques. Among many possible studies, the data will be used for high-resolution Earth rotation studies, investigations of reference frame stability, and investigations of daily to sub-daily site motions. For the duration of the CONT11 campaign an ultra-rapid dUT1 determination was performed on the baseline Onsala–Tsukuba. Near real-time correlation and analysis was performed using a sliding window in the analysis with the analysis software C5++. dUT1 estimates were obtained with very low latency during the ongoing CONT11 campaign and displayed on a dedicated Web page.

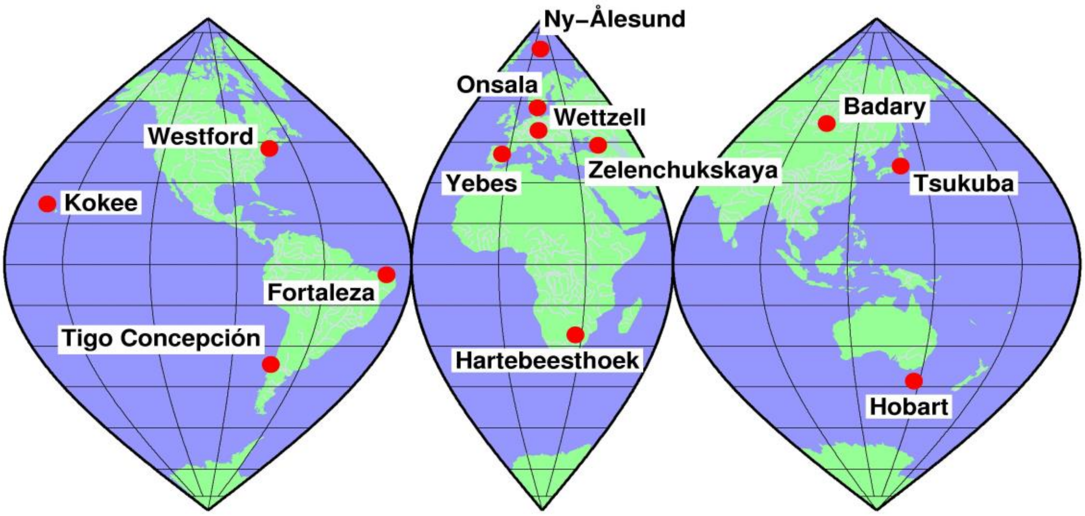

Figure 1: Geographical distribution of the thirteen IVS stations that participated in the CONT11 campaign in September 2011.

CONT14

The Continuous VLBI Campaign 2014 (CONT14) was successfully observed in early May 2014. Seventeen IVS stations at sixteen sites (see Figure 2) observed for fifteen consecutive days at a rate of 512 Mbps from 6–20 May 2014. The observing was again done on the basis of UT days. About half of the raw VLBI data was electronically transferred (e-transferred) to the target correlator. All CONT14 data were correlated at the Bonn Correlator, easing the logistics involved with module handling at the correlators and the stations as well as ensuring the creation of a homogeneous data set.

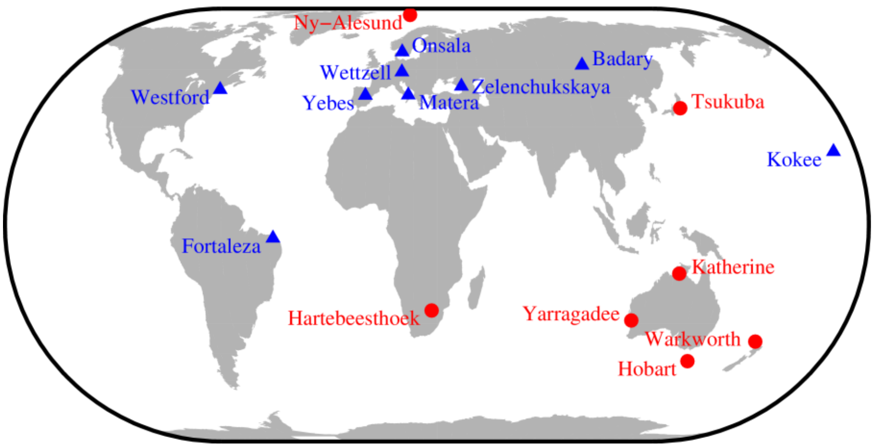

Figure 2: Geographical distribution of the sixteen CONT14 sites. The sites in red (circles) mostly e-transferred their data to the correlator, whereas the blue sites (triangles) physically shipped their recording modules.

Analysis

Earth Orientation Parameters.

The VLBI observables, mostly group delays, as produced by the IVS Correlating Centers are routinely analyzed by six to eight IVS Analysis Centers (AC) following the IERS Conventions 2010 (Petit and Luzum 2010) and individual processing strategies. Subsequently, the official IVS EOP product is generated by a combination process of the individual AC results. During the reporting period, the operational combination was carried out by the IVS Combination Center at the German Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt a.M. The input for the combination work were datum-free (constraint-free) normal equation systems in SINEX format (Solution INdependent EXchange format) containing elements for radio source positions, Earth orientation parameters, and radio telescope coordinates. Two primary combined EOP results were produced: rapid combination solutions and quarterly combination solutions. The rapid solutions were updated twice a week and contained only the IVS-R1 and IVS-R4 sessions; new data points were added as soon as the SINEX files of at least four IVS Analysis Centers were available. The long-term series were generated on a quarterly basis and included all 24-hour sessions since 1984. The quarterly series included long-term EOP series, station positions, and velocities. The results of the combination process were uploaded to the IVS Data Centers. The combined rapid EOP series, as well as the results of the quality control of the Analysis Center results, were also available directly at the BKG/DGFI Combination Center Web page (http://ccivs.bkg.bund.de/) or via the IVS Analysis Coordinator Web site (http://lupus.gsfc.nasa.gov/IVS-AC_products.htm). The inclusion of new Analysis Centers continued, a newly designed Web page was brought online, and the Web-based analysis tools were further enhanced.

Atmospheric Gradient Modeling

At the 13th IVS Analysis Workshop it was decided that the Chen and Herring model (1997) should be the conventional model of the IVS, using the constant C = 0.0031 for estimating the hydrostatic gradient. Since the hydrostatic contribution is the biggest one and the coefficient for the total gradient contribution is only slightly different (C = 0.0032), no noticeable effect on the estimates is expected. The MacMillan model (1995) produces essentially the same results, but for consistency with the analyses of the IGS, the Chen and Herring model was adopted.

Technology Development

The main focus of IVS technology development has been to achieve operational readiness for broadband observing as part of the VLBI Global Observing System (VGOS). This includes not only the development and proliferation of broadband systems but also the development of software and processes to enable efficient, and eventually automatic, operation of the VGOS stations and correlators. Already, a number of fully compliant (or nearly compliant) VGOS antennas have been constructed (many of these having already achieved first light and first fringes) with several more expected to come on line soon. The challenge is to ensure that signal chains are available for these antennas; that operating modes of the various systems are VGOS compliant, interoperable, and sufficiently robust against radio frequency interference from mobile phone transmitters and the like; and that systems can be controlled and thoroughly monitored remotely.

Automation and remote control are very important aspects of VGOS. With the expectation of 24/7 operations and a sharp rise in the number of observations per day, it is necessary (in order to keep operating costs at a reasonable level) to make all processes (including schedule generation, station operation, correlation, fringe processing, and analysis) as automated as possible. A necessary step to achieve automation and remote control is to have a language to concisely and completely describe the instrumentation, operating modes and schedule for a session. This has been the role of the VEX language over the past decades. However, with the advent of VGOS and the new broadband systems, instrumentation and operating modes, which had not been conceived of when the original version of VEX was developed, now need to be handled. As a result, over the past few years, a new version of VEX, called VEX2, has been developed. VEX2 was completed this year; it went through a brief period of community consultation; and it is now being used to write software to control instrumentation and processes in the complete VGOS operational chain.

Table 3: Progress in the build-out of the VGOS network as of early 2015.

Station	**Recent milestone**	**Broadband readiness**
GGAO	Test observations	now on fast RT
Westford	Test observations	now on legacy RT
Wettzell	Receiver tests	early 2015
Yebes	First fringes on X-band	late 2015
Noto	Receiver under construction	end 2015 on legacy RT
Ishioka	First fringes	end 2016 (initial S/X/Ka)
Santa Maria	RT constructed at site	2016
Badary	RT constructed at site	2015 (S/X/Ka)
Zelenchukskaya	RT constructed at site	2015 (S/X/Ka)
Kokee Park	RT being assembled at factory	2016
AuScope	Funding for upgrade secured	2016 on fast RTs
Tenerife	RT assembled at factory	2017
Ny Ålesund	Civil construction underway	2018

Successful 24-hour test of VGOS Broadband Delay System

On May 21, 2013, the first 24-hour session using the VGOS broadband delay system was observed on the GGAO12M–Westford baseline. The antennas, RDBE digital backends, and Mark-5C recorders were all operated under Field System control. The VGOS-ready 12-meter GGAO antenna and the 18-meter Westford antenna were each equipped with a cooled QRFH feed tailored to the specific antenna optics, followed by two cooled low noise amplifiers, one for each polarization. With a minimum scan length of 30 seconds and the minimum SNR set to 15 per band-polarization, the schedule achieved 48 scans per hour. Four 512-MHz-bands spanning 3.2 to 8.8 GHz within the available 2–12 GHz range were recorded at 2 Gbps (1 Gbps for each linear polarization) for a total of 37 Terabytes per station. Over 99% of the scans yielded good correlation.

Transition to VGOS Broadband Operations

The VGOS Project Executive Group (VPEG) developed an observing plan to guide the transition from current S/X to future VGOS broadband operations. The plan spans five years. It begins with a series of test campaigns in 2016 with as many as eight sites expected to participate. IVS technology development over the next year focuses on ensuring that systems and processes are ready for the test campaigns. Each campaign introduces a different aspect of the new VGOS mode of operation so that by 2017 the IVS will be ready to begin the VGOS pilot project. All campaigns will be roughly six weeks in duration to exercise the full “schedule to final products” operational chain in a sustained format. The Observing Plan focuses on the station aspect of the VGOS implementation. Further details were added in the Data Transmission and Correlation Plan. Currently work is actively done on an Analysis Plan.

In support and preparation of the test campaigns, a series of bi-weekly VGOS sessions have been initiated at the start of 2015 between Westford and GGAO, the goal being to establish a fully operational VGOS methodology. To support this, a so-called “parallel universe” has been put in place at Goddard that completely imitates the Master Schedules, ops mailing list, etc that have been used for years for the legacy S/X-band operations. In addition, processes are being put in place to automate as much as possible the full operational chain from schedule generation to analysis. The importance of this effort cannot be overemphasized in the quest to move from a VGOS test footing to a full VGOS operational capability.

DiFX Software Correlator for Geodetic VLBI

The so-called DiFX software correlator was originally developed at Swinburne University in Australia by Adam Deller, primarily for astronomical VLBI use. The development of an economical and powerful software correlator, a dream less than a decade ago, has been made possible by the relentless march of Moore’s Law to provide powerful inexpensive clustered PCs with high-speed data interconnections that can distribute and correlate VLBI data in an efficient manner. Several institutions that support geodetic VLBI correlation processing now have DiFX correlators (Max Planck Institute for Radio Astronomy [Bonn, Germany], U.S. Naval Observatory [Washington D.C., USA], and Haystack Observatory [Westford, MA, USA]) and have been working to augment the core DiFX software to meet the needs of geodetic VLBI. This includes the integration of much of the Mark IV post-correlation software involving data-management, output data formats, fringe finding and delay estimates, and editing/quality-assurance software. In addition, a substantial amount of work has been done to support the VDIF data-input format and to support correlation of mismatched sample rates and recording bandwidths.

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Permanent Service for Mean Sea Level (PSMSL)

http://www.psmsl.org

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Overview

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long term sea level change information from tide gauges and also provides a wider Service to the sea level community. The PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is hosted by the National Oceanography Centre (NOC), Liverpool with funding provided by the UK Natural Environment Research Council. PSMSL operates under the auspices of the International Council for Science (ICSU).

The PSMSL was established in 1933 by Joseph Proudman who became its first Secretary. Thus 2013 marked the 80th anniversary of the founding of PSMSL. To celebrate this milestone, PSMSL organised or co-organised three meetings: a workshop in Liverpool, UK, on major research topics in sea level science, including talks reviewing aspects of the IPCC Fifth Assessment Report (Working Group I); a symposium entitled "Implications of sea level change for the coastal zone - A symposium to mark the 80th anniversary of the Permanent Service for Mean Sea Level (PSMSL)" at the IAHS/IAPSO/IASPEI Joint Assembly in Gothenburg, Sweden; and a session at EGU 2013**:** Global and regional sea level rise and variability: from past to future.

The primary aim of the PSMSL is providing the global data bank for long term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last 4 years over 10000 station-years of data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 65000 station-years. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), are responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly values and higher frequency) from the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (GLOSS) core network.

New products have been made available over the last four years including trend maps and associated uncertainty values; links with the Système d'Observation du Niveau des Eaux Littorales (SONEL) have been further developed to facilitate distribution of additional geodetic data; and data from *in situ* ocean bottom pressure (OBP) recorders from all possible sources is being made available through PSMSL. PSMSL has also taken the lead in data archaeology through GLOSS.

PSMSL staff have continued to be active in a variety of international meetings, working groups, conferences and workshops including IOC GE-GLOSS and IOC Coordination Groups for tsunami warning systems, IPCC, GGOS, WDS, WCRP, and EGU over the last 4 years. In addition, they have answered many enquires relating to sea level and have appeared on radio and television discussing aspects of sea level change. PSMSL staff have also co-organised and contributed to tide gauge and sea level training courses.

Activities

1. Introduction

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long term sea level change information from tide gauges and also provides a wider Service to the sea level community. Established in 1933, the PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is hosted by the National Oceanography Centre (NOC), Liverpool with funding provided by the UK Natural Environment Research Council. The PSMSL operates under the auspices of the International Council for Sciences (ICSU) and is one of the main data centres for both the International Association for the Physical Sciences of the Oceans (IAPSO) and the International Association of Geodesy (IAG). It also has links with the Global Geodetic Observing System (GGOS). The PSMSL continues to work closely with other members of the sea level community through the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (GLOSS). The PSMSL is applying for membership of the new ICSU World Data System (WDS) and has completed the IAG Service Assessment Questionnaire.

The data set and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website. The metadata includes descriptions of benchmarks and their locations, types of instrumentation and frequency of data collection (where available) as well as notes on other issues that we feel the users should be aware of (e.g. earthquakes that are known to have occurred in the vicinity or subsidence due to local groundwater extraction). The free access to data by users is central to the PSMSL’s mission, and conversely no supplier is ever paid for their data, nor are licensing terms ever entered into.

2. Staffing and funding

Dr. Lesley Rickards continues to act as the Director of the PSMSL. The main PSMSL scientific staff concerned with the collection and analysis of monthly mean sea level data over the period have been Prof. Philip Woodworth, Dr. Simon Holgate, Dr. Svetlana Jevrejeva and Dr. Mark Tamisiea. Ms. Kathy Gordon continues to be responsible for management of the mean sea level data set and Dr. Andrew Matthews has worked on re-structuring the database, improving data delivery and providing new tools to aid data input, quality control and reporting. 2012 saw the departure of Dr. Simon Holgate, who we thank for all of his contributions over the previous 10 years. And we welcome Dr. Simon Williams, already a well-established scientist within NOC, to the PSMSL scientific staff.

Alongside the monthly mean sea level data collection, the PSMSL, together with BODC, is responsible for an archive of delayed-mode higher-frequency sea level data from the GLOSS network. This activity has so far included Miss Elizabeth Bradshaw and other colleagues in the British Oceanographic Data Centre (BODC).

Funding continues to be provided by the UK Natural Environment Research Council (NERC, the parent body of NOC). The document prepared in 2010 by PSMSL for NERC as part of its review of National Capability to aid future funding decisions resulted in PSMSL being one of the two areas in NOC given a high rating enabling us to continue to operate at the same level of funding. The document highlighted PSMSL’s unique role and the synergy generated by its co-location with NOC.

3. PSMSL-related scientific meetings, activities and events

PSMSL staff have continued to be active participants in the IOC Group of Experts on the Global Sea Level Observing System (GLOSS) and GGOS meetings, co-convened sea level sessions at the EGU and contributed to IOC coordination group tsunami warning system meetings. PSMSL has also contributed to the IPCC Fifth Assessment Report with Dr Svetlana Jevrejeva a lead author for Working Group I, Prof. Philip Woodworth a review editor and other PSMSL staff also contributing.

2013 marked the 80th anniversary of the foundation of the PSMSL. To commemorate this PSMSL hosted or co-convened the following events:

- A workshop in Liverpool, UK (October 2013), on major research topics in sea level science. The workshop included talks reviewing aspects of the IPCC Fifth Assessment Report (Working Group I). There were also presentations covering many aspects of regional variability in sea level.
- A symposium entitled "Implications of sea level change for the coastal zone - A symposium to mark the 80th anniversary of the Permanent Service for Mean Sea Level (PSMSL)" at the IAHS/IAPSO/IASPEI Joint Assembly in Gothenburg, Sweden (July 2013).
- A session at EGU 2013**:** Global and regional sea level rise and variability: from past to future.

In 2014 Dr Svetlana Jevrejeva co-organised a Summer school “Sea-level change: Observations and processes” in Delft, the Netherlands, attended by 37 students. She, together with Prof Philip Woodworth, gave lectures about tide gauge observations, PSMSL, GLOSS activities, PSMSL data sets, and data archaeology. In addition, a short demonstration of the data access at the PSMSL webpage, link to the SONEL data sets, link to the IOC manuals, and training material were given. In addition, Prof. Philip Woodworth and Dr. Simon Holgate were lecturers on the GLOSS training course held in Bangkok.

Dr. Lesley Rickards is a member of the ICSU World Data System Scientific Committee and chairs the sub-committee on Membership and Accreditation.

4. Collection, analysis, publication and interpretation of monthly and annual means of sea level from the global network of tide gauges

Currently, the PSMSL data bank for monthly and annual sea level data holds over 65,000 station-years of data from over 2200 stations. Data from each site are carefully quality controlled and, wherever possible, reduced to a common datum, whose stability is monitored through a network of geodetic benchmarks. Figure 1a indicates the number of station years added to the database each year and Figure 1b shows the number of stations. An average of approximately 2650 station years were added per year, with an exceptionally high number (4222) in 2013. This was due in part to an effort to chase up as much data as possible prior to the Group of Experts on GLOSS meeting towards the end of 2013, and also due to receiving a backlog of data from the new network in Spain. The number of stations updated has varied between 643 (2011) to 786 (2013). During the period 2011 to 2014, 1038 stations have been updated as shown in Figure 2. It can be seen that while many regions have supplied data (e.g. North America, Europe, Japan, Australia, New Zealand, South Africa, India), there are still gaps in the Arctic and Antarctic, and parts of South America and Africa.

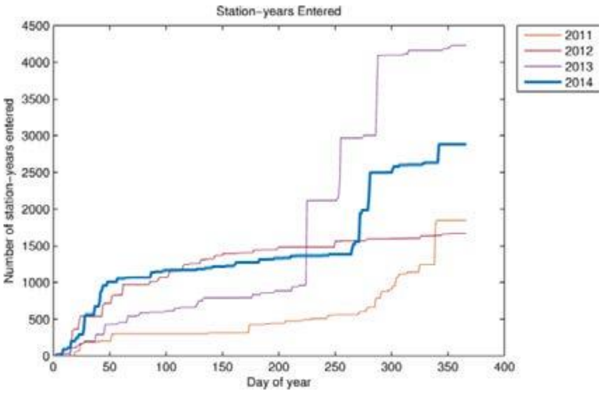


Figure 1a: Number of station years added to PSMSL database between 2011 and 2014

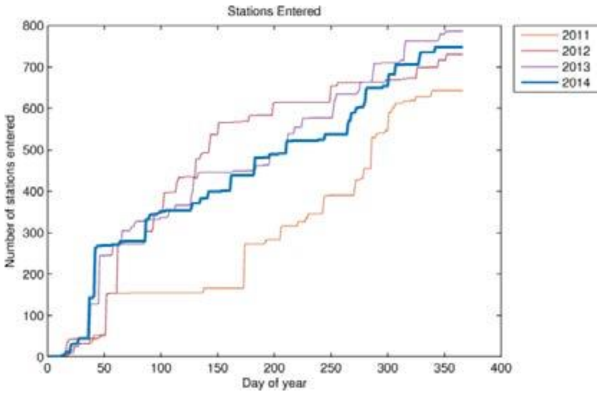


Figure 1b: Number of stations with data added to PSMSL database 2011 to 2014

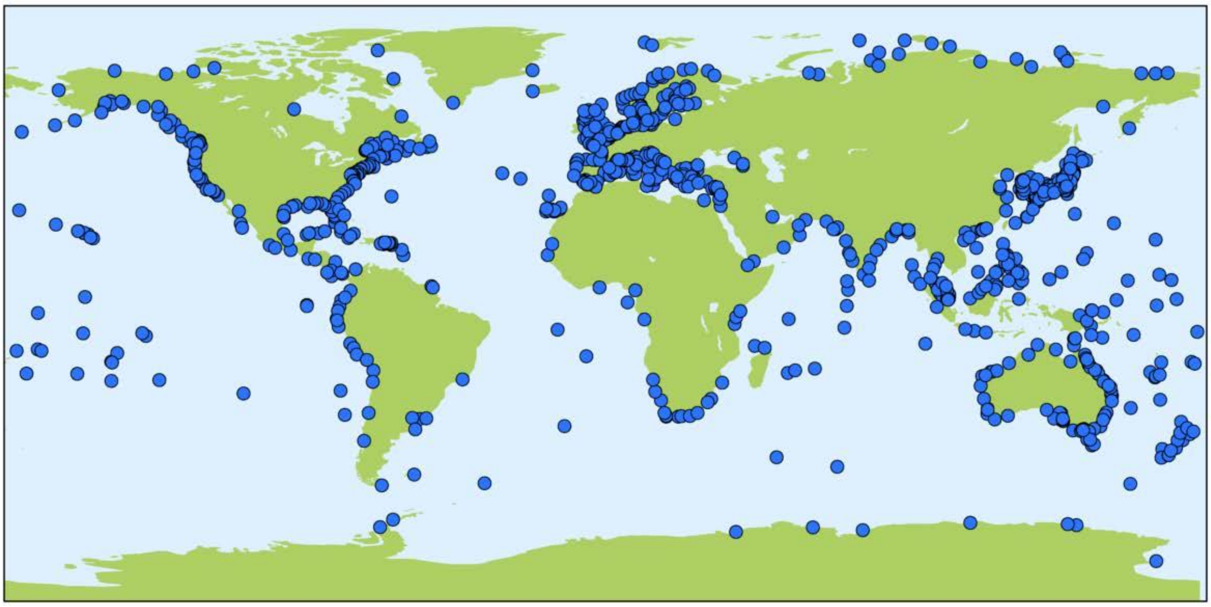


Figure 2: New PSMSL data received between 2011 and 2014

Figure 3 gives a more detailed view of the data held by PSMSL, indicating where data had been supplied in the past – in particular the decline in the number of stations in the Arctic is noticeable. 777 stations have provided data from 2013 or after with a further 196 providing data from 2010-2012. These (973 stations) can all be considered as active stations, but there are 987 stations for which no data have been supplied since before 1995. Some of these have undoubtedly ceased to operate; for others contact with the operators is being pursued. New stations are also coming on line providing near-real-time data for tsunami monitoring, but many of these do not yet supply the quality controlled mean sea level values to the PSMSL. There continue to be gaps in data receipts from parts of SE Asia, central and South America; these are presently being targeted to try to improve data flow. Africa continues to receive special attention through ODINAfrica and the Indian Ocean Tsunami Warning System (IOTWS). Although data flow has improved considerably over the last decade some of the gauges require a higher level of maintenance. Close links have been maintained with the University of Hawaii Sea Level Center and other international sea level data centres.

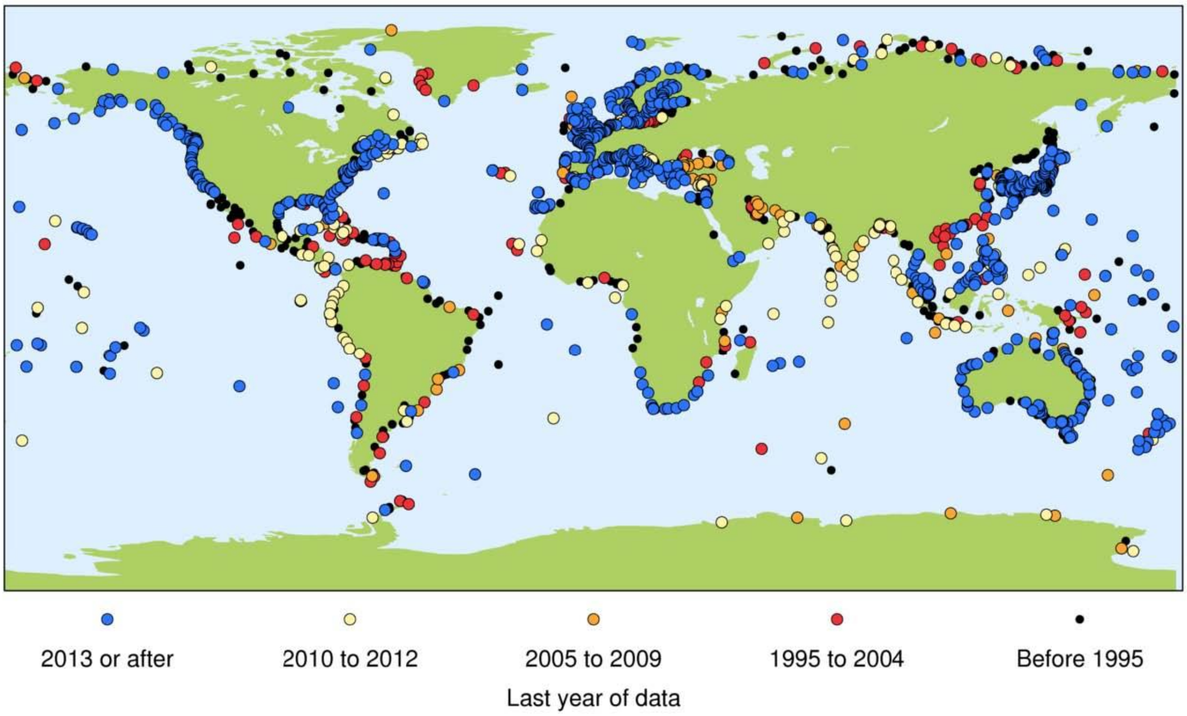


Figure 3: Year of most recent data received by PSMSL

4.1 Interactive map showing long-term trends

The relative sea level trends map allows interactive investigation of global mean sea level trends since 1900. This is updated annually to include new data, so the latest version includes data received in 2014. The limits of the period to be viewed can be selected by either moving the buttons on the slider or by entering the values in the two text boxes. A period of at least thirty years must be selected. The map will display the annual sea level trend at each station that has suitable data available over the selected period. Since its first introduction the trends map has been improved by the addition of uncertainty estimates: the pop-up boxes for each tide gauge shown on the trends map now include an uncertainty. Both the estimated trend and the uncertainty will change as the time span chosen is changed. In order to calculate these results, the methodology used has changed. Further information is available on the methods page (see: http://www.psmsl.org/products/trends/methods.php).

Note that these measured trends are not corrected for local land movement. Furthermore, no attempt has been made to assess the validity of any individual fit, so results should not be treated as a publication quality values suitable for use in planning or policy making.

The map should be used with some care as anomalous trends have many causes:

- land movements (e.g. earthquakes, glacial isostatic adjustment)
- unexplained instrumental datum shifts
- changes in atmospheric pressure
- short records

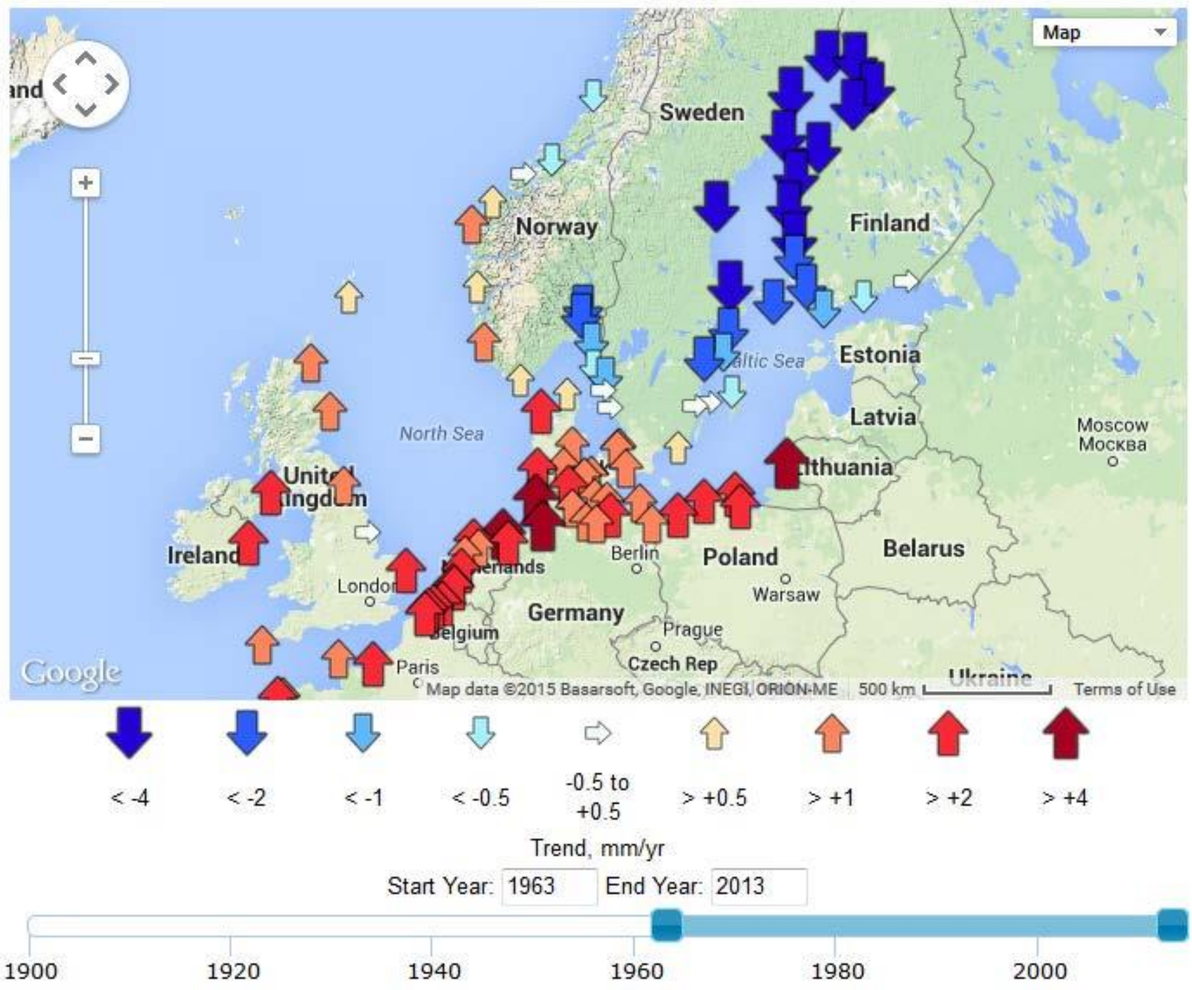
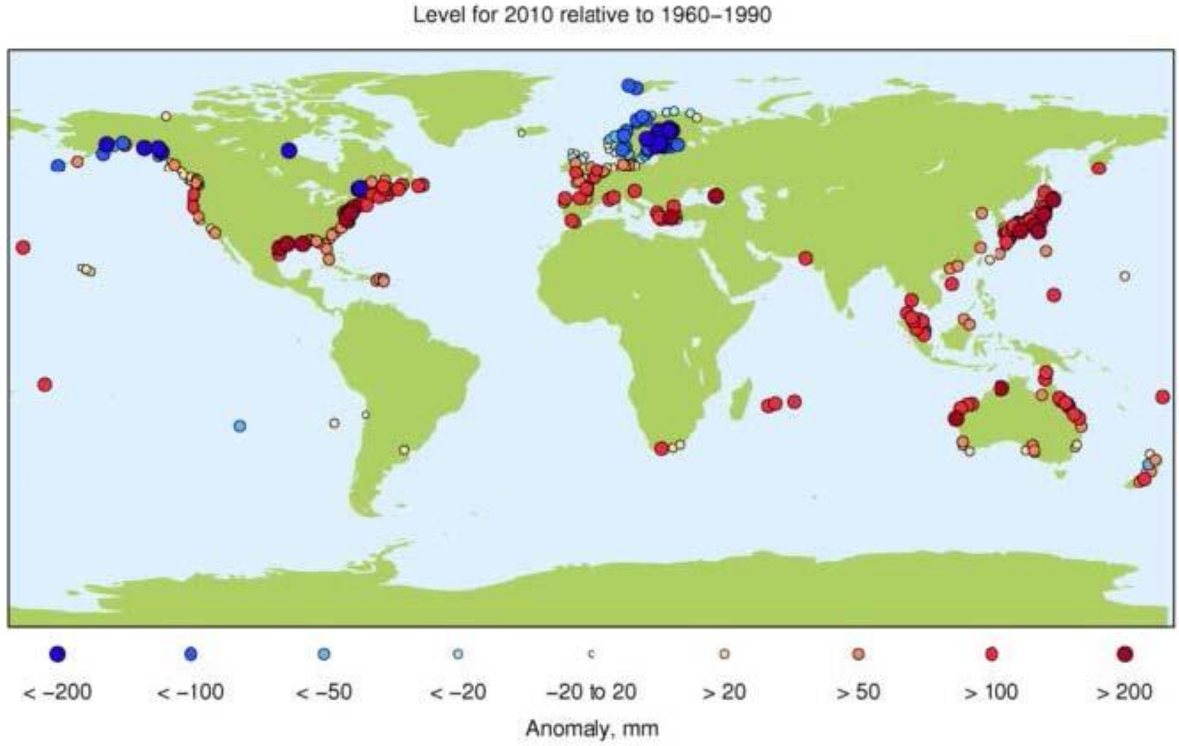


Figure 4: Sample map showing relative sea level trends

4.2 Interactive map showing sea level anomalies

Annual mean sea level can vary considerably from year to year in response to various meteorological and oceanographic forcings, typically by hundreds of millimetres. This product allows one to examine the global variations in a year of your choice: select this year using either the slider or the text box. The map presents the difference between the annual RLR data for each station (which is quality and datum controlled) compared to that station's long term mean over the baseline period of 1960-1990.

The long term trend at each station (estimated using the baseline period) can be removed if required. This will prevent results being dominated by long term changes, but will result in the loss of stations for which there is not enough data to calculate a trend. Further information is provided on the methods and derived trends pages of the PSMSL web-site.



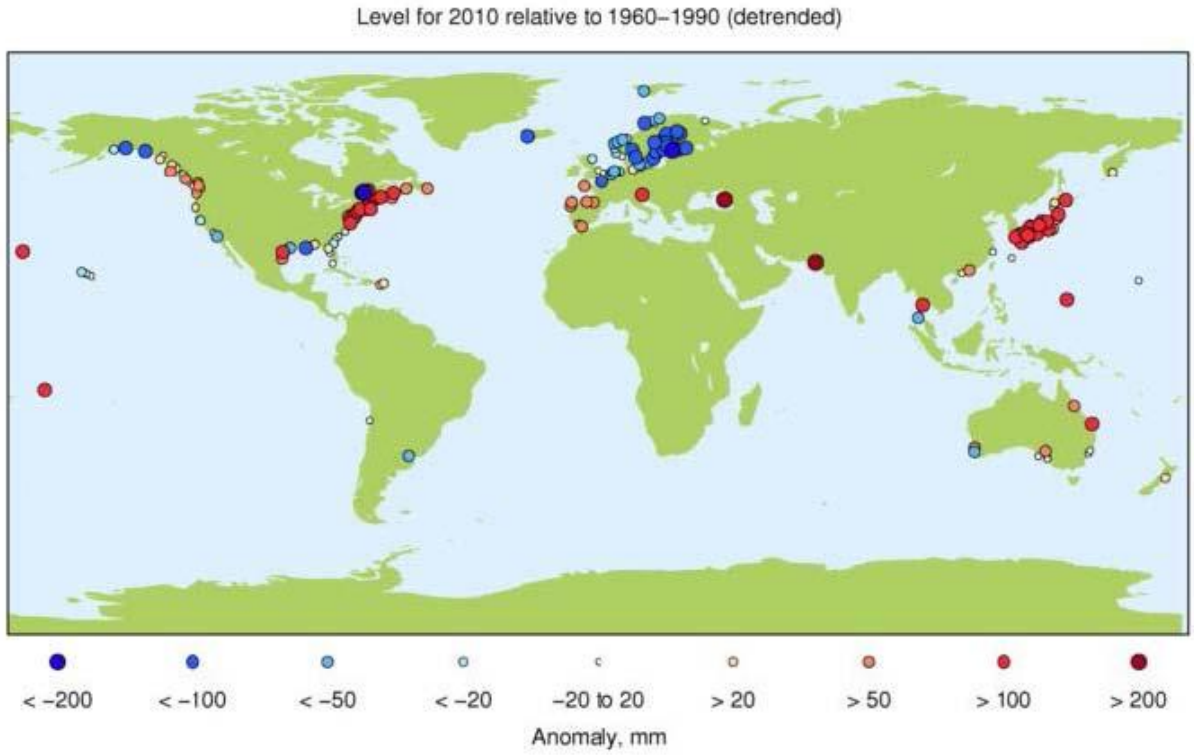


Figure 5: Sea level anomalies for 2010 relative to 1960-1990. (Top image: not detrended. Bottom image: detrended)

4.3 Land Motion at Tide Gauges: Collaboration with SONEL

PSMSL has been working with Système d'Observation du Niveau des Eaux Littorales (SONEL, http://www.sonel.org/) to facilitate distribution of additional geodetic data. SONEL is the data centre for the IAG TIGA working group, as well as a data assembly centre for the GLOSS network. Along with links to data at the other GLOSS centres, PSMSL has implemented links to the SONEL website in cases where there is GNSS data within 10 km of a tide gauge. SONEL also has used the tide gauge trends derived by the PSMSL to create a map of relative vs. absolute sea level trends on their website. It should be noted that until a TIGA combined solution exits, we are using the ULR5 solution. SONEL has also collected data where levelling ties exist between the GNSS receivers and the tide gauge. This information allows one to reference the PSMSL RLR tide gauge time series to an ITRF ellipsoidal height. PSMSL is working with SONEL to distribute this information on the PSMSL website in the near future.

5. Collection of delayed-mode higher-frequency data from GLOSS Core Network sea level measuring stations

The PSMSL together with BODC is responsible for an archive of delayed-mode higher frequency sea level data (e.g. hourly or more frequent values) from the GLOSS network of 290 stations. This activity builds on the earlier work carried out as the Delayed-mode Sea Level Data Assembly Centre (DAC) for the World Ocean Circulation Experiment (WOCE). Between August 2011 and May 2015, new data have been received from Australia, Brazil, Canada, Germany, Iceland, Japan, Korea, UK and USA (NOAA and UHSLC). Further data from UK GLOSS sites have been digitized from the original charts to fill in some gaps in the historical record. These are being added to the high-frequency delayed-mode databank. In addition, data up to the end of 2014 from the gauges that are part of the ODINAfrica and Indian Ocean network have been downloaded, processed and quality controlled, although not all of the gauges have been operational for the entire period. The data (both 1 minute and 15 minute) are available on the GLOSS web-site.

6. Data Archaeology in collaboration with GLOSS

Many historical tide gauge data still exist in non-digital form. These mostly paper-based data sets are of great potential value to the sea-level community for a range of applications, the most obvious being the extension of existing sea-level time series as far back as possible in order to understand more completely the timescales of sea-level change. In 2001, PSMSL, together with BODC and University of Hawaii Sea Level Center (UHSLC), initiated a GLOSS data archaeology and rescue project. This resulted in the digitising and quality control of paper records from nearly 100 tide gauges, extending the digital record by over 1400 years of hourly data. This data archaeology effort has been reinvigorated in 2012 with a questionnaire to all GLOSS contacts, which has identified a vast amount of non-digital historical tide gauge measurements, augmenting the large volume already catalogued, for example, in France and the U.K. Amongst existing projects, BODC is currently scanning and digitising analogue chart and manuscript sea-level records, some of which date back to 1853.

A GLOSS data archaeology group, under the leadership of Elizabeth Bradshaw, is collating tools and guidelines for the scanning, digitising and quality control of historical tide gauge charts and sea level ledgers. In the future, coordination of a tide gauge data rescue project with the Atmospheric Circulation Reconstructions over the Earth (ACRE) programme (carrying out rescue of air pressure data) could result in interesting synergies. To date several GLOSS members have developed software to automatically digitise analogue records on charts which were reported to the 13th meeting of the GLOSS Group of Experts. As a result GLOSS will create a repository of software for scanning analogue charts.

The other major form of analogue sea level data is handwritten ledgers. Transcribing these is labour intensive and usually undertaken by people entering numbers by hand. GLOSS is exploring other methods for use in the future: one possibility is to have a Citizen Science approach as with the OldWeather project run in partnership with ACRE. An alternative approach is to investigate the adaption of Handwritten Text Recognition technology for use with handwritten tide gauge ledgers.

7. Ocean Bottom Pressure Records

With a recent grant from the UK Natural Environment Research Council, the PSMSL is working to provide data from *in situ* ocean bottom pressure (OBP) recorders from all possible sources, a remit given to the PSMSL by IAPSO in 1999. The aim is to provide consistently-processed bottom pressure records with hourly and daily sampling for use in tidal, oceanographic and geophysical research. Typically, the original data sets are not distributed to avoid duplication with existing repositories. The processing procedures, described on the web-site, provide estimates of tidal signal and the instrumental drift for each deployment. The page on file formats describes the data provided in the hourly and daily data files.

Figure 6: Location of Ocean Bottom Pressure Recorder data available from PSMSL

Currently, a limited set of data is available; this will continue to grow with time. The map below shows the 66 sites for which data are currently available. This initial release contains data from the National Oceanography Centre's Drake Passage deployments, ten tsunameters archived at the US National Data Buoy Center, and a collection of records from the north-east Atlantic provided by Prof. Wendell S. Brown. Effort has focused on longer records (a year or more) and frequently occupied locations. The best record in this respect is the NOC's 19-year-long record at a southern location in the Drake Passage. However, the data provided by Prof. Brown illustrates another important aspect of the effort: improving the availability of historic data. While most of the records in this data set are short in length, they previously had not been easily available. Not all of the historical data collected by the NOC is included, but details are provided on the web-site of how to obtain those additional OBP records.

8. Publications

Selected recent papers published by NOC scientists partially supported by the PSMSL are listed in Annex 1. These address global sea-level rise and regional changes, as well as dynamic ocean topography. Perhaps the most notable, in terms of high-level quality control, is the paper by Woodworth et al., "Towards worldwide height system unification using ocean information". The work on this paper and the continuing research has led to a systematic review of the datum information at the studied tide-gauge sites.

One further paper that merits inclusion is an updated overview of PSMSL and its data sets. This paper replaces the previous overview by Woodworth and Player (2003) and is now the definitive article for citation of the PSMSL data set:

Holgate, S.J; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamisiea, M.E.; Bradshaw, E.; Foden, P.R.; Gordon, K.M.; Jevrejeva, S. & Pugh, J., "New Data Systems and Products at the Permanent Service for Mean Sea Level" *Journal of Coastal Research*, 2013, Volume 29, Issue 3: pp. 493 – 504. doi: http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1

In order to assess the wider usage of the PSMSL data set, a search of the scientific literature for the years between 2011 and 2014 was carried out. The result is that approximately 60 papers have been published per year which have used the PSMSL data set.

9. Summary and forward look

It can be seen that the last four years have been a further active period with regard to important workshops and conferences, and a busy one with regard to data acquisition and analysis. The functions provided by the PSMSL are in as much demand as ever, and several successful events were organised to celebrate the 80th anniversary of the Service in 2013. In addition new products continue to be developed and activities have expanded to include provision of data from *in situ* ocean bottom pressure (OBP) recorders.

Future plans include:

- Improved integration of the mean sea level data set with higher frequency data and improving the quality of accompanying metadata;
- Keeping contact with data suppliers (the trend being to acquire data from websites rather than direct supply) and ensuring that data made available in real-time are also contributed to PSMSL;
- Continue collaboration with SONEL (IAG TIGA Working Group data centre) and with GGOS;
- Expansion of bottom pressure record section and data;
- Further develop data archaeology with the Group of Experts on GLOSS;
- Redevelopment of capacity building/training material.

Particular thanks as usual go to PSMSL staff and to colleagues at the National Oceanography Centre and British Oceanographic Data Centre who contribute part of their time to PSMSL activities.

Annex 1: Selected Papers

Bos, M. S.; Williams, S. D. P.; Araujo, I. B. & Bastos, L. “The effect of temporal correlated noise on the sea level rate and acceleration uncertainty.”, *Geophysical Journal International*, 2014, 196, 1423-1430.

Gehrels, W. R. & Woodworth, P. L., “When did modern rates of sea-level rise start?”, *Global and Planetary Change*, 2013, 100, 263-277.

Henry, O.; Prandi, P.; Llovel, W.; Cazenave, A.; Jevrejeva, S.; Stammer, D.; Meyssignac, B.

& Koldunov, N., “Tide gauge-based sea level variations since 1950 along the Norwegian and Russian coasts of the Arctic Ocean: Contribution of the steric and mass components”, *Journal of Geophysical Research-Oceans*, 2012, 117, C06023.

Jevrejeva, S.; Moore, J.; Grinsted, A.; Matthews, A. & Spada, G. “Trends and acceleration in global and regional sea levels since 1807”, *Global and Planetary Change*, 2014, 113, 11-22.

Long, A.; Barlow, N.; Gehrels, W.; Saher, M.; Woodworth, P.; Scaife, R.; Brain, M. & Cahill, N. “Contrasting records of sea-level change in the eastern and western North Atlantic during the last 300 years”. *Earth and Planetary Science Letters*, 2014, 388, 110-122.

Perez, B.; Payo, A.; Lopez, D.; Woodworth, P. L. & Alvarez Fanjul, E. “Overlapping sea level time series measured using different technologies: an example from the REDMAR Spanish network”, *Natural Hazards and Earth System Sciences*, 2014, 14, 589-610.

Rickards, L., Matthews, A., Gordon, K., Tamisiea, M., Jevrejeva, S., Woodworth, P. and Bradshaw, E. 2014. Celebrating 80 years of the Permanent Service for Mean Sea Level (PSMSL). pp.11-15 in, Complex Interfaces Under Change: Sea-River-Groundwater-Lake. International Association of Hydrological Sciences, Publication 365, Proceedings of HP2/HP3, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013. (eds. C. Cudennec, M. Kravchishina, J. Lewandowski, D. Rosbjerg & P. Woodworth). ISBN 978-1-907161-43-8. pp, 100 + viii.

Tamisiea, M. E.; Hughes, C.; Williams, S. D. P. & Bingley, R. M. “Sea level: measuring the bounding surfaces of the ocean.”, *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences*, 2014, 372

Woodworth, P.; Hughes, C.; Bingham, R. & Gruber, T., “Towards worldwide height system unification using ocean information”, *Journal of Geodetic Science*, 2012, 2, 302-318.

Woodworth, P. L.; Foden, P. R.; Jones, D. S.; Pugh, J.; Holgate, S. J.; Hibbert, A.; Blackman, D. L.; Bellingham, C. R.; Roussenov, V. M. & Williams, R. G., “Sea level changes at Ascension Island in the last half century” *African Journal of Marine Science*, 2012, 34, 443-452.

Woodworth, P. L.; Maqueda, M. Ã. M.; Roussenov, V. M.; Williams, R. G. & Hughes, C. W. “Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation”, *Journal of Geophysical Research: Oceans*, 2014,

Report on Activities in Latin America and the Caribbean

Claudio Brunini (Argentina)

Most of the activities developed in the region in fulfilment of the IAG goals have been conducted by the SC 1.3b (Reference Frames for Central and South America) and the SC 2.4b (Geoid and Gravity Field in South America).

This report is possible thanks to many Latin American and Caribbean colleagues and institutions that might not be properly credited; apologies are presented in advance for any involuntary oblivion.

Activities developed in the frame of SC 1.3b

This SC encompasses the "Geocentric Reference System for the Americas" (SIRGAS), a joint endeavour of more than 50 institutions from 19 countries, including the national geographic institutes of the region, universities and research centres in the world.

The SIRGAS reference frame is a regional densification of the ITRF. It is realized by a network of ~400 continuously operating GNSS stations, ~100 of which have been installed during the last four years. The growth of the number of stations has been accompanied by the diversification of the data produced by the stations, and by the improvement of the capabilities to convert the data in useful products to the community.

Presently, 235 stations of the network are capable to track GLONASS, 16 GALILEO, and 2 BEIDOU (in addition to GPS), and almost 100 have real time capabilities. The data are archived by 10 centres, and processed by 11 centres following the IERS and IGS standards. In addition, other two centres, both in Argentina, are processing the GNSS measurements to compute state-of-the-art maps of the electron content distribution in the ionosphere and the integrated water vapour in the neutral atmosphere. Five of these centres have been installed during the last four years.

Processing centres in Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Germany, Mexico, Uruguay and Venezuela, generate redundant loosely constrained weekly solutions of different sub-networks, which are later combined by two redundant combination centres, one in Brazil and another in Germany.

This leads to weekly solutions of the entire network, multi-year solutions with station positions and constant velocities (almost once per year), and frequent updates of the model to interpolate the horizontal velocities measured by the stations. All these results are available at ftp://ftp.sirgas.org/pub/gps/SIRGAS/ or at www.sirgas.org, and constitute the backbone of the national networks of 15 countries that have already adopted SIRGAS as geospatial reference for their national infrastructures.

The accuracy of the weekly positions is estimated to be ±2,0 mm horizontally, and ±4,0 mm vertically. Due to the IGS08/IGb08 discontinuity, the computation of multi-year solutions has been discontinued until three years of weekly normal equations are available. The last released solution (SIR11P01) refers to IGS08 (ITRF2008), epoch 2005.0, includes 230 stations with 269 occupations from January 2000 to April 2011, and its precision is estimated to be ±1,0 mm horizontally and ±2,4 mm vertically for the positions at the reference epoch, and ±0,7 mm/yr horizontally and ±1,1 mm/yr vertically for the constant velocities. The last update of the horizontal velocity mode has been presented to the community in November 2014; it accounts for the changes in the station velocities caused by the 2010 Maule (Chile) earthquake.

This SC has contributed to the United Nations Global Geospatial Information Management (UN-GGIM) initiative, providing the vision of the region to the Resolution on the Global Geodetic Reference Frame for Sustainable Development that was released by the UN General Assembly in February 2015.

In addition, a close cooperation is being deployed between this SC and other regional organizations, in the framework of the "2013-2015 Joint Action Plan to Expedite the Development of the SDI of the Americas", which specifies four focal points:

- The SC 1.3b provides a unique reference frame of well-marked observation stations with three-dimensional, time-dependent coordinates for ordnance survey, cadastre, geo-information, precise navigation, geodynamic studies etc.;
- The UN-GGIM-Americas promotes and coordinates a variety of actions targeted to a better management of the SDI;
- The GeoSur Program, a specialized program supported by the Development Bank of Latin America, provides www facilities to access and use spatial data;
- The Pan American Institute for Geography and History (PAIGH), a specialized body of the Organization of American States, provides support and coordination.

Major efforts have been dedicated by this SC to the definition and realization of a gravity field-related vertical reference system following the advices of the IAG WG 0.1.1 on Vertical Datum Standardization. On-going tasks include the continental adjustment of the first order vertical networks in terms of geopotential numbers referred to a global W_0; determination of a unified (quasi)geoid model for the region (under the responsibility of the IAG SC 2.4b, 'Gravity and Geoid in South America'); and transformation of the existing height systems into the new one.

Although still insufficient, significant progress have been made in collecting and validating the existing databases of levelling, gravity and tide gauges; transcription of old field notebooks to digital format; levelling field works to connect the fundamental points of the vertical networks with the SIRGAS reference stations and with the main national tide gauges; establishing levelling connections between neighbouring countries.

Four symposia were held by this SC during the period 2011 – 2014: Costa Rica, 2011; Chile, 2012; Panama, 2013; and Bolivia, 2014 (170 attendants from 20 countries on average). During the same period, a variety of capacity building activities were developed, including: 2 workshop on "vertical reference systems" (Brazil 2012; and Brazil 2015); 4 schools on "reference systems" (Costa Rica, 2011), "real time GNSS positioning" (Chile 2012), "reference systems, crustal deformation and ionosphere monitoring" (Panama 2013), and "vertical reference systems" (Bolivia, 2014); and 3 courses on precise GNSS data processing at the Instituto Geográfico Militar of Chile (2011), Universidad Nacional of Costa Rica (2012), and Instituto Geográfico Militar of Bolivia (2013). The activities developed by this SC have been presented in 23 international meetings and 32 pear-reviewed papers.

Advertisement in a main street of La Paz, Bolivia (right) and attendants (right) of SC 1.3b 2014 Symposium.

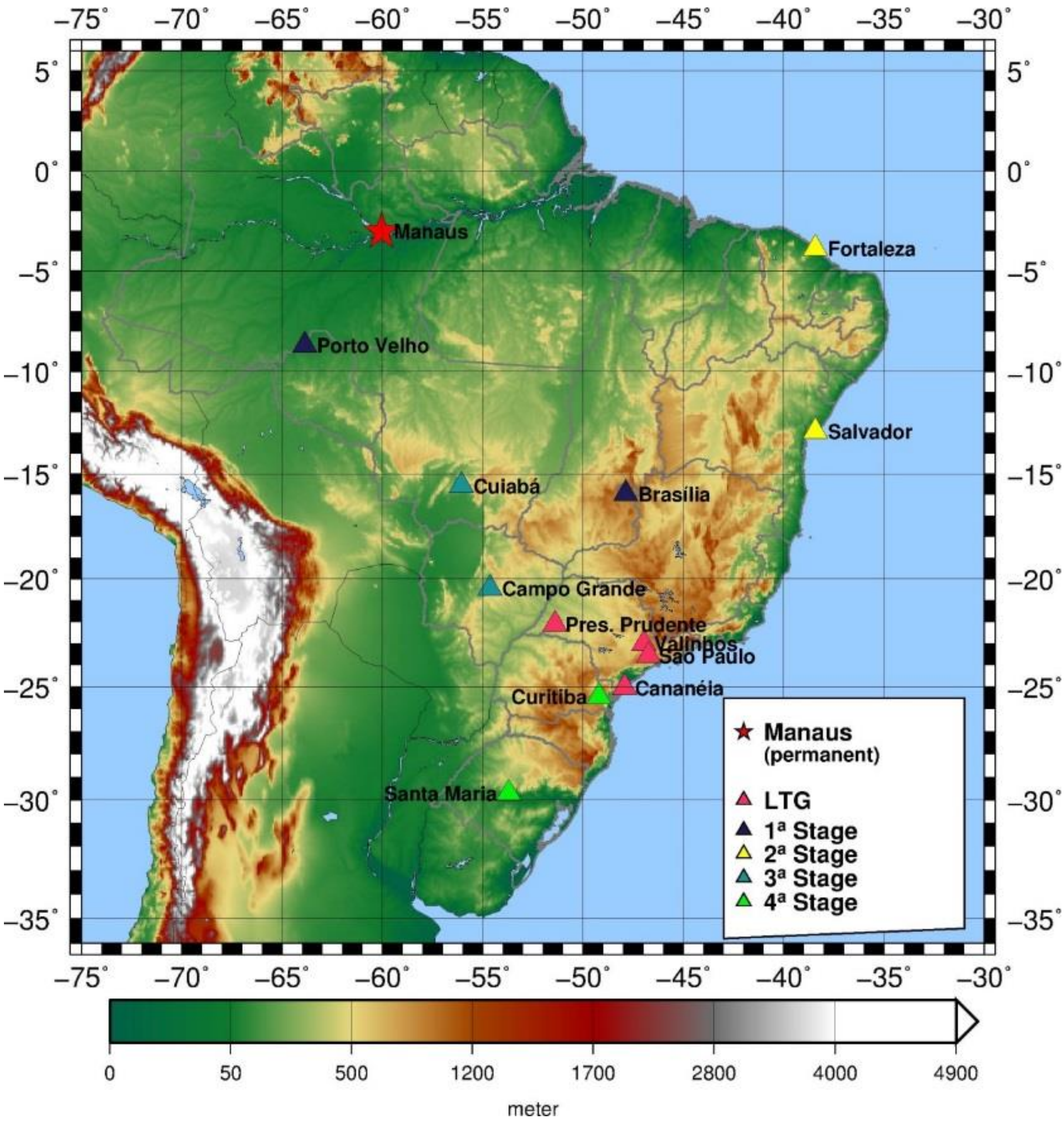
Activities developed in the frame of SC 2.4b

This SC reports a significant improvement in the coverage of the gravity data over South America (~10^6 gravity stations are presently available for computing the geoid). Orthometric heights for recent surveys have been derived from geodetic height using EGM2008 restricted to degree and order 150. LaCoste&Romberg and/or CG5 gravity meters and dual-frequency GNSS receivers have been used for establishing 504 new stations in Argentina, 11,941 in Brazil, 543 in Ecuador, and 771 in Paraguay.

Since 2014, the National Geographic Institute (IGN) of Argentina is developing a project devoted to install an absolute gravity network with 10 µGal accuracy covering the entire country. The activities are being developed through a joint effort supported by the IGN, the Brazilian University of Sao Paulo, the Argentinean universities of La Plata, Rosario and San Juan, and the French Institute of Research for the Development.

The Brazilian Institute of Geography and Statistics (IBGE) have dedicated large efforts to improve the Brazilian gravity network and, further, the geoid model in Brazil. 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 will be released in October 2015, in substitution to MAPGEO1010. It will include airborne gravity data in the Amazonas and the Paraiba basins.

In cooperation with other institutions, the Brazilian University of São Paulo has been working to improve the Earth tide model in Brazil. Thirteen stations around the country are being occupied for one year using 2 gPhone gravitymeters. Measurements are already completed in Cananeia, Valinhos, São Paulo and Presidente Prudente; are being conducted in Porto Velho and Manaus; and are planned in Brasília, Fortaleza, Salvador, Cuiabá, Campo Grande, Curitiba and Santa Maria.



The Institute of Geography and Cartography of São and the São Paulo University are cooperating for the establishment of absolute gravity points in Brazil, Argentina, Venezuela, Ecuador and Peru, using an A-10 gravitymeter.

Other activities

During the period 2011-2013 the Fundamental Geodetic Observatory TIGO operated in Concepción, Chile, in partnership between the Chilean Universidad de Concepción and the German Bundesamt für Kartographie und Geodäsie (BKG). In this frame, TIGO provided high quality data to the IVS, ILRS, IGS, IGFS, IERS, and Time Section of BIPM. In 2013, the partners decided to stop the cooperation and BKG decided to move the Observatory to Argentina, in the frame of a new agreement with the Argentinean National Council of Science and Technology (CONICET). The now called Argentina – German Geodetic Observatory (AGGO) is almost ready to enter in operation in the vicinity of La Plata, where its official opening is schedule for July 2015.

IAG Symposia Series

http://www.springer.com/series/1345

Editor-in-Chief: Chris Rizos (Australia)
Assistant Editor-in-Chief: Pascal Willis (France)

Overview

The IAG Symposia Series (IAG Symp.) is a book series of peer-reviewed proceedings of selected IAG Symposia organised by the International Association of Geodesy. It deals primarily with topics related to Geodesy as applied to the Earth Sciences and Engineering: terrestrial reference frame, Earth gravity field, geodynamics and Earth rotation, positioning and engineering applications.

Volumes are available online at the Springer web site (http://www.springer.com/series/1345), since volume 101 (Global and Regional Geodynamics, 3-5 August 1989), published in 1990. Most recent volumes are also available from the Springer web site as e-Books. It must be noted that articles published in the IAG Symposia Series since 2000 are referenced in bibliographic databases, such as Scopus and ISI Web of Knowledge, implying in particular that their citations are used in the ISI Web of Science (Thomson SCI) for journal Impact Factors and authors' h-index and citation analysis.

According to the IAG Statutes and By-Laws, the de facto Editor-in-Chief of this series is the IAG President. Following the IUGG General Assembly in Melbourne (July 2011), the new Editor-in-Chief is Chris Rizos for 2011-2015, replacing Michael G. Sideris who was the Editor-in-Chief for the previous four years. In August 2011, Pascal Willis was invited to become Assistant Editor-in-Chief and to organise the peer-review procedure for the IAG Symposia Series. Contacts were made with the publisher of this series (Springer) and the review procedure was significantly changed, starting with volume 139 (Earth on the Edge, Science for a Sustainable Planet, Melbourne, Australia, June 28 – July 1, 2011). A dedicated web site was developed by Springer (http://www.editorialmanager.com/iags) to allow full electronic manuscript submission and management of a standard peer-review process. While Pascal Willis handled this web site on behalf of the Editor-in-Chief, editors were selected for each symposium from the list of convenors, taking into account the number of expected symposium manuscripts. Guidelines for authors were developed and are now provided to all authors through the Springer web site. These guidelines include the length of article (6 pages in double column for regular contribution and 8 pages for invited paper) and format description. Written procedures were also provided to all editors to ensure a fair and transparent review process within all sessions and within all the IAG Symposia. For each manuscript, most of the time, three independent experts were selected by the editors to review the submitted manuscript. Based on the returned reviewer reports, the editor makes a decision, which needs to be confirmed by the assistant Editor-in-Chief. Guidelines for editors were also written to allow a consistent reviewing procedure for all manuscripts. To improve communications with the authors, monthly reports were sent out by the assistant Editor-in-Chief to all corresponding authors, anonymously providing some key statistics on the status of manuscripts under review for each symposium, from start of paper submissions to end of the review process. Information emails were also sent out to authors, while papers are handled by Springer Production, until their final publication online and in print. Regular information concerning the review process and the publication of the IAG Symposia Series was regularly send out through the IAG Newsletter. Finally, following long discussions with Springer, the publication procedure was changed in early 2015 and authors of accepted papers now receive a DOI from Springer with their galley proofs shortly after acceptance, on a paper-by-paper basis, instead of having to wait for the last paper of their symposium to be accepted.

Structure and activities

The following paragraphs provide information on the IAG symposia volumes published or under review process in the 2011-2015.

Volume 136

Geodesy for Planet Earth Buenos Aires, Argentina, August 31 - September 4, 2009

Editors: Steve Kenyon, Maria Cristina Pacino, Urs Marti

Co-editors: Rodrigo Abarca del Rio, Zuheir Altamimi, Mike Bevis, Denizar Blitzkow, Sylvain Bonvalot, Claudio Brunini, Rene Forsberg, Yoichi Fukuda, Richard Gross, Shuanggen Jin, Roland Pail, Hans-Peter Plag, Marcelo Santos, Claudia Tocho, Charles Toth, Tonie van Dam, Sandra Verhagen, Leonid Vituskhin

Published in 2012, 130 articles, 1046 pages

ISBN: 978-3-642-20338-1

Volume 137

VII Hotine-Marussi Symposium on Mathematical Geodesy

July 6-10, 2009, Rome, Italy

Editors: Nico Sneeuw, Pavel Novàk, Mattia Crespi, Fernando Sansò

Co-editors: Zuheir Altamimi, Athanasios Dermanis, Richard Gross, Wieslaw Kosek, Jürgen Kusche, Hansjörg Kutterer, Torsten Mayer-Gürr, Michael Schmidt, Giorgio Spada, Florian Seitz, Sandra Verhagen, Yanming Wang, David Wolf

Published in 2012, 36 articles, 407 pages

ISBN: 978-3-642-22078-4

Volume 138

References Frames for Applications in Geosciences

Marne-la-Vallée, France, October 4-8, 2010

Editors: Zuheir Altamimi, Xavier Collilieux

Co-editors: Claude Boucher, David Coulot, Mike Craymer, Richard Gross, Johannes Ihde, Markus Rothacher, Harald Schuh, Michael Sideris, Peter Steigenberger, Joao Agria Torres

Published in 2013, 40 articles, 284 pages

ISBN: 978-3-642-32997-5

Volume 139

Earth on the Edge: Science for a Sustainable Planet

Melbourne, Australia, June 28 – July 1, 2011

Editors: Chris Rizos, Pascal Willis

Co-editors: Jozsef Adam, Zuheir Altamimi, John Dawson, Athanasios Dermanis, Reinhard Dietrich, Xiaoli Ding, Jeff Freymueller, Yoichi Fukuda, Dorota Grejner-Brzezinska, Richard Gross, Urs Hugentobler, Johannes Ihde, Matt King, Hansjörg Kutterer, Frank Lemoine, Mikael Lilje, Ruth Neilan, Markus Rothacher, Laura Sanchez, Marcelo Santos, Harald Schuh, Nico Sneeuw, Oleg Titov, Joao Agria Torres, Sandra Verhagen, Jens Wickert, Herbert Wilmes

Published in 2014, 80 papers, 617 pages

ISBN: 978-3-642-37221-6

Volume 140

Quality of Geodetic Observation and Monitoring Systems (GuGOMS'11)

Garching/Munich, Germany, 13-15 April 2011

Editors: Hansjörg Kutterer, Florian Seitz, Hamza Alkhatib, Michael Schmidt

Published in 2015, 25 papers

Volume 141
Gravity, Geoid and Height Systems (GGHS2012)
Venice, Italy, October 9-12, 2012
Editor: Urs Marti
Co-editors: Oliver Baur, Jianliang Huang, Isabelle Panet, Riccardo Barzaghi, Carla Braitenberg, Shuanggen Jin, Laura Sanchez, Herbert Wilmes
Published in 2014, 42 papers

Volume 142
VIII Hotine-Marussi Symposium on Mathematical Geodesy (HM2013)
Rome, Italy, 17-21 June 2013
Editors: Nico Sneeuw, Pavel Novàk, Mattia Crespi, Fernando Sansò
Co-editors: Robert Čunderlík, Athanasios Dermanis, Thomas Hobiger, Richard Gross, Wieslaw Kosek, Eric Pottier, Michael Schmidt, Matthias Weigelt
Publication expected in summer 2015, 40 papers

Volume 143
IAG Scientific Assembly
Potsdam, Germany, 1-6 September 2013
Editors: Chris Rizos, Pascal Willis
Co-editors: Hussein Abd-Elmotaal, Zuheir Altamimi, Dorota Grejner-Brzezinska, Xiaoli Deng, Annette Eicker, Jeff Freymueller, Richard Gross, Manabu Hashimoto, Jianliang Huang, Urs Hugentobler, Allison Kealy, Hansjörg Kutterer, Urs Marti, Roland Pail, Laura Sanchez, Joao Torres, Tonie van Dam, Pawel Wielgosz
Publication expected in summer 2015, 99 papers

Volume 144
Third International Gravity Field Service (IGFS) General Assembly (IGFS2014)
Shanghai, China, 30 June – 6 July, 2014
Editors: Shuanggen Jin, Riccardo Barzaghi,
Co-editors: René Forsberg, Urs Marti, Roland Pail
Publication expected in fall 2015, 37 papers submitted, review in progress

Volume 145
International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH2014)
Matsushima, Miyagi, Japan, 22-26 July 2014
Editors: Manabu Hashimoto
Co-editors: Jeff Freymueller, Richard Gross, Shuanggen Jin, Cécile Lasserre, Simon McClusky, Yusaku Ohta, Tim Wright
Publication expected in fall 2015, 30 papers submitted, review in progress

Volume 146
Reference Frames for Applications in Geosciences (REFAG2014)
Kirchberg, Luxemburg, 13-17 October 2014
Editor: Tonie van Dam
Co-editors: Zuheir Altamimi, Johannes Boehm, Tom Herring, Mikael Lilje, Richard Wonnacott
Publication expected in late 2015, 31 papers submitted, review in progress

Statistical information

Submissions

In total, since the creation of the Springer submission Web site, 475 manuscripts were submitted, without counting volume 141 for which the review was done prior to the existence of this system. As shown in Figure 1, the IAG Symposia has been quite successful in attracting authors from a large number different countries all over the world, 46 in total, as expected for proceedings of the International Association of Geodesy.

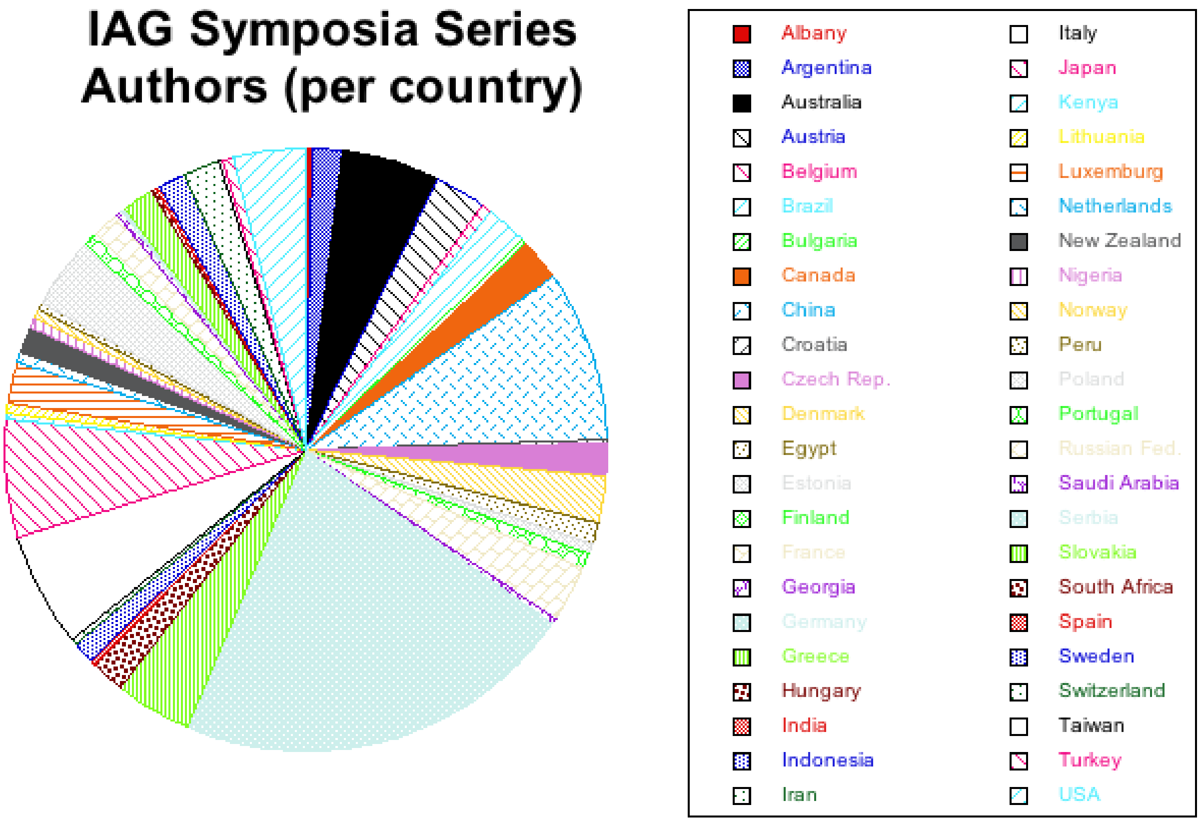


Figure 1: Geographical distribution of corresponding authors of manuscripts submitted to the IAG Symposia Series (2011-2015)

The following Table provides the top 10 countries which submitted the largest number of manuscript from 2011 to 2015 (using the Springer submission Web site):

Table 1: Number of manuscripts submitted per country in 2011-2015 (first 10)

Country	Submitted manuscripts
Germany	95
China	40
Japan	29
Italy	26
Australia	23
Greece	19
Poland	17
USA	17
France	13
Austria	12

The number of submission varies with the number of IAG Symposia per year and also on the number of manuscripts submitted to each meeting (also see below).

Review statistics

Reviewers were selected by editors from key experts from all over the world, from 45 different countries, indicating a good international representation (see Figure 2).

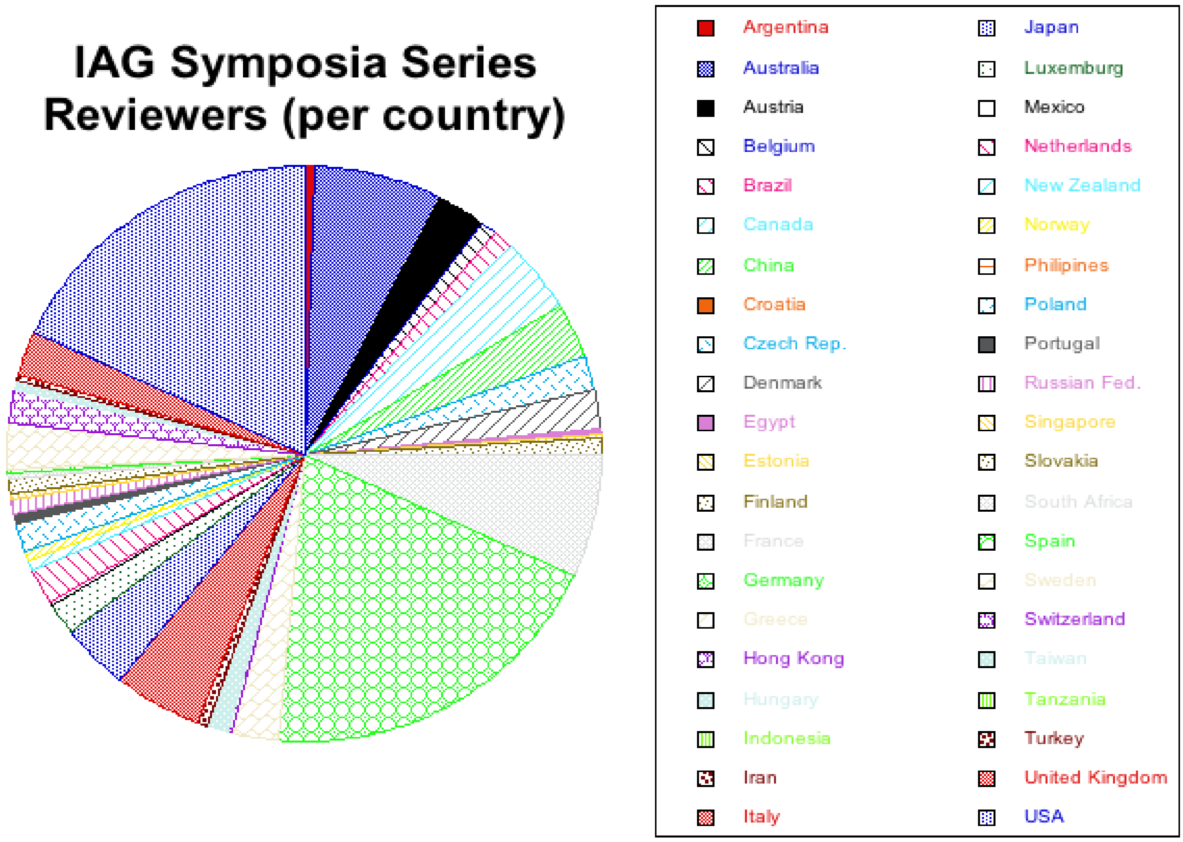


Figure 2: Geographical distribution of reviewers of manuscripts submitted to the IAG Symposia Series (2011-2015)

The rejection rate for the IAG Symposia varies from 20% to 30%, which is quite low compared to the current rejection rate for regular peer-reviewed journals (usually over 50%). The IAG Symposia Series has been able to attract young authors, and authors from developing countries, which may have not submitted a paper to a regular international peer-reviewed journal. It is expected that these new authors will continue publishing in such journals, notably the Journal of Geodesy.

It must be noted that this rejection rate also includes papers that were rejected before the review process because of self-plagiarism related problems, or because a few authors were not able to correct their manuscript as recommended by the editor and chose to withdraw their paper. In several cases, successive major revisions were necessary before the paper could be accepted for publication in these proceedings, to ensure the scientific quality of the published articles.

Turnaround time for review

The duration of the review process is of critical importance for the authors and for the long-term value of these proceedings. Following regular intervention by the assistant Editor-in-chief concerning the review process of each manuscript, the duration of the whole review process has been kept to a minimum. On average, it takes less than 1 day for Springer to do the technical check of the papers, and less than 1 day for the associate Editor-in-Chief to assign a manuscript to the proper editor, after verifying length of the article and possible plagiarism problems using iThenticate. It then takes about 10 days for the editors to invite three independent reviewers. On average it takes about 2 months for an author to get a first decision for this manuscript, and at worst 9 months for all papers to get a final decision.

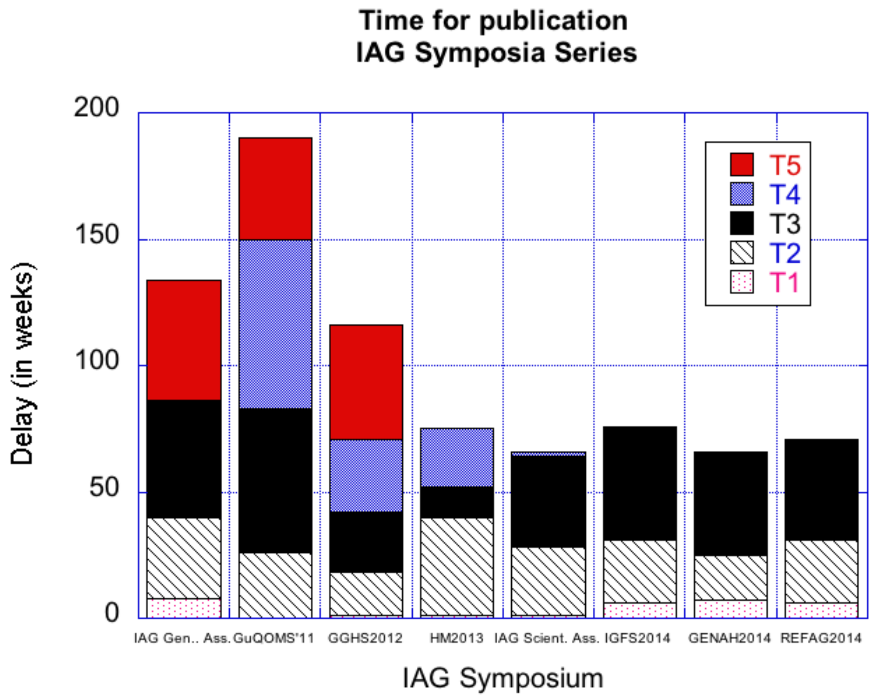


Figure 3: Successive steps and delays involved from symposium organization and publication of the proceedings of the IAG Symposia Series (2011-2015).

T1 = time between the attendance at the symposium and the submission of the first manuscript

T2 = time between the submission of the first manuscript and the submission of the last manuscript

T3 = time between the decision for the last paper in review and the submission of the last paper

T4 = time for preparing files and editorial documents for Springer Production

T5 = time for Springer to publish the volume

Figure 3 requires some explanation and proper analysis in order to provide some guidance for the publication of future volumes of the IAG Symposia Series. First of all, the review process (T3) is kept to a minimum, ranging from 12 to 57 weeks, and usually takes about 6 months, including several revision(s) of the article. This is only a third of the total time for publication after the symposium. This is much faster than regular peer-reviewed journals for which the average period for the review process can be up to a year. Surprisingly the time allowed by the editors to submit a paper after the symposium is quite long (T1 + T2), and is usually close to 30 to 40 weeks, taking about the same time as the review process itself. It is suggested in the future that authors submit shortly after the symposium and that submissions may not be accepted for review if submitted too late, for example more than 3 months after the symposium. The publication by Springer is taking much too long (from 40 to 45 weeks). The expected publication time as announced by Springer was supposed to be about 3 months. In Figure 3, T4 is rather large because it was decided not to send out the editorial material and the files to Springer that were prepared, as Springer was already unable to publish the volume corresponding to the IAG General Assembly in Melbourne, and had received already too much work to do. As shown for other symposia, the preparation of such files is done in advance and the finalisation between the assistant Editor-in-chief and the editor(s) of the volume takes less than a week.

In conclusion, the IAG now has a good tool with the Springer submission web site which allows for a timely and efficient review process, using standard procedures and documents developed during this four-year period. Most of the delays for publication come from the inability of Springer to publish these volumes in a timely manner, even when all files are now available for all papers in Doc or LATex format. It is suggested that the IAG investigate this cooperation agreement with Springer, and perhaps look for other potential publishers if some significant improvement cannot be made. Finally, some delay in publication could also be minimised by the IAG deciding to fix a deadline for submission after an IAG symposium (e.g. a maximum 3 months after the meeting). For information, some scientific associations ask authors to submit their manuscript before the symposium, as a condition to be allowed to make their presentation. This is probably an extreme solution, however some limit should be established.

Report of the Advisory Board on Law of the Sea (ABLOS)

Submitted by: Chair, ABLOS

ABLOS is a joint board established by the International Hydrographic Organization (IHO) and the International Association of Geodesy (IAG)

Chair: Sunil Bisnath, Canada (IAG Member)
Vice-Chair: John Brown, United Kingdom (IHO Member)
Secretary: David Wyatt, IHB
Members IHO: Brazil, Japan, Republic of Korea, United Kingdom
Members IAG: Canada, Chile, Denmark, Indonesia
Ex Officio: UN DOALOS and IHB
Observers: Australia, Bangladesh, Brazil, Croatia, India, Japan, United Kingdom
see Annex A for full details

Meetings Held During Reporting Period

ABLOS 21, 21 – 22 October 2014, Copenhagen, Denmark

Future Meetings

ABLOS 22, 19 and 23 October 2015, Monaco

ABLOS 8 Conference, 20 – 22 October 2015, Monaco

Work Program

The 21st meeting of ABLOS was hosted by the DTU Space – the National Space Institute of Denmark, and held at the First Hotel King Frederik in Copenhagen, Denmark from 21 -22 October 2014. It was followed by a seminar titled “UNCLOS and the Arctic – Changes now and in the near future” on 23 October at the Technical University of Denmark in Copenhagen. ABLOS members and observers from Australia, Brazil, Canada, Denmark, Japan, Republic of Korea and the United Kingdom were present. The seminar was attended by approximately fifty people, and included presentations from Danish government authorities and ABLOS members.

The business meeting focused on preparations for the 8th ABLOS Conference under the title “UNCLOS – Advances in governing the blue world”, which will be held in Monaco in from 20 -22 October 2015. Detailed information for the Conference has been announced by IHO Circular Letter, on the ABLOS page of the IHO web site, and on the conference web site: www.ablosconference.com.

The revised Manual on Technical Aspects of the United Nations Convention on the Law of the Sea -1982 (TALOS Manual -C-51) – edition 5.0.0 was accepted by the IHO and IAG and published. Main contributions to this edition include a complete reworking on the geodesy chapter.

The ABLOS Terms of Reference were slightly modified. Due to the special circumstances concerning ABLOS where it is the only working group reporting to two parent bodies i.e. the IAG as well as the IHO it is felt that the current wording of paragraph 2.1 of the HSSC ToRs does not take this into account. It is proposed that the second sentence be amended to read:

The Chairs of the relevant subordinate bodies of the Committee *or their nominated representatives should* attend and report at all Committee Meetings. The modifications were accepted by both the IHO and the IAG.

2015 work includes completing preparations for the ABLOS 8 conference, the conference itself and associated ABLOS 21 business meeting. Also, reviewing the TALOS manual for any necessary updating, delivering standard training programmes on request, and providing advice and guidance on the technical aspects of the Law of the Sea.

Annex A to ABLOS Report to IAG

MEMBERS OF ABLOS

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- **Professor Clive Schofield**
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Joint Board of Geospatial Information Societies (JBGIS)

http://www.fig.net/jbgis/

The Joint Board of Geospatial Information Societies (JBGIS) is a coalition of the Presidents, Secretaries-General or equivalent office bearers or their nominees that lead recognized international organisations involved in the coordination, development, management, standardisation or regulation of geospatial information and related matters. These organisations are:

- Global Spatial Data Infrastructure (GSDI) Association
- IEEE Geoscience and Remote Sensing Society (GRSS)
- International Association of Geodesy (IAG)
- International Cartographic Association (ICA)
- International Federation of Surveyors (FIG)
- International Geographical Union (IGU)
- International Hydrographic Organization (IHO)
- International Map Industry Association (IMIA)
- International Society of Photogrammetry and Remote Sensing (ISPRS)
- International Steering Committee for Global Mapping (ISCGM)

The JBGIS meets formally once each year, typically when the UN-GGIM Committee of Experts meet, and informally when schedules permit. This year it will be 5-7 August, in New York, at the UN Headquarters.

1. Global Spatial Data Infrastructure (GSDI) Association

The Global Spatial Data Infrastructure Association (GSDI) exists to promote international cooperation and collaboration in support of local, national and international SDI developments that will assist members to better address social, economic, and environmental issues of pressing importance in their nations.

The GSDI has 38 Organisational Members from national and regional associations, government agencies, academia and private industry, from 20 countries, including 4 regional (transnational) organisations and the UN ECA. Over 400 individuals formerly members of the Association's International Geospatial Society are being invited to renew their participation in the Association as GSDI Individual Members, a new membership category introduced as a result of the GSDI Strategy 2015-2020 adopted in October 2014, and new Bylaws adopted in April 2015. The Individual Members continue to have representation on the GSDI Board. GSDI has MoUs with the International Cartographic Association (ICA), the International Federation of Surveyors (FIG) and the International Society for Photogrammetry and Remote Sensing (ISPRS), and the new Centre for Disaster Management and Public Safety (CDMPS) at the University of Melbourne for joint promotion of activities. MoUs are being pursued with the OSGeo Foundation and International Society for Digital Earth (ISDE).

Activities, Areas of Work

a. GSDI has representation on the UN GI Working Group (UNGIWG) and Special Consultative status with the UN ECOSOC Office for Support and Coordination since 1 May 2014. GSDI promotes the open data principles of GEO/GEOSS, and is involved in SDI capacity building activities in many developing nations via the GSDI Small Grants Program and training activities. In January 2015 the Association also began contributing to the International Hydrographic Organisation (IHO) Marine SDI Working Group, especially in capacity building activities.

b. GSDI Association immediate Past President Prof. Abbas Rajabifard delivered a keynote talk on "Disaster Management and Spatial Data Infrastructure" at the 3rd High Level UN Forum on Global Geospatial Information Management in Beijing in November 2014. Current President David Coleman delivered invited presentations on SDI developments at the Pan Canadian Spatial Data Infrastructure Summit held in Calgary, Canada in September 2014, and the Joint International Conference on Geospatial Theory, Processing Modeling and Applications held in Toronto, Canada in October 2014.

c. Project oriented work is underway for two GSDI Projects, one focusing on producing a Geoinformation Legal Interoperability Map of the World (GLIM), started in 2014 under the leadership of Bastiaan van Loenen, TU Delft, and is continuing in 2015 led by Joep Crompvoets of KU Leuven. Managing the GSDI Small Grants Program has also become a GSDI Project, led by Brigitta Urban-Mathieux, USGS.

d. In January 2015, GSDI was represented at the IHO Marine SDI Working Group Technical Meeting in London and accepted work assignments in the new IHO MSDIWG Work Plan. In April, GSDI conducted a workshop on Marine/Coastal SDI Best Practice in Cape Town, South Africa, as part of the CoastGIS 2015 Conference. The Association is also represented on the Steering Group of the UNESCO IOC IODE International Coastal Atlas Network (ICAN) Project.

e. GSDI were also present at the pan-European INSPIRE GWF 2015 Conference in May 2015 in Lisbon, Portugal, where several Members and Member Organisations made presentations and/or ran workshops on a range of SDI-related topics and projects in which they are involved.

f. The Association will also be presenting an SDI Best Practice workshop at the forthcoming Digital Earth 2015 Summit in Halifax, Nova Scotia in October 2015 and is actively seeking similar regional or global events where similar workshops can be presented.

g. Through its many different educational activities, GSDI provides support to initiatives such as GEO/GEOSS, Eye on Earth and ISCGM by: a) helping to prepare young professionals to participate in national and global geospatial initiatives, b) supporting collaboration among professionals of all sectors who are working in SDI implementation, and c) offering global networking and learning opportunities between students, young professionals and SDI experts in tackling geospatial interoperability issues that are at the core of SDI implementation globally.

Priority Issues and Challenges

The main activities of GSDI are: 1) supporting growth of harmonised local, national, and regional SDIs that are globally interoperable; 2) fostering international communication and collaborative efforts for advancing SDI innovations; 3) supporting interdisciplinary research and education that advances SDI concepts and methods; and 4) promoting access to, and appropriate use of, public geographic information. Our main outreach and networking activities include the GSDI World Conferences, seminars and workshops, the monthly global and regional newsletters and discussion forums, individual capacity building actions, and support to SDI initiatives in developing nations via the GSDI Small Grants Program and targeted training activities. All conference papers are available in the online Proceedings of all 14 GSDI World Congresses held since the first conference in 1996. Another key source of SDI implementation information is the GSDI SDI Cookbook, maintained as an online wiki under guidance of the GSDI Technical Committee. Since its launch in 2003, the GSDI Small Grants Program has supported more than 100 national and sub-national projects across the globe. The program has been sponsored by the GSDI Association, the U.S. Federal Geographic Data Committee, and the GISCorps of URISA and in 2014 financial support was provided by GeoConnections, a national collaborative initiative led by GSDI member Natural Resources Canada. Awards consist of a cash grant of up to US$ 2500 per project, SDI/GIS consulting services up to the value of US$ 2500, or a combination of the two.

Perspectives/Outlook, Future Plans

Through its many different educational activities, GSDI provides support to initiatives such as GEO/GEOSS, Eye on Earth and ISCGM by: a) helping to prepare young professionals to participate in national and global geospatial initiatives, b) supporting collaboration among professionals of all sectors who are working in SDI implementation, and c) offering global networking and learning opportunities between students, young professionals and SDI experts in tackling geospatial interoperability issues that are at the core of SDI implementation globally. More details on GSDI activities can be found on their web site http://www.gsdi.org.

2. IEEE Geoscience and Remote Sensing Society (GRSS)

The Geoscience and Remote Sensing Society (GRSS) seeks to advance technology in geoscience, remote sensing and related information fields using conferences, education programs and through member participation in Technical Committees, Workshops, Publications and local and regional based Society Chapters.

With over 3200 individual members worldwide, GRSS is continuing to promote the use and application of remote sensing related to environmental and societal needs worldwide. The GRSS and its predecessor organisation, the Geoscience Electronics Group, has existed since 1962. During this time the society has thrived and attained significant worldwide prominence among the other 38 professional organisations found within the Institute of Electrical and Electronics Engineers (IEEE). Today the Society is recognised as a world leader in the research, dissemination and application of remote sensing technologies, as well as an organisation committed to enhancing and promoting the professional standing of its members.

Activities, Areas of Work

a. As well as being an active member of the JBGIS, GRSS is working with international agencies including UN-SPIDER and GEO and with regional and country organisations to improve access to remotely sensed data. Through its Globalisation Initiatives Program GRSS assists scientists and engineers in Africa, Latin America and Asia to become more proficient in information extraction from space imagery in order to help meet the needs for community based mapping, monitoring and for environmental assessment, disaster mitigation, planning and human management.
b. A number of Technical Committees provide a forum for technical assessments; research collaborations and guidance to the Society on key issues in remote sensing policy and practice Current Committee's include; Earth Science Informatics; Frequency Allocation in Remote Sensing; Instrumentation and Future Technologies; Image Analysis and Data Fusion and International Imaging Spectroscopy.
c. The Society publishes three journals. The *Transactions on Geoscience and Remote Sensing* (TGRS), focuses on advances in the development of sensing instrumentation and processing techniques used for the acquisition of geo-scientific information. *Geoscience and Remote Sensing Letters* (GRSL) is a quarterly publication for short papers addressing new ideas and formative concepts in remote sensing as well as for presenting new results. *Selected Topics in Applied Earth Observations and Remote Sensing* (JSTARS) addresses current issues and techniques in applied remote and in-situ sensing and their integration into modelling and information creation for understanding earth environments.
d. Over 50 Local GRSS Chapters exist around the globe. These Chapters offer both technical and social events as well as networking and career advancement opportunities to members.
e. The annual International Geoscience and Remote Sensing Symposium (IGARSS) is the flagship conference of the Society and attracts over 2200 participants each year. The next IGARSS will be held in Beijing, China, in July 2016. GRSS also co-sponsors more than twenty international Symposia on an annual or biennial basis.

Priority Issues and Challenges

GRSS has embarked on three major initiatives; 1) Globalisation, 2) Education, and 3) Industry Engagement. These initiatives are aimed at enhancing service to our members and expanding activities in developing countries. In globalisation GRSS efforts are focused on capacity building activities in Latin America, China, India, and Southeast Asia and Africa and the Middle East. GRSS works through local Chapter formation; supports a Distinguished Speakers program; organises Specialty Symposia and Remote Sensing Caravans for dispersing educational, training and capacity building support activities. GRSS is seeking to engage more effectively with industry in remote sensing technology development. Close collaboration among scientists, practitioners, and industry can be beneficial to all parties involved and lead to the uptake of geo-spatial products and remote sensing applications.

Perspectives/Outlook, Future Plans

With an ever growing world population and the continued increasing demand for food, water and other natural resources; for public services, security and improved transport facilities, the interdisciplinary field of remote sensing is among the most promising contributing technologies to meeting habitat demands. In the future GRSS is committed to advancing the frontiers of remote sensing science and applications and by so doing contribute to improving the life of this planet and its peoples. More details on GRSS activities can be found on their web site http://www.grss-ieee.org.

3. International Association of Geodesy (IAG)

The mission of the IAG is the advancement of geodesy. The IAG implements its mission by:
(a) advancing geodetic theory through research and teaching; (b) collecting, analysing and modelling observational data; (c) stimulating technological development; and (d) providing a consistent representation of the figure, rotation and gravity field of the Earth and planets, and their temporal variations.

The IAG is structured into four Commissions, the Inter-Commission Committee on Theory, fourteen International Scientific Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch. The Commissions are divided into Sub-commissions, Projects, Study Groups and Working Groups. The ICCT investigates geodetic science problems in close cooperation with the Commissions. The Services generate scientific products by means of Operations, Data and Analysis Centres. GGOS has as one of its roles the coordination of the work of the different IAG components, relating in particular to the maintenance of the global reference frame for measuring and consistently interpreting key global change processes, and to promote its use to the scientific community, policy makers and the public. The detailed programme of the IAG is published in the quadrennial *Geodesist's Handbook*, and reports are published in the biennial *Travaux de l'AIG*. The IAG publishes the *Journal of Geodesy*, and a series of *Symposium Proceedings*.

Activities, Areas of Work

a. On 26 February 2015 the United Nations General Assembly adopted its first resolution recognising the importance of a globally-coordinated approach to Geodesy. It was acknowledged that Geodesy plays an increasing role in people's lives, from finding disaster victims to finding directions using a smart phone. The General Assembly resolution, A Global Geodetic Reference Frame for Sustainable Development, outlines the value of ground-based observations and satellite remote sensing when tracking changes in populations, land use, ice caps, oceans, the atmosphere, and the environment over time. Such geospatial measurements, when referred to a high quality geodetic reference frame, can support sustainable development policymaking, climate change monitoring and natural disaster management, and also have a wide range of applications for transport, preserving the natural and built environments, supporting agriculture and resource exploitation, and for land use planning, infrastructure provision and construction.

b. The FIG and IAG co-organised and delivered the “Technical Seminar on Vertical Reference Frames in Practice”, in Singapore, 27-28 July.

c. The best known of the IAG services, the International GNSS Service (IGS), continues to have a major impact at a number of forums. Its products support high precision positioning applications for science and society. The most recent progress is expansion in IGS products to include GNSS constellations apart from GPS and GLONASS, the Real-Time Service to support geohazard applications, and participation in a planned International GNSS Monitoring and Assessment (IGMA) service/project organised under the auspices of the International Committee on Global Navigation Satellite Systems (ICG).

Priority Issues and Challenges

a. GGOS is IAG’s observing system to monitor the geodetic and the global geodynamic properties of the Earth as a system. The new structure was refined and implemented over the past few years. It includes a Consortium composed by representatives of the Commissions and Services, the Coordinating Board as the decision-making body, the Executive Committee, and the Science Panel. The scientific work of GGOS is coordinated by Themes, Working Groups and Bureaus. The optimal structure of GGOS, and the establishment of linkages with the Commissions and Services continues to be a work-in-progress.

b. Following the UN General Assembly resolution on the Global Geodetic Reference Frame (GGRF), the challenge is to develop a “roadmap” on how to encourage greater use of the GGRF, data sharing amongst all States, and increased investment in geodetic infrastructure (see http://ggim.un.org/UN_GGIM_wg1.html).

c. The IAG continues to work closely with other organisations within JBGIS, other associations within the International Union of Geodesy and Geophysics (IUGG), as well as the Group on Earth Observation (GEO), International Standards Organization (ISO), the UN Office for Outer Space Affairs (UN-OOSA, with participation in Space-based Information for Disaster Management and Emergency Response, UN-SPIDER, and the ICG), and the UN-GGIM.

Perspectives/Outlook, Future Plans

The IAG is one of eight Associations of the IUGG. The IUGG meets every four years in a General Assembly. This year the General Assembly was held in Prague, Czech Republic, 22 June – 2 July. A new leadership team will be installed for the next quadrennial period. The new IAG President is Dr Harald Schuh, the Vice President is Dr Zuheir Altamimi, and the Secretary-General is Dr Hermann Drewes. More details on IAG activities can be found on their web site http://www.iag-aig.org.

4. International Cartographic Association (ICA)

The International Cartographic Association (ICA) is the world authorative body for cartography and GI Science. The mission of the ICA is to promote the disciplines and professions of cartography and GIScience in an international context.

Whenever spatial data or geoinformation needs to be presented and communicated to a human user it can very often only be "unleashed" through a map. This is because maps are most efficient in enabling human users to understand complex situations. Maps can be understood as tools to order information by their spatial context. Maps can be seen as the perfect interface between a human user and all those big data and thus enable human users to answer location-related questions, to support spatial behaviour, to enable spatial problem solving or simply to be able to become aware of space. What we can expect in the near future is, that information is available anytime and anywhere. In its provision and delivery it is tailored to the user's context and needs. In this the context is a key selector for which and how information is provided. Cartographic services will thus be wide spread and of daily-use in a truly ubiquitous manner. Modern cartography applications are already demonstrating their huge potential and change how we work, how we live and how we interact.

As the International Cartographic Association is a forum of and for those which work with maps, produce maps, have to use maps the organisation is especially interested in not only linking those which deal with maps but also to promote the importance and power of maps as instruments to communicate spatial information to everybody.

In this sense instruments like the endorsement of Education programmes dedicated to modern Cartography such as the International Master of Science Programme in Cartography (http://www.cartographymaster.eu/), the Barbara-Petchenik-Children Map Drawing Competition (http://icaci.org/tag/barbara-petchenik-competition/) or dedicated Capacity Building Workshops are very popular. ICA is active through its several Commissions (www.icaci.org), Publications (Book Series, International Journal of Cartography), Conferences and cartographic exhibitions to name a few.

Activities, Areas of Work

ICA has been endorsed by UN-GGIM in its meeting 2014 to organise the International Map Year 2015/16. The main idea of the International Map Year (IMY) is a worldwide celebration of maps and their unique role in our world. The purposes of the IMY include:

- making maps visible to decision makers, citizens and school children in a global context,
- demonstrating how maps and atlases can be used in society,
- showing how information technology can be used in getting geographic information and producing one's own maps,
- displaying different types of maps and map production,
- showing the technical development of mapping and atlas production,
- showing the necessity of a sustainable development of geographic information infrastructures, and
- increasing the recruitment of students to cartography and cartography-related disciplines.

The IMY will be officially opened at the ICA conference in Rio de Janeiro in August, 2015 by Mr. Greg Scott on behalf of the UN-GGIM secretariat and then continue until December 2016. Several activities have therefore been started. ICA has installed a Working Group to coordinate the activities. National Committees in several countries have been established. Map exhibitions, children map competitions, workshops, map seminars, cartographic conferences are taking place or are in preparation. The book "The World of Maps" is already available in three languages and freely downloadable (http://mapyear.org/the-world-of-maps-book/).

Priority Issues and Challenges

Further priority issues of ICA include the further development of the Research Agenda of Cartography and GI Science, especially in the context of the recently endorsed full membership of ICA in the International Council of Science (ICSU). ICA aims to contribute significantly through this partnership to scientific efforts in tackling global challenges in relation to geospatial information management. A special focus is given as well to outreach programmes and capacity building. In several related workshops and activities in the last few years it became more then visible that several countries and regions of the world have a high demand and necessity in capacity building towards modern cartography tools, techniques and methods. ICA is actively involved in the "Geo4All" initiative (http://www.geoforall.org/), allowing geospatial education, materials and instruments accessible for all. This, accompanied with a long record of highly successful ICA hands-on workshops on modern cartography, can be requested from ICA by UN-GGIM national delegations.

Perspectives/Outlook, Future Plans

Finally it has proven to be a most successful strategy in the context of Global Geospatial Information Management to allow for a better awareness of the crucial role of the map as the interface between geo-data and human users. In this context ICA will continue to offer its expertise and consultancy for understanding the context of why maps are important, relevant and attractive, thus are key in making all geo-domains being able to reach out beyond the limits of the disciplines to all citizens. More details on ICA activities can be found on their web site http://icaci.org.

5. International Federation of Surveyors (FIG)

The International Federation of Surveyors (FIG) is a United Nations and World Bank recognised non-governmental organisation of national member associations that covers the whole range of professional fields within the global surveying community. It provides an international forum for discussion and development aiming to promote professional practice and standards.

The FIG seeks to collaborate and to ensure that the disciplines of surveying and all who practice them are relevant and meeting the needs of both the community and the market we service. This worldwide professional community measures, maps, estimates, costs, values, assesses, models, plans and manages the natural and built environment for the effective planning and efficient administration of the land, the seas and any structures thereon. The FIG vision is of a modern and sustainable surveying profession in support of society, environment and economy by providing innovative, reliable and best practice solutions to our rapidly changing and complex world, acting with integrity and confidence about the usefulness of surveying, and translating these words into action.

Activities, Areas of Work

a. New FIG publications during the last year:

- Publication 60: Fit-For-Purpose Land Administration, joint FIG/World Bank publication, 2014**.**
- Publication 61: CADASTRE 2014 and Beyond, 2014.
- Publication 62: Ellipsoidally Referenced Surveying for Hydrography, Commission 4 Working Group 4.1, 2014.
- Publication 63: The Africa Task Force, 2014.
- Publication 64: Reference Frames in Practice Manual, Commission 5 Working Group 5.2, 2014.
- Publication 65: The Surveyor’s Role in Monitoring, Mitigating, and Adapting to Climate Change, Task Force on Surveyors and Climate Change, 2014.
- A Review of the Social Tenure Domain Model (STDM) Phase II, Summary Report May 2014.
- Publication 66: FIG Statutes and Internal Rules, FIG Regulations, 2015.

b. The FIG Working Week 2015 was held in Sofia, Bulgaria 17-21 May 2015, with almost 1000 participants. The Working Week offered around 350 presentations within the various fields of surveying during the three conference days. The General Assembly voted on the destination for the FIG Working Week 2019 with Vietnam Association of Geodesy, Cartography & Remote Sensing, Hanoi, Vietnam, declared the winner.

c. At the World Bank Conference 2015 the FIG organised a side event. In January 2015 a kick off event took place in Athens, Greece to mark the change of the leadership in the FIG. FIG Commission 7 Annual Meeting 2014 was organised in cooperation with FIG’s membership in Canada and the FGF (Fédération des géomètres francophones) in Quebec City, and held on the sideline of the GeoConference 2014. The FIG Commission 3 Annual Meeting and 2014 Workshop with the overall theme "Geospatial Crowdsourcing and VGI: Establishment of SDI & SIM" was held in Bologna, Italy.

Priority Issues and Challenges

a. FIG has been a member of the UN-GGIM Working Group on A Statement of Shared Guiding Principles for Geospatial Information Management. The aim of the Working Group was to draft a proposed Statement for the consideration of UN-GGIM at its 5th Session.
b. Valuation of Unregistered Land and Properties Expert Group Meeting (EGM) is a collaborative activity between Global Land Tool Network (GLTN) facilitated by UN-Habitat, FIG and other key partners that have embarked on a process to develop a tool for the valuation of unregistered lands and properties. An EGM on 13-14 October 2014, Bangkok, Thailand brought together experts to facilitate the development of a framework document on current thinking and methodologies for the valuation of unregistered lands and properties, based on current valuation practices and research. The valuation of unregistered lands and properties is a "frontier" in valuation and the outcome from the EGM is expected to include not just recommendations, rather a conceptual framework and outline methodology that should take on board calculated risks on new and unusual ideas, offer different and innovative options to solve problems and meet the needs of GLTN and its partners, particularly partners supporting poor and marginalised communities with valuation related initiatives. A follow up expert group meeting was held during the FIG Working Week 2015.
c. Modernising Land Agencies Budgetary Approach: Costing and Financing of Land Administration Services in Developing Countries is another initiative by GLTN in collaboration with FIG and key partners including Kadaster International (The Netherlands), Lantmateriet (Sweden), Statkart (Norway), Geodata Agency (Denmark) and LINZ (New Zealand). The aim was to develop a tool that can assist policy makers and those responsible for land administration to adopt appropriate technologies and methodologies that will provide and sustain land administration services most efficiently, cost effectively and with options most appropriately tailored for incorporating all tenure types. The first version (CoFLAS I) was released during the FIG Congress 2014, and this milestone triggered a need for a validation exercise held on 15-16 October 2014, Bangkok, Thailand to review, advise and provide guidance on the piloting of the current version and its ongoing development. CoFLAS has started its phase II using the tools on a national level and was also on the agenda at the FIG Working Week 2015.
d. GLTN and FIG with the support of FIG Young Surveyors Network and the FIG Foundation convened a GLTN/FIG STDM (Social Tenure Domain Model) Training-of-Trainers Workshop in Addis Ababa, Ethiopia in November 2014, with focus on young professionals from grassroots organisations as well as young surveying professionals from Africa. The concept of the STDM is to bridge gaps by providing a standard for representing 'people-to-land' relationships independent of the level of formality, legality and technical accuracy. Another STDM Training day was held during the FIG Working Week 2015.

Perspectives/Outlook, Future Plans

At the FIG Congress 2014 the new leadership was elected, and the new President, Chryssy Potsiou, together with her Council took over the leadership of FIG on 1 January 2015. For the 2015-2018 time period the FIG Council agreed on an overall theme for the next period of office: *"Ensuring the Rapid Response to Change, Ensuring the Surveyor of Tomorrow".* More details on FIG activities can be found on their web site http://www.fig.net.

6. International Geographical Union (IGU)

No report tent.

7. International Hydrographic Organization (IHO)

The International Hydrographic Organization (IHO) is an intergovernmental consultative and technical organisation. 85 States are currently members of the IHO, with 8 more States in the process of acceding to membership. Each Member State is normally represented by its national Hydrographer.

The overarching objective of the IHO is to ensure that all the world's seas, oceans and navigable waters are surveyed and charted adequately. As the competent inter-governmental authority for surveying and charting the world's oceans, seas and coastal waters, the IHO coordinates the provision of the marine component of spatial data infrastructures at the regional and worldwide levels. It does this through the setting of international standards, the coordination of the endeavours of national hydrographic offices and through capacity building. The IHO sets the standards for hydrographic data and for the provision of hydrographic services, such as nautical charts, in support of safety of navigation and the protection and sustainable use of the marine environment. As reported to previous sessions of UN-GGIM, the relevant IHO standards relating to hydrographic surveying and nautical charting services have been universally adopted.

Activities, Areas of Work

a. The latest IHO standard is known as S-100 - The IHO Universal Hydrographic Data Model. S-100 is based on and compatible with the ISO 19100 geographic data standards and enables hydrographic data to be easily merged and used with other non-hydrographic geographic data - especially in geospatial information systems. As well as the IHO, a growing number of international organisations with diverse maritime interests are taking up S-100 as their data exchange standard, such as the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.
b. The IHO operates its own Capacity Building Programme aimed at assisting individual States and regions to develop their hydrographic capabilities. The IHO also cooperates with various other intergovernmental and international organizations in complementary capacity building programmes under the UN theme of "delivering as one". Capacity Building partners include the International Maritime Organization (IMO), WMO, IOC, and IALA.

Priority Issues and Challenges

The principal shortcoming in the hydrographic domain remains the lack of depth measurements and related hydrographic information for most of the world's seas and oceans coupled with the limited resources being made available to address the problem. The lack of a comprehensive, detailed global bathymetric dataset is a major constraint on the safe, cost effective and sustainable development of the blue economy. The IHO maintains IHO Publication C-55 - *Status of Surveying and Nautical Charting Worldwide*. C-55 provides statistics for each coastal State on the percentage of sea area that is unsurveyed and the percentage that meets modern requirements. C-55 is available from the IHO web site (see below). The IHO operates a Data Centre for Digital Bathymetry (IHO DCDB) as the principal web-based data store that provides access to most of the existing depth measurements for the ocean. Some of this data can be downloaded directly from http://www.ngdc.noaa.gov/mgg/bathymetry/iho.html for use; other data and metadata can be identified and then obtained from other sources. The IHO DCDB is currently undergoing an upgrade to make it the world portal for the upload and download of so-called Crowd-sourced Bathymetry (CSB). It will be a resource for everyone. CSB is depth data that is collected by ships and boats using their navigation echo sounders during their normal voyages across the sea and along the coastline. Harnessing the collecting power of all mariners is an efficient way of obtaining depth data where there is currently no data or the data is uncertain.

Perspectives/Outlook, Future Plans

As well as encouraging all coastal States to increase their emphasis on hydrographic surveying and charting, the IHO and the IOC jointly govern the long-running General Bathymetric Chart of the Ocean (GEBCO) project. The GEBCO project seeks to provide the most authoritative and openly available bathymetric dataset by harvesting observations from all sources. Further details are available on the dedicated GEBCO web site at http://www.gebco.net. More details on IHO activities can be found on their web site http://www.iho.int.

8. International Map Industry Association (IMIA)

The International Map Industry Association (IMIA) is a truly global organisation that represents the world of maps. IMIA is where mapmakers, publishers, geospatial technology companies, location-based services, content producers, and distributors come together to conduct the business of maps.

IMIA endorses the "International Map Year 2015 – 2016" (IMY) as proposed by the International Cartographic Association as a valuable means to promote the importance of maps and Geo information. To celebrate IMY, IMIA has a number of activities planned, including IMY themes at the IMIA Americas and IMIA Asia Pacific conferences and the IMIA Blog series "What is a Map?" To further celebrate and recognise the importance of maps and geoinformation, the IMIA is also conducting Student Map Awards under the IMY guidelines.

Activities, Areas of Work

a. IMIA Asia Pacific hosted a MapHack Day where cartographers, programmers and students worked together to build maps using open source tools and public data. These projects were then presented at the IMIA Asia Pacific Conference in Melbourne 2014.
b. IMIA Asia Pacific participated in the Brisbane International GIS Day 2014, which promotes GIS and its associated spatial technologies and brings together people from across Australia – government, professionals, businesses and university students to connect the geospatial industry to potential or existing users and clients. The Brisbane International GIS Day is organised by IMIA Asia Pacific member, GIS People, and is the largest GIS Day event in the world.
c. IMIA Asia Pacific member Spatial Vision helped Aboriginal artist Dion Beasley from Canteen Creek, in the Northern Territory to create an online interactive map at http://barklyarts.com.au/digital-mapping-interactive-map/. The project was funded by the Australia Council for the Arts through the Artist with Disability Program and is designed to further develop Dion's skills in drawing and mapping and to develop new skills in photography and video.

Priority Issues and Challenges

To celebrate IMY the IMIA Asia Pacific Conference will focus on the importance and use of maps and geoinformation. IMIA Student Map Awards are being held to allow students to become involved in the art, science and technology of making maps and the use of geographic information. IMIA Asia Pacific Conference and Brisbane GIS Day 2015 will run together as a three day event and aim to raise awareness and highlight the importance of maps and geospatial information to the wider community.

Perspectives/Outlook, Future Plans

More details on IMIA activities can be found on their web site http://imiamaps.org.

9. International Society of Photogrammetry and Remote Sensing (ISPRS)

Photogrammetry and Remote Sensing is the art, science, and technology of obtaining reliable information from non-contact imaging and other sensor systems about the Earth and its environment, and other physical objects and processes through recording, measuring, analysing and representation. The International Society for Photogrammetry and Remote Sensing (ISPRS) is a non-governmental organisation devoted to the development of international cooperation for the advancement of photogrammetry and remote sensing and their applications.

During the past 12 months ISPRS has started a host of new activities. Foremost, in spring ISPRS has decided to introduce a new commission structure. As of next year there will be five commissions:

- Commission I Sensor Systems
- Commission II Photogrammetry
- Commission III Remote Sensing
- Commission IV Spatial Information Science
- Commission V Education and Outreach

Activities, Areas of Work

a. On the publication side ISPRS is proud to announce that its GI journal, the *ISPRS International Journal of Geo-Information*, is now also indexed in the Web of Science, and has thus joint the flag ship publication, the *ISPRS Journal of Photogrammetry and Remote Sensing*. For the latter journal ISPRS has appointed Qiohao Weng from Indiana State University to join Derek Lichti (Calgary University) as editor-in-chief. The *International Archives,* which contain abstract reviewed proceedings papers, is part of the Conference Proceedings Citation Index of Thomson-Reuters and of SCOPUS, the *ISPRS Annals*, which contain full-paper double-blind reviewed contributions, has been accepted for inclusion into the DOAJ (the Directory of Open Access Journals).

b. In autumn 2014 the second round of the ISPRS Scientific Initiative was launched with a budget of 33.000,- CHF, resulting in the funding of seven scientific projects over the next 12 months. Topics range from benchmark tests on multi-platform photogrammetry to a project on the assessment of learning pedagogy in GeoInformatics.

c. Another important project, being carried out in cooperation with UN-GGIM is the assessment of the “Global Status of Land Cover Mapping and Geospatial Database Updating”.

d. Starting in November 2013 ISPRS has introduced a biennial series of scientific meetings called the ISPRS Geospatial Week (GSW). The motivation is to offer interested participants from research, development and applications in photogrammetry, remote sensing and geospatial sciences a platform for discussion also in odd years and thus to increase the visibility of the society. ISPRS GSW is a bundle of workshops with different topics, organised under a common roof. This year they will be held in Montpellier, France from 28 September to 2 October.

Priority Issues and Challenges

In order to intensify cooperation with both, the field of GI and of open source, ISPRS has recently signed an MoU with AGILE, the Association of Geographic Information Laboratories in Europe, and OSGeo. As of May 2014 ISPRS offers individuals to become a member of the society (if interested, apply here: www.isprs.org/members/individuals/ RegisterIndividuals.aspx). Membership is free of charge, the offer is primarily directed to people in areas without an active ISPRS ordinary member. As of June 2015 we have nearly 300 individual members.

Perspectives/Outlook, Future Plans

More details on recent ISPRS activities can be found on the ISPRS web site http://www.isprs.org. The ISPRS cordially invites you to attend the XXIII ISPRS Congress to be held in Prague from 12-19 July 2016.

10. International Steering Committee for Global Mapping (ISCGM)

The International Steering Committee for Global Mapping (ISCGM) was established in February 1996 to spearhead Global Mapping in response to the call for urgent actions at the 1992 Earth Summit in Rio de Janeiro for greater information support on 'the status and trends of the planet's ecosystem, natural resources, pollution and socioeconomic variables'. Twenty years later, in 2012, the same call was repeated at the UN Conference on Sustainable Development (Rio+20). In its Outcome Document, 'The Future We Want', the Rio+20 conference made specific references to 'the relevance of global mapping', and called for reliable geospatial information for sustainable development policy making, programming and project operations, and disaster prevention and mitigation.

Operationally, the ISCGM has two key tasks. First, it serves as the platform to "advocate the importance of Global Mapping, exchange views, facilitate coordination, and give recommendations". This is the 'advocacy' function of ISCGM. Second, the ISCGM has the responsibility to develop a Global Map, which is defined as "a group of geographical data sets of known and verified quality, with consistent specifications which will be open to the public". This is the 'production' function of the ISCGM. Over the past seventeen years, the ISCGM has been addressing these two core tasks.

Activities, Areas of Work

a. Global Map data (national and regional version) were released for 111 countries and eight regions from the ISCGM web site (see below), or from those of some participating organisations as of 1 June 2015. These data correspond to 65% of the total land area of the Earth.
b. Participating countries and regions are steadily increasing and now total 167 countries and 16 regions. This represents 96% of the whole land area of the earth.
c. The Third UN World Conference on Disaster Risk Reduction (WCDRR) was held in Sendai-City, Miyagi-Prefecture, Japan from 14-18 March 2015. As a pre-event of the Conference, the ISCGM and Geospatial Information Authority of Japan (GSI) co-organised the symposium on Application of Geospatial Information Technology in Urban Disaster Management on 13 March. A common understanding was gained on the importance of listing urban hazard maps of the world and understanding their development. In order to contribute to the efforts, it was agreed that ISCGM advances the work for the launch of the Urban Hazard Maps Web Portal.

Priority Issues and Challenges

The ISCGM has proposed the development of a catalogue service of global map thematic layers and a web platform for urban hazard maps. Prototypes of these services are now available from the ISCGM web site (see below).

Perspectives/Outlook, Future Plans

The 22nd meeting of the ISCGM will be held in New York, on 4 August 2015. One of the important agenda items was discussion on importance of geospatial information for disaster risk reduction. More details on ISCGM activities can be found on their web site http://www.iscgm.org.

Report of the Ad-hoc Group on an International Height Reference System (IHRS)

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Motivation

To determine and investigate the global changes of the Earth, geodetic reference systems with long-term stability and homogeneous consistency worldwide are required. Thus, the sea level rise of a few millimeters per year can only be detected when a stable spatial reference over a long period with globally high accuracy is realized. For this, an integrated global geodetic reference frame with millimeter accuracy must be implemented. To reach this goal, the inconsistencies existing between analysis strategies, models, and products related to the Earth's geometry and gravity field must be solved. Consequently, this is at present a main objective of the International Association of Geodesy (IAG) and especially of the Global Geodetic Observing System (GGOS), see e.g., Plag and Pearlman (2009), Kutterer et al. (2012).

Physical heights are potential differences of the Earth's gravity field and a global vertical reference frame provides the reference for Earth's gravity field parameters. The geoid potential parameter W_0 defines the zero-level of the global height reference system and determines the relationship between the physical heights and the body of the Earth. The parameter W_0 must be consistent between systems to ensure that the relevant relations are reproducible.

The objective of this work is to define the necessary standards for a global physical height reference system based on existing developments and past project results, and to draft and implement relevant products from this information. Conventions and guidelines resulting from this work are directly related to the activities of several IAG sub-entities: GGOS Bureau for Products and Standards (Angermann et al. 2015), GGOS Theme 1 *Unified Height System* (Sideris 2013) and Theme 3 *Understanding and Forecasting Sea-Level Rise and Variability* (Schöne et al., 2013), the Inter-Commission Project 1.2 *Vertical Reference Frames* (Ihde 2007, Ihde et al. 2007), the working group *Vertical Datum Standardization* (Sánchez 2012); as well as the joint activities of IAG Commission 2 *Gravity Field* and the *Consultative Committee for Mass and Related Quantities* to agree about a *Strategy for Metrology in Absolute Gravimetry* (Marti et al., 2015). This work should provide a basis to homogenize the products of the geometry, the gravity field, and the time reference.

I. General Concepts

a) Earth Gravity Field and Physical Height

There is a basic relationship between Earth gravity and geopotential. The Earth gravity field can be represented by means of: The geopotential scalar field $W(\mathbf{X})$ or the outer Earth gravity vector field $\mathbf{g}(\mathbf{X})$ at a spatial position $\mathbf{X}$. Both fields are related by the theorem

$$\mathbf{g} = \mathrm{grad}\,W = -g\begin{pmatrix} \cos\Phi & \cos\Lambda \\ \cos\Phi & \sin\Lambda \\ & \sin\Phi \end{pmatrix}, \tag{1}$$

with the natural coordinates astronomical latitude □□ and astronomical longitude □□ For the gravity there is the relation:

$$g_P = \mathbf{g}(\mathbf{X}) = \left|\mathrm{grad}\ W_P\right| = \left(-\frac{\partial W}{\partial H}\right)_P \tag{2}$$

In a very general notation, equations (1) and (2) can be expressed as:

$$P(\mathbf{X}, W, g) = P(\mathbf{X}, W, -\partial W/\partial H) \text{ or} \tag{3a}$$

$$W(\mathbf{X}) = W_P \text{ collocated with } \mathbf{g}(\mathbf{X}) = g_P = -\partial W_P/\partial H\,. \tag{3b}$$

The geopotential scalar field $W(\mathbf{X})$ and the outer Earth gravity vector field $\mathbf{g}(\mathbf{X})$ are completely consistent with each other, and are functions of time in Euclidean space. Because of this, physical heights H may be expressed as potential differences of the Earth gravity field.

Subsequently, the inverse relationship equation (3b) may be used to estimate the disturbing potential T_P, which is defined as:

$$T_P = W_P - U_P\,, \tag{4}$$

at any point $P(\mathbf{X})$ on the Earth's surface, by solving the geodetic boundary value problem (GBVP) and integrating gravity over the whole Earth's surface □,

$$T_P = \frac{R}{4\pi}\iint_\sigma (\Delta g + G_1 \cdots) S(\psi)\, d\sigma \tag{5}$$

or by applying a global gravity model (GGM) to obtain the real gravity potential Wp at the point $P(\mathbf{X})$.

The aforementioned equivalent field configurations of the Earth gravity field require the consistent treatment of gravity, potential, and physical heights. For this reason, the interactions of the definition and realization of the International Height Reference System (IHRS) with the definition and realization of an International Gravity Reference System (IGRS) as well as the International Terrestrial Reference System (ITRS) must be considered.

The gravity acceleration is the only measurable characteristic within the vector field, and in the vertical direction there are almost no observables or products. Potential values and potential differences cannot be measured directly and therefore they must be estimated within the gravity field modeling, where the physical height is a main component. The accuracy of the at present widely used gravity reference network (IGSN71: International Gravity Standardization Net 1971, Morelli et al. 1974) is one to two orders lower than the current accuracy of absolute gravity measurements and generated products (Jiang et al. 2012), yet IGSN71 is still officially recognized as a valid tool despite this shortcoming. Overall, the IAG has paid little attention to gravity (absolute gravity) and gravity variations. This deficiency creates an opportunity for the IAG to take a leadership role in gravity studies by developing a new gravity standard.

b) Physical Height Reference Systems

In general, a reference system defines constants, conventions, models, and parameters required for the mathematical representation of geometric and physical quantities. A reference frame realizes a reference system in two ways: physically, by a solid materialization of points; and mathematically, by the determination of coordinates referring to that reference system; i.e. the coordinates of the physical points are computed from the measurements, but following the definition of the reference system. The datum fixes univocally the relation between a reference frame and a reference system. In the case of a vertical o height reference system, the primary components are a reference surface (i.e. the zero-height level) and a vertical coordinate (i.e. a physical height o more general, level differences). Its realization is given by a vertical network, i.e. a set of points, whose heights are of the same type specified in the definition and refer to the vertical datum that establishes the level of the reference surface.

Physical Height Reference Systems (HRS) are related to the Earth's gravity field on or outside the solid Earth body. A global HRS is a geopotential reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points attached to the solid surface of the Earth are given by geopotential values and geocentric Cartesian coordinates **X** in a defined Terrestrial Reference System (TRS). A height or vertical reference frame (HRF) is a set of physical points with precisely determined geopotential values W_P or level differences C_P with respect to a geopotential reference value W_0. Such a HRF is said to be a realization of the HRS. The disturbing potential (Eq. 4) undergoes only small variations in time, due to geophysical effects (mass transports and tectonic or tidal deformations).

The height components are differences ΔW_P between the potential W_P of the Earth gravity field level surface passing through the considered point P and the potential of the HRS zero-level W_0. The potential difference $-\Delta W_P$ is also designated as geopotential number C_p:

$$C_P = -\Delta W_P = W_0 - W_P \,. \qquad (6)$$

The zero-level W_0 to which the geopotential numbers C_p are related is called the vertical datum of the HRS.

II. Standards, Conventions, Guidelines

a) Numerical standards

In 1979, the International Union of Geodesy and Geophysics (IUGG), International Association of Geodesy (IAG), and International Astronomical Union (IAU) have agreed upon the Geodetic Reference System 1980 (GRS80, Moritz 1980 and 2000) to define major parameters for a geodetic reference system related to a geocentric equipotential ellipsoid. At the IUGG General Assembly 1991 in Vienna, new values for the geocentric gravitational constant (*GM*), and the semi-major axis (*a*) of the level ellipsoid were recommended. The two other defining parameters (dynamical form factor J_2 and mean angular velocity of the Earth's rotation ω) of the equipotential ellipsoid were not changed. The value of the geocentric gravitational constant (*GM*) has not changed since 1991. These values (or others very close to them) have been used in the computation of global gravity models since 1991.

Table 1 of this paper contains defining parameters for different level ellipsoids. The gravitational constants *GM* of the GRS80 and IERS Conventions 2010 differ by about 0.9 m^3s^{-2}; the semi-major axis *a* of both standards differs by 0.4 m. and the geopotential reference values (U_0 and W_0) differ by 4.85 m^2s^{-2}. Also noteworthy is that the IERS Conventions 2010 recommend different level ellipsoid parameters for different applications.

In the IERS Conventions 2010, Table 1.1 lists parameters that represent the current best estimations, and the best estimates for level ellipsoid parameters have not changed since 2003. It is not immediately evident how the 2010 estimates were determined. In addition, Table 1.2 of the same Conventions contains the parameters of the GRS80 ellipsoid and it is designated as convention for the conversion of Cartesian coordinates into ellipsoidal ones. This is new against the IERS Conventions 2003. These inconsistencies in the IAG and the IERS conventions shall be removed in view of the development of integrated geodetic products and applications.

Since the most accepted definition of the geoid is understood to be the equipotential surface that coincides (in the sense of the least-squares) with the worldwide mean ocean surface, the reference level for a global height system can be defined with the potential at the mean sea level, W_0. The value of W_0 depends from the Earth's gravity field, on the definition of mean sea level, and conventions about processing procedures including used models. This is independent from measurements. The definitions, conventions, and conditions shall documented for further comparisons and monitoring of mean sea level. It is to be expected that the mean sea level will change by mm/a. On the other hand, outgoing, that W_0 can be introduced as a defining parameter of the mean Earth ellipsoid, the semi-major axis (*a*) of the level ellipsoid would be a derived parameter and it would change if W_0 changes. To provide a reference ellipsoid that remains unchanged with time, it would be necessary to decouple W_0 from the sea surface variations.

The IERS Conventions (2003 and 2010) include a W_0 value that was derived in 1998 (Burša et al. 1998, Groten 1999, Groten 2004). This value presents discrepancies of more than -2 m^2s^{-2} against recent computations (Sánchez et al. 2014). It must be decided whether a new value W_0 should be introduced as a more accurate estimate. As mentioned, for each new W_0 estimation, a new value for the semi-major axis (*a*) of the level ellipsoid would have to be derived. However, by a recalculation of the parameter W_0, the discrepancy existing between the value included in the IERS Conventions 2010 (see Table 1) and recent calculations will be eliminated and the estimation procedure can be documented to ensure the reproducibility of the new adopted W_0 value.

From this perspective, W_0 is the only measurable defining parameter of the level ellipsoid that depends on changes in the Earth system. J_2 also depends on changes in the Earth system, but these changes are not measurable yet. As a fundamental parameter, W_0 shall not be changed from time to time; i.e. a change of W_0 per year in $m^2s^{-2}a^{-1}$ cannot be applied practically. For a global height reference system, any value W_0 within a range of a few decimeters can be defined as conventional without affecting the task of defining and realizing a global height reference system. Like any reference system, W_0 should be based on adopted conventions that guarantee its uniqueness, reliability, and reproducibility; otherwise there would be as many W_0 reference values (i.e., global zero-height surfaces) as computations.

In any case, the complete set of ellipsoidal parameters must be computed for the best estimate of a new level ellipsoid as done for the GRS80. So far, this has not been the case.

Table 1. Defining parameters of level ellipsoids (equipotential or mean Earth ellipsoids)

Ellipsoid	Semi-major axis a in [m]	Dynamical form factor J_2	Geocentric gravitational constant GM in 10^8 [m^3s^{-2}]	Normal potential at ellipsoid U_0, geoidal potential W_0 in [m^2s^{-2}]	Normal gravity at equator γ_e in [ms^{-2}]
GRS 80	6 378 137	$1.082\ 63 \times 10^{-3}$*	3 986 005	U_0 = 62 636 860.850	9.780 326 7715
IERS 2010 Conventions	6 378 136.6** ± 0.1	$1.082\ 63\ 59 \times 10^{-3}$** $\pm 1 \times 10^{-10}$	3 986 004.418 ± 0.008	W_0 = 62 636 856.0 ± 0.5	
The Mean angular velocity of the Earth's rotation ω remains the same in any case ($7\ 292\ 115 \times 10^{-11}$ rad s^{-1})					

* *Value given in tide-free system.*
***Value given in zero-tide system.*

In addition to the existing IERS numerical standards, other parameters shall be calculated and included in the IERS Conventions, for instance the normal gravity at equator (γ_e) and at pole (γ_p).

Independently of the decision to replace the GRS80 by a new conventional set of level ellipsoid parameters the current best-estimated value for W_0 shall be defined (and fixed) as the potential value of the geoid. To ensure the reproducibility and interpretability of these changes, the procedure applied for the determination of W_0 must be well documented including conventions and guidelines.

It is desirable that the recent best-estimates for the parameters of the level ellipsoid are applied for all products of measurements and modeling of the Earth's gravity field and geometry, including the global height reference system. In this case, a new GRS shall be computed. If the GRS80 remains as the conventional level ellipsoid, all necessary parameters must be then derived in accordance with the GRS80 values. For combination products such as GNSS/leveling, the regulations for the reductions should be specified based on the different numerical parameters and underlying geometrical and gravity field relations.

Within the next four years, an IAG inter-commission working group should be established to investigate the necessity and usefulness of replacing GRS80 with a new GRS. If the computation of a new GRS is decided, this working group shall prepare and propose a full set of parameters to be presented and adopted at the IUGG 2019 General Assembly.

b) Permanent Tide

A HRS is comprised of geometric and gravity potential parameters, including their variations with time, and in particular those generated by Earth tides.

The foundations of the IAG Resolution Number 16, adopted in 1983 at the General Assembly in Hamburg (Tscherning 1984), have not changed. The zero-tide system is the most adequate tide system applicable to both gravity acceleration and gravity potential of the rotating and deforming Earth. The pendent for the geometry is the mean/zero crust concept, where the mean sea surface corresponds to a crust deformed by mean/zero tides.

Table 2. Tide systems used in the determination of physical and geometrical coordinates

	gravity	**geoid**	**levelling height**	**altimetry**	**mean sea level**	**position**
	$\mathbf{g \leftrightarrow \Delta g}$	$\mathbf{W \leftrightarrow N}$	$\mathbf{\Delta H}$	**h**	**Msl**	$\mathbf{X \leftrightarrow h}$
Mean tidal system **Mean/zero crust** **(**Stokes is not valid if masses outside the Earth surface)	$\mathbf{\Delta g_m}$	$\mathbf{N_m}$	$\mathbf{\Delta H_m}$	**Relation to $\mathbf{N_m}$ for oceanographic studies $\mathbf{h_{msl}}$**		
Zero tidal system **Zero/mean crust** (Recommended by IAG Res. No. 16, 1983)	$\mathbf{\Delta g_z}$ → Stokes $\mathbf{N_z}$		$\mathbf{\Delta H_z}$ $\mathbf{C_p}$			
Non-tidal system **Non-tidal crust** (far away from the real earth shape – there is no reason for the non-tidal concept)	$\mathbf{\Delta g_z}$ → Stokes $\mathbf{N_n}$					$\mathbf{X_n}$ ITRF

There is no justification for the application of a tide-free concept for both the geometry and the gravity field, since the tide-free crust and gravity are far away from the real Earth shape and are unobservable (Ekman 1989, 1996; Mäkinen and Ihde, 2009). For the mean-tide geopotential the condition of the Laplace equation is not fulfilled, and even if the tide-free concept is kept for the terrestrial reference system parameters, the IAG Resolution No. 16 adopted in Hamburg in 1983 shall be used for gravity and geopotential. (see also table 2)

For practical applications, parameters and products of a HRS shall be related to the mean-tide system or mean crust. This means that a consistent transformation between the three tidal systems must be considered before combining gravity field and geometrical products.

III. Definition of an International Height Reference System (IHRS)

The International Height Reference System (IHRS) is a geopotential reference system co-rotating with the Earth in its diurnal motion in space. Coordinates of points attached to the solid surface of the Earth are given by (1) geopotential values $W(\mathbf{X})$ (and their changes with time $dW(\mathbf{X})/dt$) defined within the Earth's gravity field and, (2) geocentric Cartesian coordinates $\mathbf{X}$ (and their changes with time $d\mathbf{X}/dt$) referring to the ITRS. For practical purposes, potential values $W(\mathbf{X})$ and geocentric positions $\mathbf{X}$ can be transformed in vertical coordinates given with respect to a reference surface.

Five conventions define the IHRS:

1. The vertical reference level is the normal potential (or geopotential at the geoid or the geoid potential parameter) W_0 as an equipotential surface of the Earth gravity field. $U_0=W_0$ is a defining parameter of the conventional geocentric level ellipsoid. The relationship between W_0 and the Earth body must be defined and reproducible.
2. Parameters, observations, and data shall be related to the mean tidal system/mean crust.
3. The unit of length is the meter (SI). The unit of time is the second (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions, and is obtained by appropriate relativistic modeling.
4. The vertical coordinates are the differences $-\Delta W_P$ between the potential W_P of the Earth gravity field at the considered points P, and the geoidal potential of the level ellipsoid W_0. The potential difference $-\Delta W_P$ is also designated as geopotential number c_P:

   $$-\Delta W_P = c_P = W_0 - W_P.$$
5. The spatial reference of the position P for the potential $W_P = W(X)$ is related as coordinates X of the International Terrestrial Reference System.

IV. Conventions for the Realization of an International Height Reference System (IHRS)

The IHRS shall correlate the Earth gravity field (gravity, potential) with the geometry of the Earth and the timescale. The IHRS is to be realized by combining a global station network, a Global Gravity Model (GGM), and values for a set of parameters as an International Height Reference Frame (IHRF). The IHRF must be in accordance with the conventions underlying the definition of an International Height Reference System (IHRS), especially for conventions outlining how the elements can be derived. It is important to distinguish between the definition of IHRS, physical heights derived in the IHRF (important for applications and users), and the unification of existing physical height systems aligned to a defined and realized IHRS (Ihde and Sánchez 2005).

Proposal for the elements of an IHRF:

(1) The reference geopotential value W_0 is achieved through best estimates. The procedure of the W_0 determination must be documented in conventions and guidelines, to ensure the reproducibility and interpretability of changes.

(2) A central element of the IHRF is a Global Gravity Model (GGM). It is proposed to dedicate one satellite-only GGM for homogenous long wavelength approximation of the Earth gravity potential, as a matter of convention. One GGM combined with terrestrial data is recommended for applications in sparsely surveyed regions. For this, a maximum degree has to be defined as well, due to the fact that satellite-only models are usually regularized (constrained towards zero) in the high degrees, i.e. the higher degrees of the model do not contain the full signal. This is problematic if the models are combined with complementary (near-surface) data.

(3) The Earth gravity potential difference ΔW_P in relation to a conventional W_0 shall be known through an existing highest-accuracy network of geodetic observation stations, where observations can be generated to derive the defining elements in a highest level of quality consistent with other reference systems/frames.

(4) The reference network conforming the IHRF shall follow the same hierarchy of the ITRF reference network; i.e. a global network with regional/national densifications. This network shall be collocates with:
- reference tide gauges (local vertical datum points);
- main nodal points of the levelling networks;
- border points connecting neighboring vertical datum zones;
- geometrical reference stations (ITRF and densifications);
- fundamental geodetic observatories (connection between W_0, TAI, and absolute gravity).

Conventions and guidelines for products are necessary for all the aforementioned elements.

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Report 2011–2014 of the IAG Secretary General

http://iag.dgfi.tum.de

Secretary General: Hermann Drewes (Germany)

Introduction

The objective of the IAG is to study all geodetic problems related to Earth observation and global change. This includes the establishment of reference systems, determination of the Earth gravity field, monitoring Earth rotation, positioning of surface points, and studies of crustal deformation, mass transport and sea level changes. To accomplish the objectives, IAG is divided into four Commissions, fourteen Scientific Services, the Global Geodetic Observing System (GGOS), the Communication and Outreach Branch (COB), and the Inter-Commission Committee on Theory (ICCT). The administration is supervised by the Council and operated by the Bureau, the Executive Committee and the Office. The outreach is done by the COB. All these entities are in steady contact and inform about their activities through the IAG Newsletter and the bi-annual IAG Reports (Travaux de l'AIG).

Administration

IAG Council

The Council met twice during the IUGG General Assembly 2011 in Melbourne, Australia, and once at the IAG Scientific Assembly 2013 in Potsdam, Germany. The list of national correspondents forming the IAG Council was regularly updated in contact with the IUGG Secretary General. The Council was informed by e-mail about activities of the Bureau and the Executive Committee.

IAG Executive Committee (EC)

The Executive Committee is composed by the IAG President, immediate Past-President, Vice-President, Secretary General, the four Commission Presidents, the Chairperson of GGOS, the President of the COB, three representatives of the Services, and two members at large. Seven EC meetings were held during the legislative period from 2011 to 2014: Melbourne, Australia, July 2011, San Francisco, CA/USA, December 2011, Singapore, August 2012, Vienna, Austria, April 2013, Potsdam, Germany, September 2013, Vienna, Austria, April 2014, and San Francisco, CA/USA, December 2014. The meeting summaries were published by e-mail in the IAG Newsletter in IAG`s Journal of Geodesy (Springer-Verlag) and are available online in the IAG Homepage (http://www.iag-aig.org) and in the IAG Office Homepage (http://iag.dgfi.badw.de).

Main agenda items at the EC meetings were the regular reports of the Commissions, Services, GGOS, ICCT, COB, the Editor in Chief of the Journal of Geodesy, and the Editor of the IAG Symposia Series (both at Springer). They were followed by the discussion on specific scientific issues, changes in the structures of GGOS and Services, and IAG publications. Other important topics were the IAG Scientific Assembly 2013, the preparation of the IAG Symposia during the IUGG General Assembly 2015, the discussion of the bi-annual IAG Reports (Travaux de l'AIG), sponsoring of symposia, and the links to other organizations, e.g. FIG, GEO, JBGIS, IHO, ISO, and UNOOSA (see below).

IAG Bureau

The IAG Bureau, consisting of the President, the Vice-President and the Secretary General, held monthly teleconferences and met regularly before each EC meeting. The President and Secretary General participated in the IUGG Executive Committee Meetings. The Bureau members represented

IAG at various international scientific meetings and in several anniversaries, e.g. the 150th anniversary of the Swiss Geodetic Commission, Zürich, Switzerland, 10 June 2011, the 150th anniversary of the Arc Measurement in the Kingdom of Saxony, Dresden, Germany, 1 June 2012, the 150th anniversary of the Central European Arc Measurement, Vienna Austria, 14 September 2012, the 150th anniversary of the Austrian Geodetic Commission, Vienna, Austria, 7 November 2013.

Activities

IAG Office

The IAG Office assists the Secretary General in the administrative organization of all IAG business, meetings and events. This includes the budget management, the record keeping of the individual IAG membership, and the preparation and documentation of all Council and Executive Committee meetings with detailed minutes for the EC members and meeting summaries published in the IAG Newsletters and the IAG Homepage. Important activities were the preparation and execution of the IAG Scientific Assembly 2013 together with the celebration of the 150th IAG anniversary and the IAG symposia of the IUGG General Assembly 2015, the edition of the Geodesist's Handbook 2012 as the organisational guide of IAG with the complete description of the IAG structure (reports, terms of reference, documents), and the Mid-Term Reports 2011–2013 (Travaux de l'AIG Vol. 38). The accounting of the Journal of Geodesy and the IAG Symposia series, both published by Springer, were supervised. Travel grants for young scientists to participate in IAG sponsored symposia were handled.

Communication and Outreach Branch (COB)

The task of the COB is the IAG public relation in particular by maintaining the IAG Homepage and publishing the monthly Newsletter online and in the Journal of Geodesy. It also keeps track of all IAG related events by the meetings calendar. The IAG newsletter is sent to all IAG Officers, individual members, the Presidents and Secretaries General of the IUGG Associations and liaison bodies. The COB prepared, printed and distributed a new IAG leaflet and a big IAG brochure and participated in the preparation of the Geodesist's Handbook 2012.

Commissions and Inter-Commission Committee

The four IAG Commissions (Reference Frames, Gravity Field, Earth Rotation and Geodynamics, Positioning and Applications) and the Inter-Commission Committee on Theory established their structure and scientific programme for the period 2011 – 2015 (published in the Geodesists' Handbook 2012) and coordinated their implementation. They reported regularly to the EC and prepared the mid-term reports 2011 – 2013 for publication in the IAG Reports (Travaux de l'AIG). Each Commission maintained its individual Homepage and held several symposia, workshops and other meetings (see below). All of them organized a symposium at the IAG Scientific Assembly 2013.

Services

There are fourteen IAG Services which may be split into three general fields: geometry (IERS, IDS, IGS, ILRS, and IVS), gravity (IGFS, ICGEM, IDEMS, IGeS, and BGI) and combination (IAS, BIPM, ICET, and PSMSL). All of them maintain their own Homepages and data servers and hold their administrative meetings (Directing Board or Governing Board, respectively). They published their structure and programme 2011 – 2015 in the Geodesists' Handbook 2012, and the progress reports 2011 – 2013 in the IAG Reports (Travaux de l'AIG). Most of the Services held international meetings (see below).

Global Geodetic Observing System (GGOS)

The GGOS is IAG's observing system to monitor the geodetic and the global geodynamic properties of the Earth as a system. A complete new structure was set up during a retreat in 2011 and implemented in 2012. It includes a Consortium composed by representatives of the Commissions and Services, the Coordinating Board as the decision-making body, the Executive Committee, and the Science Panel. The scientific work of GGOS is structured by Themes, Working Groups and Bureaus. The outreach is done by the GGOS Portal, Webpages (www.ggos.org), an exhibit booth, brochures and books. Several retreats were held in the following years for updating the structure.

Coordination with other organisations

IAG maintains close cooperation with several organizations outside IUGG. There were frequent meetings with the Advisory Board on the Law of the Sea (ABLOS, together with IHO), Group on Earth Observation (GEO, with IAG as a participating organization), International Standards Organization (ISO, TC211 Geographic Information / Geomatics), Joint Board of Geospatial Information Societies (JBGIS), United Nations Offices for Outer Space Affairs (UN-OOSA, with participation in Space-based Information for Disaster Management and Emergency Response, UN-SPIDER, and International Committee on Global Navigation Satellite Systems, ICG), and the United Nations Global Geospatial Information Management (UN-GGIM).

Meetings

Important meetings of IAG components and sponsored IAG meetings were in 2011 – 2014:

- 20th EVGA Meeting. & 12th VLBI Analysis Workshop, Bonn, Germany, March 29-31, 2011;
- 1st International Workshop "The Quality of Geodetic Observation and Monitoring Systems" (QuGOMS), Garching/Munich, Germany, 13-15 April 2011;
- Third Conference "Earth Observation for Global Changes (EOGC2011)", Munich, Germany, 13-15 April 2011;
- 17th International Workshop on Laser Ranging and 23rd General Assembly of the International Laser Ranging Service (ILRS), Bad Kötzting, Germany, 15-20, May 2011;
- Sub-Commission 1.3a "EUREF" Symposium, Chisinau, Republic of Moldova, 25-28 May 2011;
- 2nd GIA Modeling Training School, Gävle, Sweden, 13-17 June 2011;
- Sub-Commission 1.3b "SIRGAS" General Meeting, Heredia, Costa Rica, 8-10 August 2011;
- International Workshop on GNSS Remote Sensing for Future Missions and Sciences, Shanghai, China, 7-9 August 2011;
- 3rd International Colloquium "Scientific and Fundamental Aspects of the Galileo Programme, Copenhagen, Denmark, 31 August – 2 September 2011;
- Internat. Symposium on Deformation Monitoring, Hong Kong, China, 2-4 November 2011.
- IGS Workshop on GNSS Biases, Bern, Switzerland, 18-19 January 2012;
- IVS VLBI2010 Workshop on Technical Specifications (TecSpec), Bad Kötzting/Wettzell, Germany, 1-2 March 2012;
- 7th IVS General Meeting "Launching the Next-Generation IVS Network", Madrid, Spain, 12-13 March 2012;
- Symposium and Workshop on PPP-RTK and Open Standards, Frankfurt am Main, Germany, 12-14 March 2012;
- IERS Global Geophysical Fluids Center (GGFC) Workshop, Vienna, Austria, 20 April 2012;
- EUREF 2012 Symposium, Saint Mandé, France, 6-8 June 2012;
- IGS Analysis Center Workshop, Olsztyn, Poland, 23-27 July 2012;
- IAG Symposium at the AOGS-AGU (WPGM) Joint Assembly, Singapore, 13-17 August 2012;

- International Symposium on Space Geodesy and Earth System (SGES2012), Shanghai, China, 19-20 August 2012;
- WEGENER 2012 Symposium, Strasbourg, France, 17-20 September 2012;
- 17th International Symposium on Earth Tides and Earth Rotation (ETS 2012), Cairo, Egypt, 24-28 September 2012;
- 20 Years of Progress in Radar Altimetry, Venice, Italy, 24-29 September 2012;
- IDS Workshop, Venice, Italy, 25-26 September 2012;
- 7th IAG-IHO ABLOS Conference, Salle du Ponant, Monaco, 3-5 October 2012;
- European VLBI Network (EVN) Symposium, Bordeaux, France, 9-12 October 2012;
- Workshop on Reflectometry using GNSS and Other Signals, Prudue University, West Lafayette, IN, USA, 10-11 October 2012;
- International Symposium on Gravity, Geoid and Height Systems, Venice, Italy, 10-12 October 2012;
- Sub-Commission 1.3b "SIRGAS" Meeting 2012, Concepción, Chile, 20-31 October 2012;
- International VLBI Technology Workshop, Westford, Massachusetts, USA, 22-24 October 2012;
- International Technical Laser Workshop "Satellite, Lunar, and Planetary Laser Ranging: Characterizing the Space Segment", Frascati, Italy, 5-9 November 2012;
- 21st European VLBI for Geodesy and Astrometry Workshop, Helsinki, Finland, 6-8 March 2013;
- 17th Int. Symposium on Earth Tides "Understand the Earth", Warsaw, Poland, 15-19 April 2013;
- Internat. Symposium on "Mobile Mapping Technology", Tainan, Taiwan, 30 April – 2 May 2013;
- Seventh IVS Technical Operations Workshop, Westford, Massachusetts, USA, 6-9 May 2013;
- IERS Workshop on Local Ties and Co-locations, Paris, France, 21-22 May 2013;
- IAG Sub-Commission 1.3a "EUREF" Symposium 2013, Budapest, Hungary, 29-31 May 2013;
- International Symposium on "Reconciling Observations and Models of Elastic and Viscoelastic Deformation due to Ice Mass Change", Ilulissat, Greenland, 30 May – 2 June 2013;
- GNSS Precise Point Positioning: Reaching Full Potential, Ottawa, Canada, 12-14 June 2013;
- VIII Hotine-Marussi Symposium, Rome, Italy, 17-21 June 2013;
- Int. Conference on "Earth Observations and Societal Impacts", Tainan, Taiwan, 23-25, June 2013;
- International Symposium on Planetary Sciences (IAPS2013), Shanghai, China, 1-4, July 2013;
- IAG Scientific Assembly, Potsdam, Germany, 1-6 September 2013;
- 2nd Joint Int. Symposium on Deformation Monitoring, Nottingham, UK, 9-11 September 2013;
- IAG Third Symposium on "Terrestrial Gravimetry: Static and Mobile Measurements (TGSMM-2013)", St Petersburg, Russian Federation, 17-20 September 2013;
- Scientific Developments from Highly Accurate Space-Time Reference Systems, Observatoire de Paris, Paris, France, 16-18 September 2013;
- ITU/BIPM Workshop on "The Future of the International Time Scale", Geneva, Switzerland, 19-20 September 2013;
- 2nd International VLBI Technology Workshop, Seogwipo, South Korea, 10-12 October 2013;
- IAG Subcommission 1.3b "SIRGAS" Symposium, Panama City, Panama, 24-26 October 2013;
- 18th International Workshop on Laser Ranging, Fujiyoshida, Japan, 9-15 November 2013;
- European VLBI Network Technical and Operations Group (EVN TOG) Meeting, Bad Kötzting, Germany, 23-24 January 2014;
- International VLBI Service for Geodesy and Astrometry (IVS) General Meeting, Shanghai, China, 2-7 March 2014;
- European Reference System (EUREF) Symposium, Vilnius, Lithuania, June 04-06, 2014;
- International GNSS Service (IGS) Workshop "Celebrating 20 Years of Service", Pasadena, CA, USA, 23-27 June 2014;
- 3rd International Gravity Field Service (IGFS) General Assembly, Shanghai, China, 30 June - 6 July 2014;

- International Symposium on Geodesy for Earthquake and Natural Hazards (GENAH 2014), Matsushima, Miyagi, Japan, 22-27 July 2014;
- 18th WEGENER General Assembly: Measuring and Modelling our Dynamic Planet, Leeds, UK, 1-4 September 2014;
- Journees 2014 "Systèmes de reference spatio-temporels", Pulkovo Observatory, St. Petersburg, Russia, 22-24 September 2014;
- 12th European VLBI Network (EVN) Symposium, Cagliari, Italy, 7-10 October 2014;
- Reference Frames for Applications in Geosciences (REFAG2014), Luxembourg, Luxembourg, 13-17 October 2014;
- International DORIS Service (IDS) Workshop, Konstanz, Germany, 27-28 October 2014;
- International Laser Ranging Service (ILRS) Technical Workshop, 27-31 October 2014, Greenbelt, MD, USA;
- Third International VLBI Technology Workshop, Groningen/Dwingeloo, The Netherlands, 10-13 November 2014;
- PECORA 19 Fall Meeting (ASPRS, IAG, ISPRS) "Sustaining Land Imaging: Unmanned Aircraft Systems (UAS) to Satellites", Denver, Colorado, USA, 17-20 November 2014;
- Sub-Commission 1.3b "SIRGAS" Symposium, La Paz, Bolivia, 24-26 November 2014;
- 11th International Symposium on Location-Based Services, Vienna, Austria, 26-28 November 2014.

The following IAG Schools were held 2011 – 2014:

- SIRGAS School "Geodetic Reference Systems", Heredia, Costa Rica, 3-5 August 2011;
- GNSS School, Hong Kong, China, 14-15 May 2012;
- Internat. Summer School "Space Geodesy & Earth System", Shanghai, China, 21-25 August 2012;
- SIRGAS School "Real Time GNSS Positioning", Concepción, Chile, Oct., 24-26, 2012;
- EGU-IVS Training School for the Next Generation Geodetic and Astrometric VLBI, Helsinki, Finland, 2-5 March 2013.
- 11th School of the International Geoid Service: Heights and Height Datum, Loja, Ecuador, 7-10 October 2013.
- SIRGAS School "Reference Systems, Crustal Deformation and Ionosphere Monitoring", Panama City, Panama, 21-23 October 2013.
- SIRGAS School "Vertical Reference Systems", La Paz, Bolivia, 20-22 November 2014.

Publications

The Journal of Geodesy, the official IAG scientific periodical with an Editor in Chief approved by the IAG Executive Committee, was continuously published with monthly issues in Springer-Verlag. In the IAG Symposia proceedings Series, the following volumes were published in:

- 136: Geodesy for Planet Earth; Proceedings of the IAG Scientific Assembly 2009 (2012);
- 137: VII Hotine-Marussi Symposium on Mathematical Geodesy 2009 (2012);
- 138: Reference Frames for Applications in Geosciences; Symposium of Commission 1 (2013);
- 139: Earth on the Edge: Science for a sustainable Planet; Proceedings General Assembly 2011 (2014);
- 140: Quality of Geodetic Observation and Monitoring Systems Workshop 2011 (on-line 2014).

Reports of all IAG components were published in the Travaux de l'AIG Vol. 37 (2011) and 38 (2013).

Awards, anniversaries, obituaries

The following medals and prices have been awarded:

- Levallois Medal to Ruth Neilan, USA (2011);
- Bomford Prize to Johannes Boehm, Austria (2011);

- Young Author Award to Elizabeth Petrie , UK (2011);
- Young Author Award to Thomas Artz (2013);
- Young Author Award to Manuela Seitz (2013).
- 53 Travel Awards to young scientists for participation in 15 IAG sponsored symposia.

The following anniversaries were celebrated with IAG participation:
- 150th anniversary of the Swiss Geodetic Commission, Zürich, Switzerland, 10 June 2011;
- 150th anniversary of the Arc Measurement in the Saxony, Dresden, Germany, 1 June 2012;
- 150th anniversary of the Central European Arc Measurement, Vienna Austria, 14 September 2012;
- 150th anniversary of the Austrian Geodetic Commission, Vienna, Austria, 7 November 2013;

Obituaries were written for former IAG officers and outstanding geodesists who passed away:
- 2011: A. Bjerhammar, Sweden; I. Fejes; Hungary; A. Finkelstein, Russia, S. Henriksen, USA;
- 2012: K.-P. Schwarz;
- 2014: C. C. Tscherning.

Opening Session of the IAG Scientific Assembly on the occasion of the 150th Anniversary of IAG, Potsdam, Germany, 1-6 September 2013

IAG Presidents Gerhard Beutler (2003-2007), Wolfgang Torge (1991-1995), Ivan I. Mueller (1987-1991), Chris Rizos (2011-2015), Michael Sideris (2007-2011) and Secretaries General Hermann Drewes (2007-…) and Claude Boucher (1991-1995) at the IAG Scientific Assembly, Potsdam, Germany, 1-6 September 2013