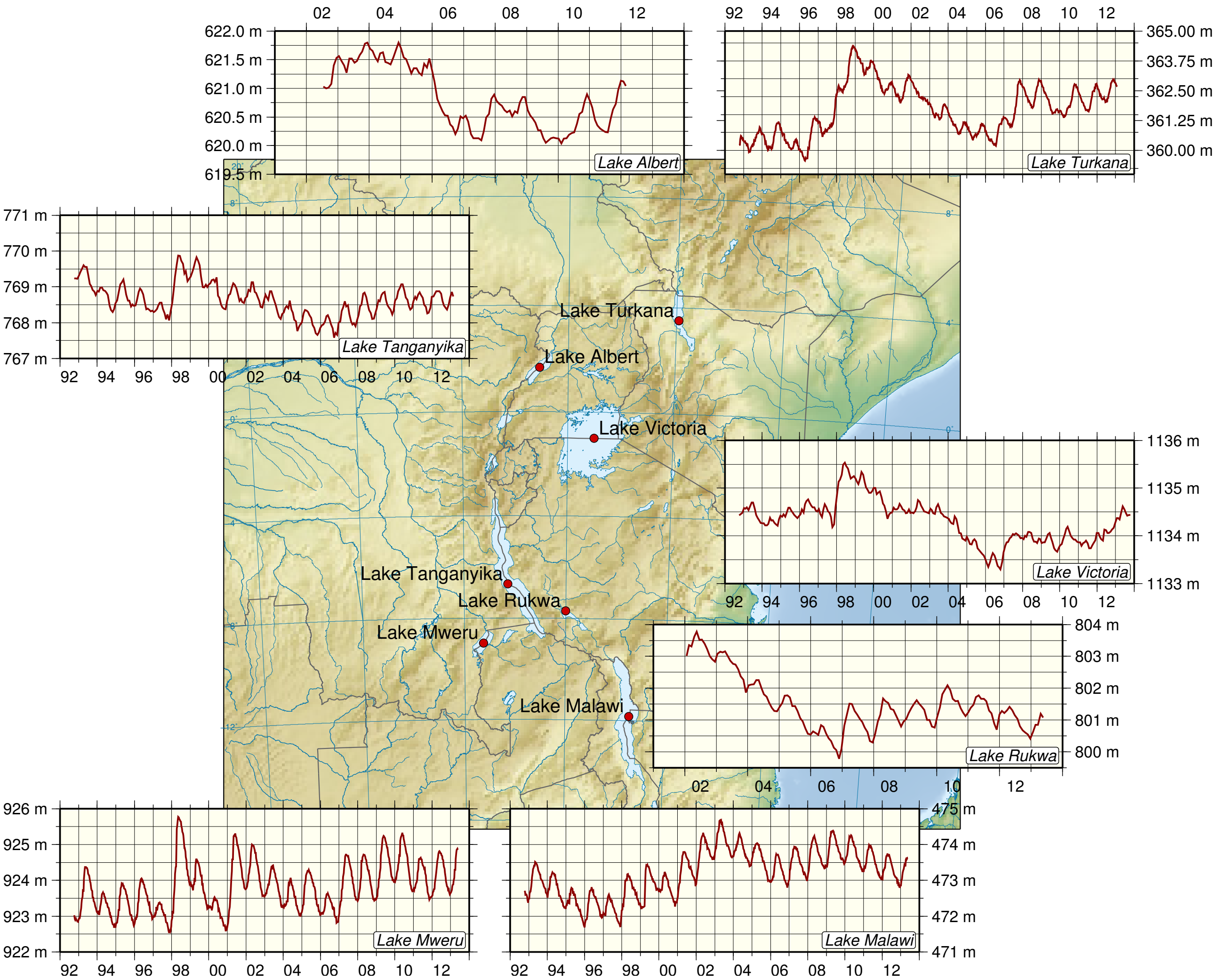
Deutsches Geodätisches Forschungsinstitut

ANNUAL REPORT
2013



The "Database for Hydrological Time Series of Inland Waters" (DAHITI) provides water level time series for lakes, rivers, and reservoirs using multi-mission satellite altimetry. This image shows time series for seven lakes in Central Africa which were estimated using a Kalman filter approach.

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The Institute

DGFI - Basic geodetic research for Earth system science

The Deutsches Geodätisches Forschungsinstitut (DGFI) is an autonomous research institute at the Bavarian Academy of Sciences (BAdW) in Munich. It was established in 1952 based on a decision of BAdW's German Geodetic Commission (DGK). DGFI is funded by the Free State of Bavaria and regularly supervised by an international scientific council.

Over more than six decades the institute has performed notable and internationally recognised basic geodetic research, and today the acronym DGFI is well-known within the geoscientific community all over the world. The institute is strongly cross-linked with other institutions and has continuously been involved in various national and international activities. Intensive collaborations exist in particular within the framework of the international scientific organisations IUGG (International Union of Geodesy and Geophysics), IAU (International Astronomical Union) and IAG (International Association of Geodesy). DGFI recognises the outstanding role of the IAG services for science and practice and co-operates in these services as data, analysis and combination centre.

Scientists of DGFI have taken leading positions and supporting functions in IAG's Commissions, Services, Projects, Working and Study Groups, and in its Global Geodetic Observing System (GGOS). Furthermore, DGFI staff is prominently involved in the management of international scientific organisations, such as the European Geosciences Union (EGU) and the IAU. DGFI also participates in research programmes and bodies of the European Union (EU) and the European Space Agency (ESA). It co-operates in several United Nations' (UN) and intergovernmental institutions and activities.

On the national level, DGFI has been a member of the Forschungsgruppe Satellitengeodäsie (FGS) since many years. FGS is a follow-on co-operation of the former DFG-Sonderforschungsbereich SFB 78, closely affiliated with the Geodetic Observatory Wettzell in the Bavarian Forest. In the framework of FGS, DGFI co-operates with the TU München (Institut für Astronomische und Physikalische Geodäsie [IAPG], Forschungseinrichtung Satellitengeodäsie [FESG]), the Bundesamt für Kartographie und Geodäsie in Frankfurt/Main (BKG) and the Institut für Geodäsie und Geoinformation of the University of Bonn (IGG).

Since 2010, DGFI is connected with IAPG, FESG, and the section "Erdmessung" of BAdW's Kommission für Erdmessung und Glaziologie (KEG) within the framework of the Centre of Geodetic Earth System Research (CGE). Since 2011, the institutions forming the CGE work together according to a joint research and development programme, guided by the vision that geodesy can provide a high-precision, consistent and long-term valid metric for Earth system sciences. The research and development programme is realised by scientific collaborations across the institutions and within joint third-party funded projects. Within the first years of its existence, CGE has reached good visibility on the national and international level.

Through new technological achievements in Earth observation systems, in particular in satellite technology, and in the field of scientific computing, geodesy has developed towards an important discipline for Earth system research during the last decades. In the context of global change, geosciences are facing new challenges. Large-scale changes in the Earth system come along with implications on environment and living conditions, and catastrophic consequences of natural disasters become more frequent. Research of processes and interactions in the system Earth is of increasing importance. This fundamentally requires reliable observations of changes on various spatial scales over long time spans. Geodesy contributes to Earth system research in particular by providing highly precise geometrical and physical parameters from terrestrial, air-borne and satellite-based observation systems. Time series of a variety of geodetic parameters have been determined for many decades. As geodynamic processes and environmental change map into the temporal variations of these parameters, their analysis provides valuable information of long-term changes in the Earth system. The fundamental backbone for referencing the observations and, thus, for enabling a reliable interpretation over long time spans is a consistent global and long-term stable reference system.

As ITRS Combination Centre, DGFI regularly computes solutions for the highly precise International Terrestrial Reference Frame (ITRF) that is a prerequisite for the use of global navigation and positioning systems and surveying. For its realisation, IAG requires an accuracy of 1 mm for the positions of worldwide distributed observing stations and of 0.1 mm per year for their linear velocities. This accuracy is necessary in order to detect very small changes in the Earth system (e.g., the global mean sea level rise of about 3 mm per year) reliably.

DGFI possesses unique competence on several geodetic research fields, in particular in the fields of reference frame determination and satellite altimetry. The institute holds a leading position in the realisation of global and regional horizontal and vertical terrestrial reference systems and of the celestial reference system from a combined analysis of various geometrical space geodetic observing systems. In the field of satellite altimetry, DGFI computes global and regional variations of the sea level on different time scales from all altimetry missions since 1992 and investigates variations of ocean currents. Further prominent research topics of DGFI include theoretical and applied aspects of gravity field determination and ionosphere research.

DGFI research programme

The scientific activities of DGFI are oriented towards basic geodetic research. They are embedded in the overall topic “Geodetic Earth System Research” of CGE. The CGE programme is divided into the research areas (1) Geometric Techniques, (2) Gravity Field, (3) Geodetic Earth System Modelling, (4) Methodological Foundations and (5) New Technologies. Research activities within CGE are coordinated by scientists of the contributing partners.

According to the current research programme, the DGFI research areas are consistent with the research areas (1) to (4) of the CGE programme:

1. Geometric Techniques
2. Gravity Field
3. Geodetic Earth System Modelling
4. Methodological Foundations

The DGFI research programme was set up for the period from 2011 to 2014. In November 2010, it was evaluated and approved by an international scientific council (Wissenschaftlicher Beirat).

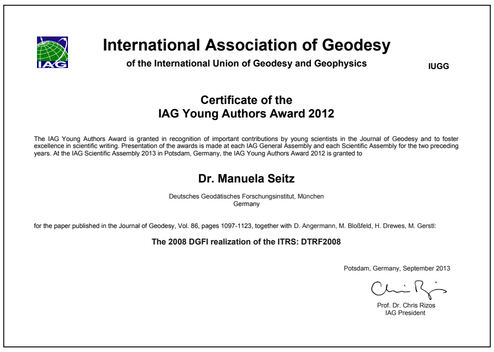
Dynamic processes and interactions within and between individual components of the Earth system (e.g., atmosphere, hydrosphere, solid Earth) map into temporal variations of geodetic parameters that describe the rotation, the gravity field and the surface geometry of the Earth. Thus, the investigation of time series resulting from the analysis and combination of geodetic observations delivers important information and contributes to Earth system research. On the one hand, geodetic research at DGFI aims at a further improvement of accuracy and consistency of geodetic parameters related to the Earth’s geometry (research area 1) and its gravity field (research area 2). This work is related to and benefits strongly from DGFI’s activities in international services. On the other hand, DGFI aims at the interpretation of geodetic parameters and their application for Earth system research in interdisciplinary co-operations. Accordingly, research area 3 is dedicated to geodetic contributions to Earth system science. One of the main tasks in research area 3 is the application of geodetic data in order to enhance the understanding of dynamical processes in the Earth system and to develop and improve respective empirical and physical models. In particular, the data analysed and provided by DGFI (which are to a very large extent based on global satellite observations) contribute information about those components of the Earth system in which processes act on large spatial scales. The geodetic observations allow for conclusions with respect to large-scale mass redistributions and exchange processes of angular momentum that involve temporal changes of gravity field, surface geometry, and rotation of the Earth. Furthermore, by suitable combination of observation techniques with different sensitivity for different processes and numerical models DGFI aims at the separation of integral parameters into contributions of individual system components and underlying dynamical processes. Finally, the cross-cutting research area 4 provides methodological foundations and support for the other research areas by the development and provision of tools, common standards and the necessary infrastructure.

Special occasions in 2013

In recognition of outstanding achievements and top-class research results several DGFI scientists were awarded with scientific prizes in 2013:

Dipl.-Ing. Mathis Bloßfeld received the *Bernd-Rendel-Preis 2013* of the German Research Foundation (DFG) for outstanding young researchers in geosciences in recognition of quality and originality of their research work. Particular importance is placed on the research approach and the candidate's scientific potential.

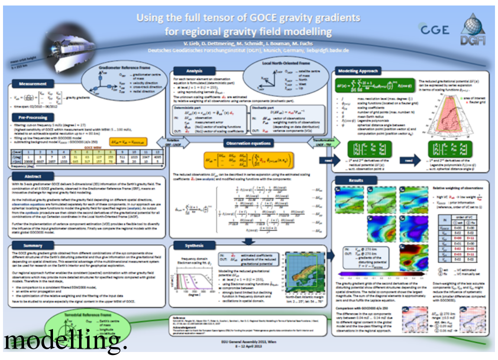
Prof. Dr.-Ing. Michael Schmidt received the *Kaarina and Weikko A. Heiskanen Award 2013* of the Division of Geodetic Science of the Ohio State University, USA. This award is conferred annually to a person who has most successfully forwarded the cause of geodesy and strengthened the reputation of the Division of Geodetic Science in the School of Earth Sciences in the field of geodesy.



Dr.-Ing. Manuela Seitz was granted the *IAG Young Authors Award 2012* of the International Association of Geodesy on the occasion of the IAG Scientific Assembly 2013 in Potsdam, Germany, for her outstanding publication in the Journal of Geodesy: Seitz, M., D. Angermann, M. Bloßfeld, H. Drewes, M. Gerstl: The 2008 DGFI Realization of the ITRS: DTRF2008.

Dipl.-Ing. Mathis Bloßfeld was awarded with the *First prize of the IAG Students' Best Talk Award 2013* in recognition of the two most excellent oral presentations by young scientists at the IAG Scientific Assembly 2013, entitled (1) Bloßfeld, M., M. Seitz, D. Angermann: Epoch reference frames as short-term realizations of the ITRS - recent developments and challenges; (2) Bloßfeld, M., V. Stefka, H. Müller, M. Gerstl: Satellite Laser Ranging – a tool to realize GGOS?

M.Sc. Wenjing Liang received the *Second prize of the IAG Students' Best Talk Award 2013* in recognition of her excellent oral presentation as young scientist at the IAG Scientific Assembly 2013, entitled: Liang, W., M. Schmidt, D. Dettmering, U. Hugentobler, et al.: Combination of GNSS observations and electron density profiles from radio occultation data for the determination of a multi-scale regional ionosphere model.



Dipl.-Ing. Verena Lieb was granted the *Outstanding Student Poster Award 2013* of the European Geosciences Union (EGU) for the best poster presentation in the Division Geodesy in acknowledgement of the scientific quality of her research and the way of presenting her work at the EGU General Assembly 2013 in Vienna, Austria: Lieb V., J. Bouman, D. Dettmering, M. Fuchs, M. Schmidt: Using the full tensor of GOCE gravity gradients for regional gravity field modelling.

Prof. Dr.-Ing. Michael Schmidt was elected president of the Division Geodesy of the European Geosciences Union (EGU) for a preiod of two years in 2013. For the same period Dr. Johannes Bouman was re-elected vice-president of the division.

1 Geometric Techniques

The work within this research field relies on the space geodetic observation techniques Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) like GPS, GLONASS or Galileo, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) as well as satellite altimetry. The research is primarily concerned with the analysis and combination of the space geodetic observations mentioned above in order to determine geometric parameters describing the shape and orientation of the Earth. In addition also the low degree spherical harmonic coefficients of the Earth's gravity field are studied as they are directly correlated with the datum parameters for the realization of the terrestrial reference system. The tasks cover the full processing chain from the original observations to the generation of geodetic results and products. They are divided into four major themes:

1.1 Observation systems, data acquisition and provision
1.2 Model development and analysis of the space geodetic observations
1.3 Analysis and refinement of combination methods
1.4 Computation of global and regional reference frames

The work in this research field benefits from the DGFI engagement in international scientific services of the International Association of Geodesy (IAG). The institute operates - mostly by virtue of long-term commitments - data centres, analysis centres, and combination centres. The following activities are closely related to the research field "Geometric Techniques":

- *IGS Regional Network Associate Analysis Centre for SIRGAS (RNAAC-SIR)*
- *IGS Tide Gauge Benchmark Monitoring Analysis Centre (TIGA)*
- *ILRS Global Data and Operation Centre*
- *ILRS Analysis Centre*
- *IVS Analysis Centre*
- *IVS Combination Centre (jointly with BKG, Frankfurt/Main)*
- *ITRS Combination Centre within the International Earth Rotation and Reference Systems Service (IERS)*

Besides the activities listed above, scientists of DGFI took over various responsibilities and functions in IAG (see Sect. 5.4). The engagement in the IAG Services and Commissions is a backbone of this research field. It ensures the direct access to the original data of the space geodetic techniques and to the products generated by the scientific services. This is on the one hand of great benefit for the research activities in this field, and on the other hand the basic research performed at the institute ensures a high-quality generation of geodetic products.

1.1 Observation systems, data acquisition and provision

Operation of permanent GNSS stations

Since 1998, DGFI has installed 21 continuously operating GNSS stations in Europe and South America; 14 of these stations are still under the responsibility of DGFI, while the others were formally transferred to local institutions to facilitate their operability. Five stations were installed along the Bavarian Alps within the framework of the European Union's Territorial Cooperation (INTERREG III) Alpine Space Project for detection and monitoring of crustal deformations in the Alpine region (ALPS-GPS

QUAKENET). Although this project already ended in 2007, the DGFI stations continue delivering measurements and are included in different European geodetic projects. The other stations contribute to various international initiatives, especially to the IGS Tide Gauge Benchmark Monitoring (TIGA), the IGS Multi-GNSS Experiment (MGEX), and the regional densification of the ITRF in Latin America (SIRGAS).

ILRS Global Data and Operation Centre

Since the foundation of the International Laser Ranging Service (ILRS) in 1998 the EUROLAS Data Center (EDC) at DGFI acts as one of two global ILRS data centres, besides the Crustal Dynamics Data Information System (CDDIS) at NASA.

In 2009, the EDC became an ILRS Operation Centre (OC) after the implementation of the so-called Consolidated Ranging Data (CRD) format. The OC has the duty to ensure that submitted data sets have the correct CRD format. Furthermore, the final transition to the new official CRD format took place at May 2, 2012.

EDC runs several mail exploders for the exchange of information, data and results. The Consolidated Prediction Format (CPF) files (37304 in 2013) for 75 satellites are exploded automatically on a daily and sub-daily basis and stored at the FTP server (*ftp://edc.dgfi.badw.de*).

The following mailing lists are maintained by the EDC:

- SLR-Mail (75 messages in 2013)
- SLR-Report (1162 messages in 2013)
- Urgent-Mail (20 messages in 2013)
- Rapid-Service-Mail (13 messages in 2013)

In 2013, 39 SLR stations observed 73 different satellites. A total of six new satellite missions were tracked by SLR stations, namely Glonass-131, IRNSS-1A, Saral, STSAT-2C, Swarm-A, Swarm-B, and Swarm-C. Figure 1.1 shows the overall amount of normal point data.

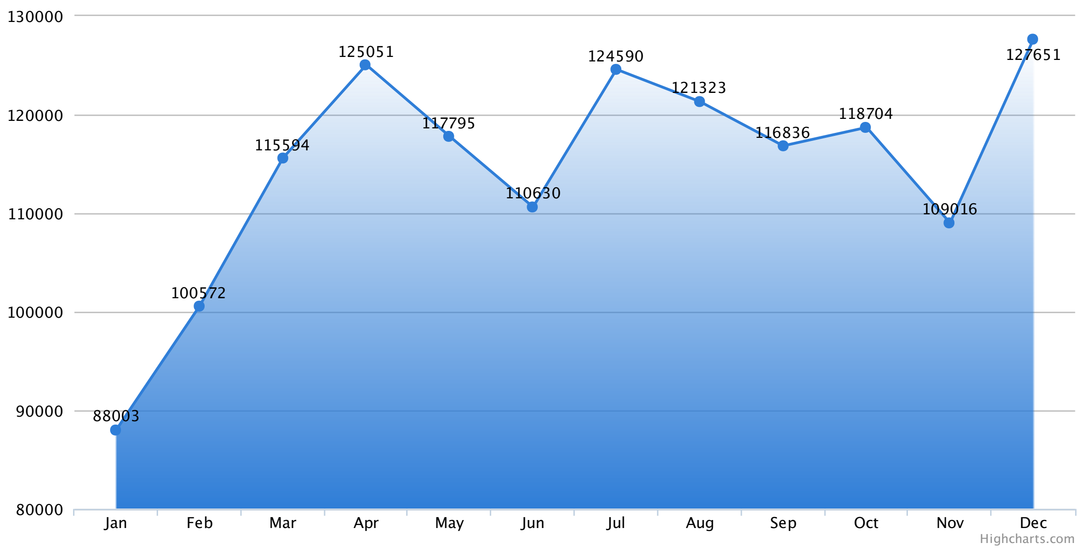


Fig. 1.1: *Number of monthly normal points in the CRD format.*

1.2 Model development and analysis of the space geodetic observations

By virtue of long-term commitments DGFI acts as official Analysis Centre both within the International Laser Ranging Service (ILRS) and the International VLBI Service for Geodesy and Astrometry (IVS). These responsibilities require a continuous analysis of SLR and VLBI data and a timely generation of geodetic products for these two services on a regular basis (e.g., daily or weekly). The obtained observation and parameter time series are also the basis for various research activities at DGFI like, e.g., the combination of space geodetic observations (see Sect. 1.3) and the computation of geodetic reference frames (see Sect. 1.4). The activities also require a regular update of the software packages (DOGS-OC for SLR; DOGS-RI/OCCAM for VLBI) according to the latest version of processing standards and models.

SLR multi-satellite solution

Besides the operational SLR data analysis within the ILRS, DGFI analyzes observations to ten different passive spherical satellites. These satellites are LAGEOS1/2 (LA1/2), Etalon1/2 (ET1/2), Stella (STE), Starlette (STA), Ajisai (AJI), Larets (LTS), LARES (LRS) and BLITS (BTS). The standard solution setup of the ILRS to estimate coordinates and EOP includes only observations to LA1/2 and ET1/2. The question is whether other satellites than LA1/2 and ET1/2 can contribute to the TRF and EOP products.

DGFI computes a multi-satellite solution with up to ten different satellites, that are combined at the normal equation level using a variance component estimation. Figure 1.2 shows the RMS of the estimated translation and scale parameter time series which are obtained from an epoch-wise performed 7-parameter similarity transformation w.r.t. the updated SLRF2008 reference frame for three different solution types. The LA1/2 solution shows the largest RMS. If the LRS observations are included, the noise of all transformation parameters is reduced. If more satellites are considered, only the z-translation benefits. In addition to the noise of the transformation parameter time series (common motion of all stations), also the transformation residuals decrease. Figure 1.3 shows the global mean weighted RMS (WRMS) values for all stations separated into north, east and height components for the three different solution types. If LRS is included, the WRMS value is improved by about 15% as regards the horizontal components, but remains almost constant as regards the height. In the 10-satellite solution, the WRMS is further reduced by about 20%. The significant improvement of the horizontal components is caused by a much better sky coverage above a station due to the inclusion of more satellites.

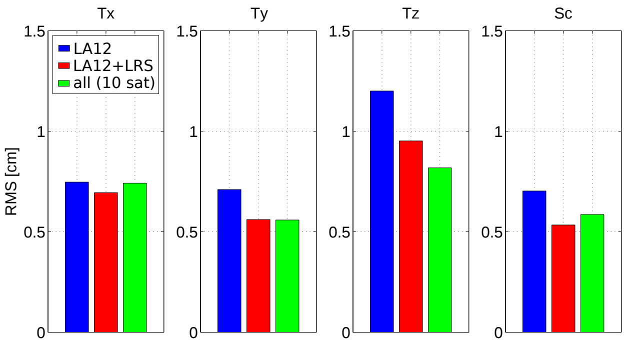


Fig. 1.2: RMS of translation and scale parameters of the solutions LA1/2 (blue), LA1/2+LRS (red) and 10 satellites (green) w.r.t. SLRF2008. The RMS values are obtained from the parameter time series of a weekly 7-parameter similarity transformation.

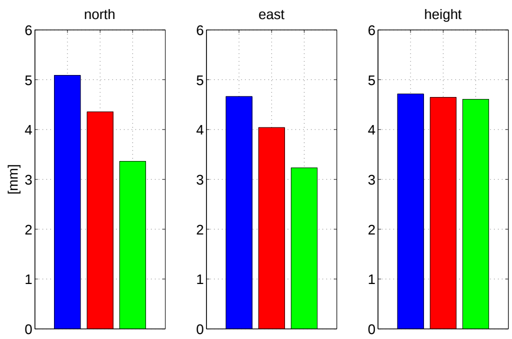


Fig. 1.3: North, east and height component of the mean WRMS values of all station coordinates for three different solution types (LA1/2: blue, LA1/2+LRS: red, 10 satellites: green).

Harmonization and calibration of satellite altimeter measurements

In order to combine all available altimeter missions and to use them in a multi-mission scenario a careful harmonization and calibration of all data sets is necessary. At DGFI, this is done by a multi-mission crossover analysis (MMXO) that allows to correct each single measurement for possible radial errors. This is the basis for deriving high-quality sea level information with optimal spatial and temporal resolution.

In 2013, a new version of MMXO was computed: MMXO14. This version comprises three important changes concerning the altimeter mission data base:

- At the end of February, the Indian/French mission **Saral** equipped with the radar altimeter AltiKa was launched. First data were already available in April for the calibration/validation team. The mission uses the old Envisat orbit and provides data at one frequency. In contrast to all other radar altimeter missions, AltiKa uses Ka- instead of Ku-band and therefore minimizes the impact of ionospheric effects.
- **Jason-1** finished its first full 406-day repeat cycle of its geodetic mission phase (GM) in summer 2013 shortly before the contact to the satellite got lost. Jason-1 had to be passivated and decommissioned on July 1st, terminating the mission after 11.5 years of operation.
- DGFI was granted access to the IGDR (Interim Geophysical Data Record) data set from the Chinese altimeter mission **HY-2A** which was launched in 2011 (many thanks to the National Satellite Ocean Application Service NSOAS!).

Both new missions (Saral and HY-2A) were included in MMXO14. The first results for Saral look very promising, although the radiometer needs some fine-tuning and a high-level sea state bias model is not available at the moment. The radial errors show a mean offset of only -6.7 cm w.r.t. TOPEX and the variance of about 1.3 cm is comparable to other missions (Jason-2: 1.0 cm / Jason-1 GM: 1.3 cm / ERS-2: 2.0 cm). Figure 1.4 shows the estimated radial errors for Jason-2 (red), Jason-1 GM (blue), Cryosat BaselineB (black), and Saral (green) for a time period of half a year.

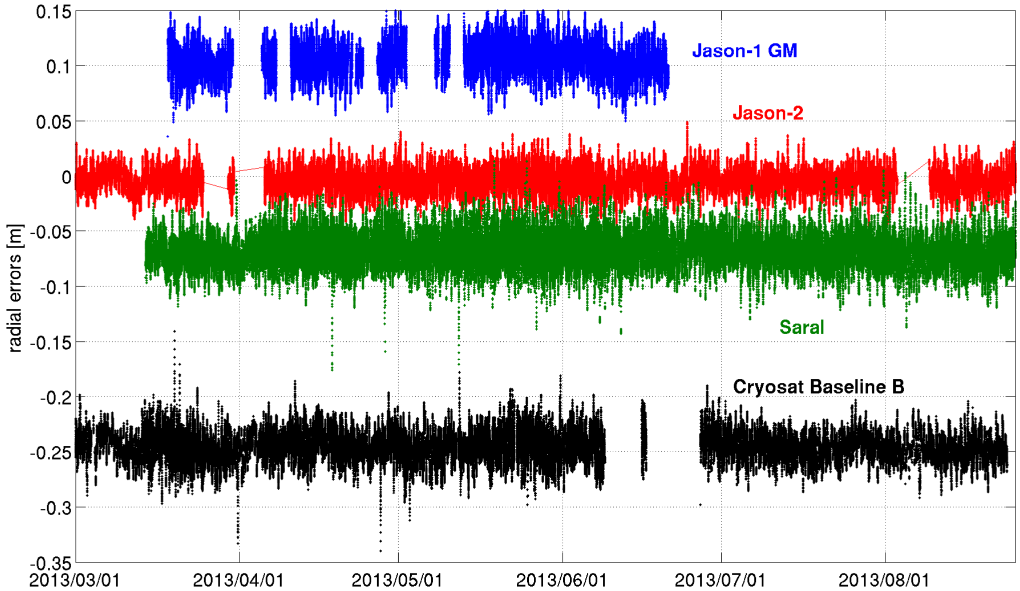


Fig. 1.4: *Radial errors for four different altimeter missions in 2013 w.r.t. TOPEX. The noise level of Saral is comparable with the other missions, and Saral only shows a small offset with respect to TOPEX.*

For HY-2A, the variance of the radial errors of about 1.8 cm for the most recent data is also very promising. However, some cycles of this mission suffer from significant large (but not constant) time-tag biases, making the use of the affected data difficult. Moreover, the range bias shows a long-term negative trend of about -0.3 m/year (cf. Fig. 1.5). For a combination with other missions it is essential to account for this effect.

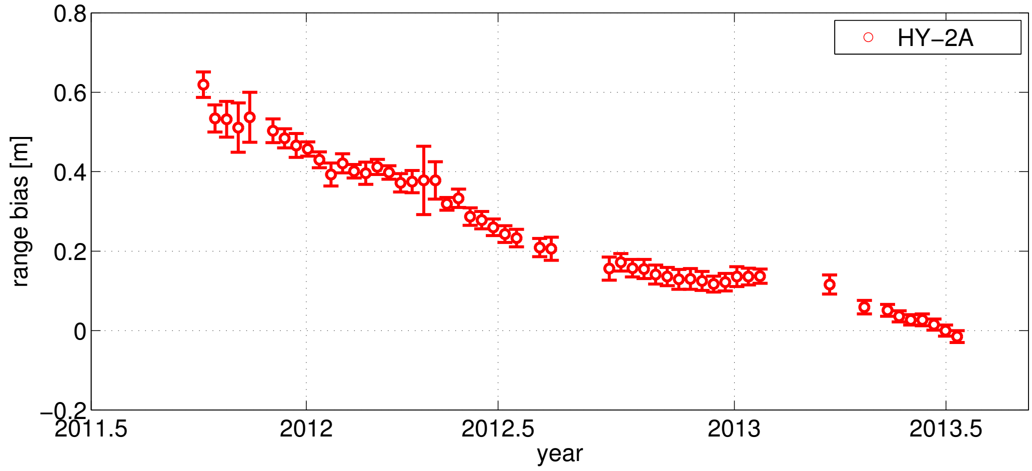


Fig. 1.5: *Range bias of HY-2A (w.r.t. TOPEX)*

Influence of time-variable gravity models on satellite orbits and regional sea level trends

MMXO is a convenient tool to perform quality assessment of different orbit solutions and to check their consistency. In cooperation with GFZ, CNES/GRGS, and CLS we investigated the influence of several gravity models with different handling of time-variable gravity on altimeter orbits and on the estimation of regional and global sea level trends. The analysis shows a strong impact of an incorrect handling of time-variable gravity (e.g. extrapolation of GRACE results to pre-GRACE time periods) on the orbits. The effect mainly affects the y-component of the center-of-origin realization (cf. Fig. 1.6) and consequently produces an east-west pattern in the orbit errors. This leads to strong orbit-dependent differences in the regional mean sea level trends of up to 3 mm/year and to mission differences in the absolute regional sea level of up to 5 cm for certain time periods. More information can be found in Rudenko et. al (submitted) which currently is in the review process.

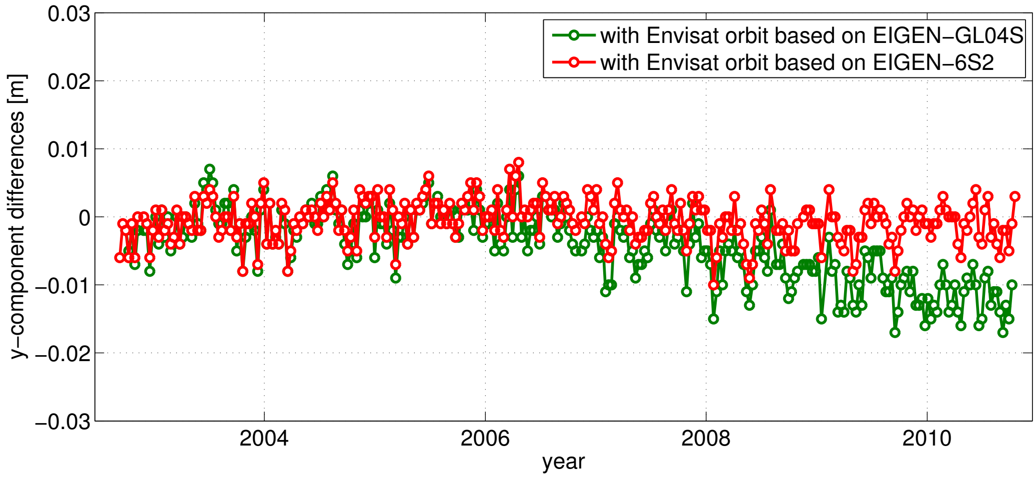


Fig. 1.6: *Differences in the realization of the origin (y-component) between Envisat and Jason-1 using two different orbit solutions for Envisat based on different global gravity fields. The two gravity models differ in the handling of time-variable gravity: in contrast to EIGEN-6S2, EIGEN-GL04S contains no drift terms for the geopotential coefficients.*

1.3 Analysis and refinement of combination methods

Since many years, the combination of space geodetic observations is a major research topic at DGFI. The combinations are performed on the level of datum-free normal equations with the DGFI software DOGS-CS. This software is continuously updated to enable the implementation of refined methodologies (e.g., epoch combinations, extended parameterization of non-linear station motions). The work within this theme provides the basis for the computation of global and regional reference frames (see Sect. 1.4) and for the contribution to various IAG services (e.g., ITRS Combination Centre, IVS Combination Centre jointly with BKG) and working groups (e.g., IERS WG "Combination at the Observation Level", Joint WG 1.4 of IAG Commission 1 and the IERS "Strategies for epoch reference frames").

DFG Research Unit "Reference Systems"

The Research Unit "Space-time reference systems for monitoring global change and for precise navigation in space" (FOR 1503) was granted by the German Research Foundation (DFG) in October 2011. DGFI is involved in two out of six projects. Project PN5 is devoted to "Consistent celestial and terrestrial reference frames by improved modeling and combination", and project PN6 aims at "Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters".

Project PN5

The goal of this joint project of BKG and DGFI is to deliver consistent celestial and terrestrial reference frames based on a common adjustment. Those reference frames are generated by combining constraint-free normal equations derived from VLBI, SLR and GNSS observations. The latter are processed homogeneously considering a unified set of processing standards. As radio source positions were fixed to their a priori values in the routine VLBI solutions submitted to IVS until the end of 2012, a VLBI reprocessing was started to have source positions included. Together with the operational solutions from 2013, a consistent VLBI time series covering two and a half years was available at the end of 2013.

In the case of SLR, weekly 10-satellite solutions are available for combination back to the year 2000 (see Sect. 1.2). The advantage of multi-satellite solutions is a better decorrelation of the estimated parameters compared to the standard LAGEOS1/2 solutions. The GNSS time series will probably be taken from the contribution of the Center for Orbit Determination in Europe (CODE) to the second IGS reprocessing campaign. This solution was estimated at TUM and covers the time span from 1994 to 2013.

For the combination of the long-term observation time series, advanced methods are developed at DGFI. Besides the realization of epoch reference frames (see below), long-term reference frames should benefit from the consideration of non-linear station motions. In order to allow for the estimation of periodic station signals besides the linear station velocities, the amplitudes of sine and cosine waves were implemented as additional parameters into DOGS-CS, DGFI's combination software.

Project PN6

PN6 is a joint project of TUM and DGFI. At DGFI, the impact of SLR on the geodetic datum parameters has been studied. For this purpose, an SLR multi-satellite solution has been computed (see Sect. 1.2) to assess the effect of different orbit heights, inclinations and observation time spans. Another focus of project PN6 was the influence of subdaily Earth rotation models on GPS solutions. When processing GPS observations the Earth rotation parameters (ERPs) are usually estimated once per day, whereas the subdaily part of the variations in the Earth rotation is fixed to an a priori model. Currently, a commonly accepted model based on an ocean model is recommended by the IERS. This IERS tidal model has errors of supposedly up to 20% due to uncertainties of the underlying ocean model, and different research groups have shown that these errors are propagated to all estimated parameters.

The DGFI approach is based on the transformation of GPS normal equation systems: free daily normal equations containing ERPs with 1-hour resolution are used as input data, these high-frequency ERPs can be transformed into tidal terms which then can be fixed to new a priori values, thus changing implicitly the underlying subdaily Earth rotation model. To study the influence of individual tidal terms on the solution we successively changed the a priori values of certain tidal terms in polar motion and compared the resulting GPS orbits, station coordinates and daily ERPs for a time interval of 13 years. The comparison reveals periodic changes in all estimated parameters with periods depending on the periods of the changed tidal terms. The dynamical reference frame realized by the GPS orbits is also affected: the whole satellite constellation shows periodic orientation variations, and each individual satellite shows periodic changes in the position of the orbit origin (Panafidina et al., accepted).

Combination methods for epoch reference frames (ERFs)

DGFI investigates the epoch-wise realization of global terrestrial reference frames (TRFs) through a combination of GPS, SLR and VLBI observations, which also contributes to the DFG Research Unit "Reference Systems". Due to the fact that the global networks vary from week to week (especially the SLR and VLBI networks), the realization of the geodetic datum is not as stable as in the case of conventional TRF realizations (multi-year reference frames, MRFs). One possibility to increase the ERF datum stability is to enlarge the sampling interval of the ERFs. The longer the time period, the more stations can be considered for each ERF solution. Consequently, the global coverage of the stations and the datum stability improves. To study the impact of the sampling interval, DGFI computed three different ERF time series with resolutions of 7, 14 and 28 days between 1998.0 and 2007.0. The solutions are based on an epoch-wise combination of GPS, SLR and VLBI normal equations (NEQs) using a variance component estimation for the estimation of weighting factors. The resulting time series were analyzed with respect to two aspects: (i) the stability of the realized datum and (ii) the ability of the different ERFs to monitor different kinds of individual station motions.

All ERF solutions are validated through a 7-parameter similarity transformation of selected GPS stations w.r.t. a combined MRF based on identical input data. Table 1.1 shows the amplitudes and phases of an

Table 1.1: *Annual amplitudes A and phases Φ of the time series of transformation parameters between the combined MRF and ERFs for different combination intervals (only a subset of GPS stations is used for the transformation). A and Φ are defined by $A\sin(2\pi(t-2000.0)+\Phi)$ with t in years and frequency f in cycles/year. The right column shows the RMS of the time series after removal of the annual signal.*

(a) *Translation parameters.*

parameter	A [mm]	Φ [days]	RMS [mm]
Tx (7d)	1.7 ± 0.2	193.4 ± 5.1	3.8
Tx (14d)	1.8 ± 0.3	211.9 ± 2.3	3.2
Tx (28d)	1.9 ± 0.2	219.0 ± 0.6	2.3
Ty (7d)	2.7 ± 0.1	303.7 ± 6.3	3.9
Ty (14d)	2.6 ± 0.1	304.3 ± 7.2	3.6
Ty (28d)	2.7 ± 0.0	306.3 ± 5.6	2.5
Tz (7d)	2.0 ± 0.6	245.9 ± 6.0	8.1
Tz (14d)	2.2 ± 0.5	245.9 ± 5.2	6.4
Tz (28d)	2.2 ± 0.4	257.4 ± 7.5	5.6

(b) *Rotation and scale parameters.*

parameter	A [mm]	Φ [days]	RMS [mm]
Rx (7d)	1.1 ± 0.0	299.6 ± 6.3	1.7
Rx (14d)	1.1 ± 0.0	298.9 ± 7.2	1.6
Rx (28d)	1.2 ± 0.0	302.4 ± 5.6	1.2
Ry (7d)	0.7 ± 0.1	356.7 ± 11.2	2.2
Ry (14d)	0.6 ± 0.2	11.0 ± 9.7	1.8
Ry (28d)	0.7 ± 0.1	24.7 ± 4.3	1.4
Rz (7d)	0.5 ± 0.0	120.9 ± 6.4	0.7
Rz (14d)	0.5 ± 0.0	119.9 ± 6.1	0.6
Rz (28d)	0.5 ± 0.0	122.4 ± 5.7	0.5
Sc (7d)	1.1 ± 0.2	183.3 ± 8.6	3.3
Sc (14d)	1.0 ± 0.2	188.2 ± 8.5	2.6
Sc (28d)	1.2 ± 0.1	190.8 ± 4.7	1.9

annual signal fitted to the time series of each transformation parameter. For all three temporal resolutions, the annual amplitudes are estimated with comparable magnitude. After the reduction of the annual signal from the time series, the RMS is computed and also summarized in Table 1.1. With an increasing time period, the noise of the transformation parameter time series is reduced. This is caused by an improved station network with a better global distribution and an improved number of available local ties (LTs). Especially the quality of the translation and scale values is important, as the transformation is conducted for a selected GPS subnetwork, whereas the origin and scale information from SLR and VLBI is transferred to that subnetwork only via LTs.

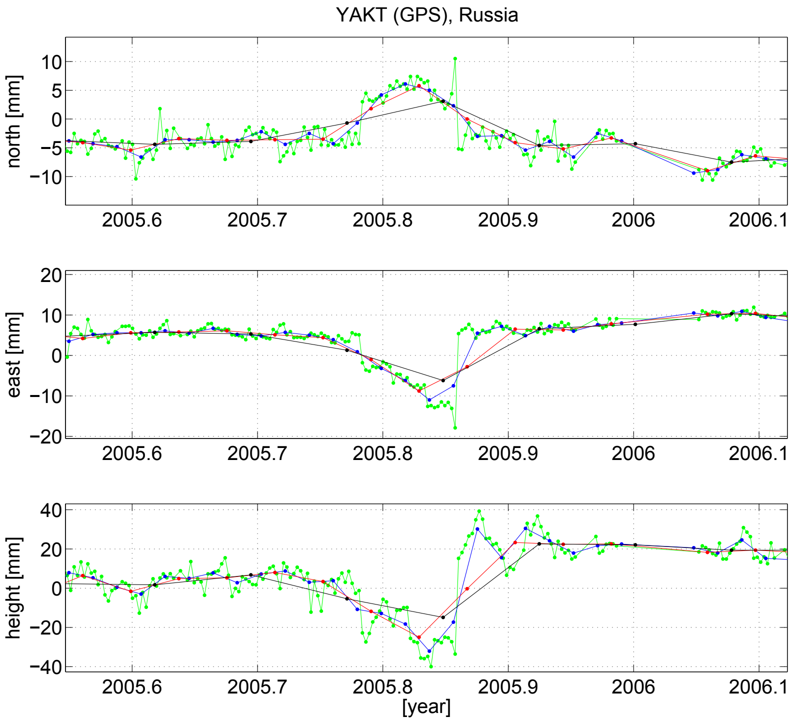


Fig. 1.7: Daily individual GPS-only (green) coordinate time series of the station Yakutsk (Russia). In addition, the 7-day (blue), 14-day (red) and 28-day (black) individual time series of the combined ERFs are shown. Figure from Bloßfeld et al. (submitted)

Figure 1.7 shows the transformation residuals of the GPS station Yakutsk (Russia) w.r.t. the three different ERF solutions. For comparison, also the daily GPS single-technique residuals are shown. The spurious short-term signals in the time series are approximated very well by the daily time series. The sampling of this short-term motion is a tool to evaluate the ability of the combined ERFs to approximate the station motion. The weekly ERF time series is the best approximation, whereas the 14-day ERFs already cause errors of up to 10 mm. The 28-day solution is not able to sample the short-term signal in any of the three components (errors increase up to 20 mm).

1.4 Computation of global and regional reference frames

DGFI hosts one of the three ITRS Combination Centres (ITRS CC) of the IERS. Compared to the ITRS CC at IGN (France) and JPL (USA) which perform a combination of solved parameters, the DGFI strategy is based on the combination of constraint-free normal equation systems. This approach allows a straightforward computation of the frame, as no similarity transformations are necessary. In consequence, the operator software impact (OSI) is much smaller than in the case of combined solutions. Besides the regular computation of ITRS realizations, the ITRS CC concentrates on research activities aiming at the improvement of ITRS realizations as regards accuracy, reliability and consistency of the products. Major activities in 2013 were investigations concerning epoch reference frames (see Sect. 1.3) and the simultaneous estimation of the terrestrial reference frame (TRF), the celestial reference frame (CRF) and EOP (see below). In the field of regional reference frame computations the activities concentrated on the processing of GPS data within the IGS Tide Gauge Monitoring (TIGA) Working Group and for SIRGAS, the Latin American reference frame (see below).

Consistent estimation of celestial and terrestrial reference frames

The IERS does not only provide the ITRF, but also an International Celestial Reference Frame solution (ICRF). Both frames and their integral EOP solutions are not fully consistent with each other nowadays as they are computed independently (see the discussion in the DGFI Annual Report 2012). This deficit can be overcome by a simultaneous estimation of TRF, CRF and the EOP series, which was performed by DGFI for the first time (Seitz M. et al. 2014). However, another requirement to reach high consistency is the processing of the individual observation data of the different space geodetic techniques according to the same processing standards. Large effort was spent to homogenize the processing of GNSS (at IAPG, TU München), VLBI (at IGG, University of Bonn) and SLR (DGFI). In 2013, a completely new setup of the solution could be realized using reprocessed data extended until 2012. With respect to VLBI, the benefit of the new data series is the inclusion of all VCS (VLBA Calibrator Survey) sessions. VCS sources represent about 60% of the ICRF (see Fig. 1.8), but are observed by the VLBA network only and often only within one session. Therefore, these sources are more sensitive to a simultaneous estimation of TRF and CRF than sources observed by global networks. Thus, the effects on the VCS sources were analyzed in detail. In 2013, the US National Radio Astronomy Observatory (NRAO) planned to schedule new VCS sessions based on the DGFI results. In future, these sessions will improve the quality of individual VCS sources but also the inter-correlation between the VCS sources as well as the connection of the VCS and the non-VCS part of the ICRF. The computation of the new TRF-CRF solution, including the currently available 24 VCS sessions, was finished in 2013. The detailed analysis of the results and the comparison with the previous solution is still ongoing.

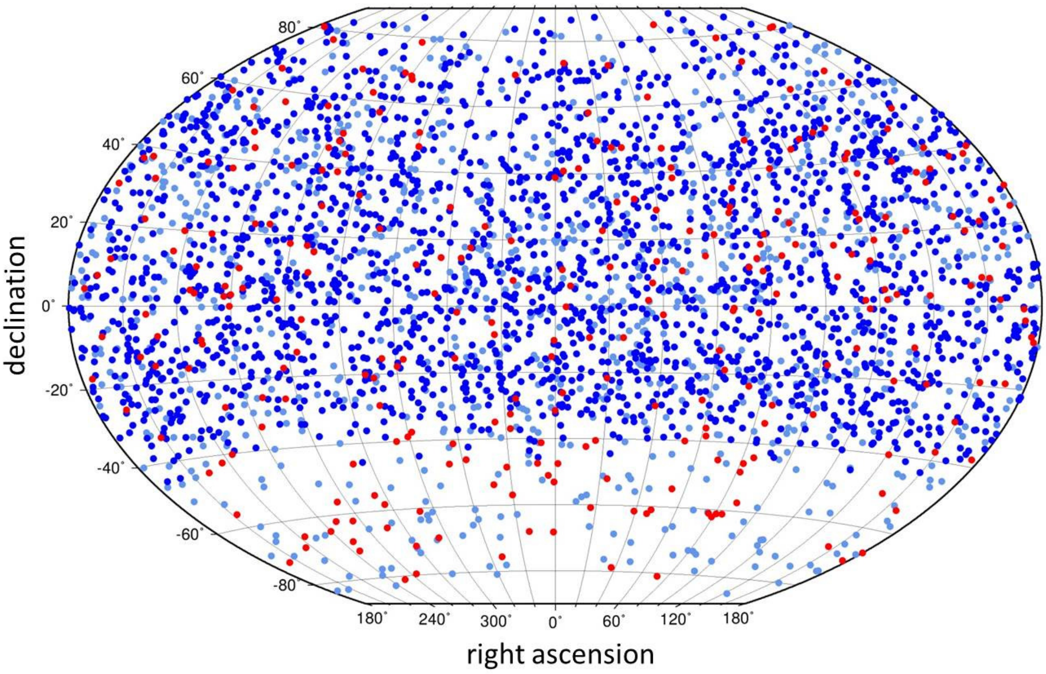


Fig. 1.8: Distribution of CRF sources in the CRF: non-VCS sources (light blue), VCS sources (dark blue), and defining sources (red). For declinations below about -45° no VCS sources are available, as the VLBA network cannot observe sources in the southern region due to its comparably small size.

SIRGAS reference frame computations

The realisation of SIRGAS (Sistema de Referencia Geocentrico para las Americas) is a regional densification of the ITRF. At present, it is composed of GNSS stations only; other geodetic space techniques like VLBI, SLR or DORIS are not involved yet. To guarantee the appropriate maintenance of the reference frame, SIRGAS comprises one core network (SIRGAS-C) as well as national reference networks (SIRGAS-N) realising densifications of the core network (see Fig. 1.9).

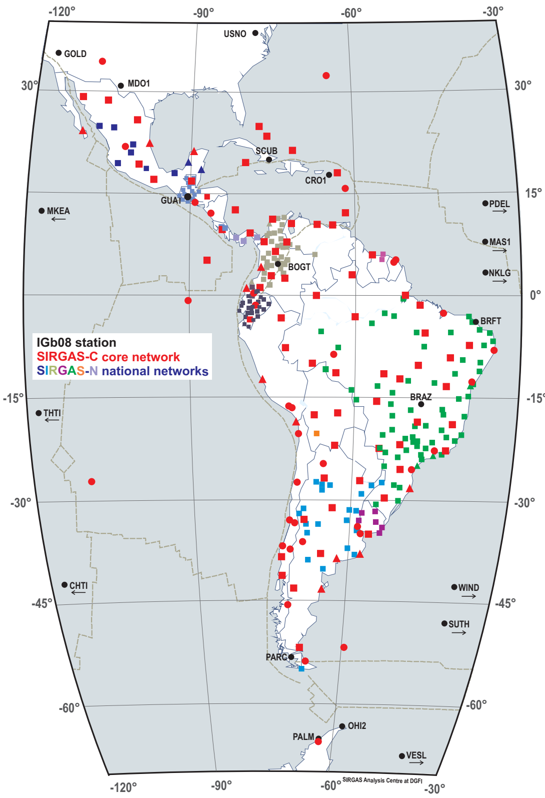


Fig. 1.9: *SIRGAS network as of December 2013.*

SIRGAS processing

The SIRGAS reference frame is computed weekly. The SIRGAS-C network is processed by DGFI since many years in accordance with its function as the IGS Regional Network Associate Analysis Centre for SIRGAS. The SIRGAS-N networks are computed by the SIRGAS Local Processing Centres, which operate under the responsibility of national Latin American organisations. At present, the SIRGAS Local Processing Centres are: CEPGE (Ecuador), 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 individual solutions are combined by the SIRGAS Combination Centres operated by DGFI and IBGE.

The SIRGAS processing centres follow unified standards for the computation of the loosely constrained solutions. These standards are generally based on the conventions outlined by the IERS and the GNSS-specific guidelines defined by the IGS. INEGI and IGN-Ar employ the software GAMIT/GLOBK; the other local processing centres use the Bernese GPS Software V.5.0. At the moment, the SIRGAS Local Processing Centres align their procedures to the standards described in the IERS Conventions 2010 and to the characteristics specified by the IGS for the second reprocessing of the IGS global network (*http://acc.igs.org/reprocess2.html*), with the exception that in the SIRGAS solutions the satellite orbits and clocks as well as the EOP are fixed to the final weekly IGS values. DGFI applies these new standards since July 2013 employing the Bernese GNSS Software V.5.2. It is expected that the other processing centres start delivering solutions based on the new standards in January 2014.

New SIRGAS multi-year solution SIR13P01

To estimate the kinematics of the SIRGAS reference frame, a cumulative (multi-year) solution is usually computed (updated) every year, providing epoch positions and constant velocities for stations operating longer than two years. As the introduction of ITRF2008 as the reference frame for the generation of the IGS products caused a discontinuity of some mm in the station position time series, the computation of multi-year solutions for the SIRGAS reference frame was discontinued until getting weekly ITRF2008-related normal equations covering a time span of at least three years. It was decided that SIRGAS will reprocess the entire SIRGAS network following IGS procedures and applying the new standards from

January 1997 to present. However, while the SIRGAS Local Processing Centres are not able to apply these new standards right now, a new multi-year solution was computed for the SIRGAS-C core network only, i.e., for the stations processed routinely by DGFI. Main objective of this multi-year solution is to identify possible secular effects caused by the Maule earthquake of February 2010 in the kinematics of the SIRGAS reference frame.

The input data for this new cumulative solution (called SIR13P01) are the weekly free normal equations covering the time span from April 2010 (GPS week 1580) to June 2013 (GPS week 1744). Since most of the existing ITRF stations in South America are affected by the earthquake in Chile in February 2010, further stations located in Europe, Africa, Oceania and North America (see Figure 1.10) are included in the SIRGAS computations to increase the availability of fiducial points. SIR13P01 includes positions and velocities for 108 SIRGAS core stations referring to the ITRF2008, epoch 2012.0. Its estimated precision is ±1.4 mm (horizontal) and ±2.5 mm (vertical) for the station positions at the reference epoch, as well as ±0.8 mm/yr (horizontal) and ±1.2 mm/yr (vertical) for the velocities. Stations CONZ (Concepción, Chile) and ANTC (Antuco, Chile) are excluded from these computations, because their post-seismic movements are very irregular and the modelling by means of constant velocities is not adequate.

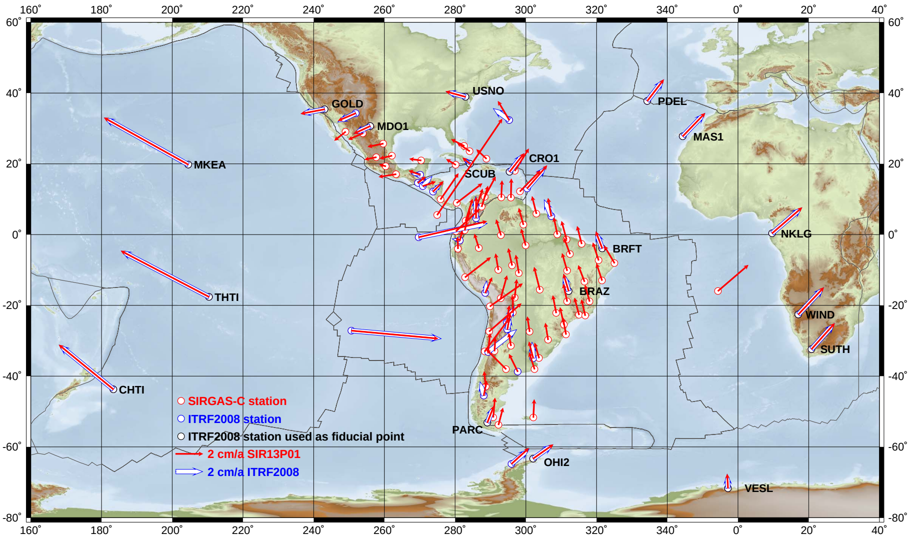


Fig. 1.10: Horizontal velocities of the SIRGAS multi-year solution SIR13P01: it covers the time span from April 2010 to June 2013, includes 108 SIRGAS core stations and refers to ITRF2008, epoch 2012.0.

To evaluate the reliability of the SIR13P01 solution, comparisons with ITRF2008 and the former solution SIR10P01 (computed before the Chilean earthquake in February 2010) were performed. The station positions and velocities of the older reference frame solutions (ITRF2008 and SIR10P01) differ significantly from the new realization (Sánchez et al., submitted). Major reasons for the disagreement are:

- ITRF2008 and SIR10P01 do not reflect the effects (co-seismic and post-seismic movements) caused by the earthquake of February 2010 in the southern part of South America;
- The weekly input solutions for ITRF2008 and SIR10P01 were computed with respect to the IGS05 frame, while SIR13P01 was computed with respect to the IGS08/IGb08 frame;
- The datum realisation in SIR10P01 and SIR13P01 is based on different fiducial points.

Acknowledgements

The operational infrastructure and results described in this report are only 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. The SIRGAS activities are strongly supported by the International Association of Geodesy (IAG) and the Pan-American Institute for Geography and History (PAIGH). More details about the activities and new challenges of SIRGAS can be found at *www.sirgas.org*.

Related publications

Bloßfeld M., Seitz M., Angermann D.: *Non-linear station motions in epoch and multi-year reference frames*, J Geod, 88(1): 45–63, DOI:10.1007/s00190-013-0668-6, 2014

Bloßfeld M., Štefka V., Müller H., Gerstl M.: *Satellite Laser Ranging - A tool to realize GGOS?* IAG Symposia Series, Sept. 2013, Potsdam, Germany, accepted

Bloßfeld M., Seitz M., Angermann D.: *Epoch reference frames as short-term realizations of the ITRS – Datum stability versus sampling*. IAG Symposia Series, Sept. 2013, Potsdam, Germany, submitted

Brunini C., Sánchez L.: *Geodetic reference frame for the Americas*. GIM International, 27(3):26–31. ISSN: 1566-9076, 2013

Dettmering D., Bosch W.: *Multi-mission crossover analysis: merging 20 years of altimeter data into one consistent long-term data record*. In: Ouwehand L. (Ed.) Proceedings of “20 Years of Progress in Radar Altimetry”, Sept. 2012, Venice, Italy, ESA SP-710 (CD-ROM), ISBN 978-92-9221-274-2, ESA/ESTEC, 2013

Dettmering D., Bosch W.: *Performance of ESA Cryosat-2 GDR data over open ocean*. In: Proceedings of the 3rd Cryosat Workshop, March 2013, Dresden, Germany, ESA SP-717, accepted

Horvath A., Dettmering D., Bosch W.: *Consistency and performance of CryoSat-2 LRM and SAR mode data over open ocean*. In: Ouwehand L. (Ed.) Proceedings of "20 Years of Progress in Radar Altimetry", Sept. 2012, Venice, ESA SP-710 (CD-ROM), ISBN 978-92-9221-274-2, ESA/ESTEC, 2013

Panafidina N., Hugentobler U., Seitz M.: *Interaction between subdaily Earth rotation parameters and GPS orbits*, IAG Symposia, Sept. 2013, Potsdam, Germany, accepted

Rudenko S., Dettmering D., Esselborn S., Schöne, T., Förste C., Lemoine J.-M., Ablain M., Alexandre D., Neumayer K.-H.: *Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends*. Advances in Space Research, submitted

Sánchez L., Seemüller W., Drewes H., et al.: *Long-term stability of the SIRGAS reference frame and episodic station movements caused by the seismic activity in the SIRGAS region*. In: Altamimi Z. and Collilieux X. (Eds.): Reference Frames for Applications in Geosciences, IAG Symposia 138: 153–161, DOI:10.1007/978-3-642-32998-2_24, 2013

Sánchez L.: *IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR). Report of activities 2012*. International GNSS Service Technical Report 2012, 111–120, 2013

Sánchez L., Drewes H., Brunini C., Mackern V., Martínez W.: *SIRGAS core network stability*. IAG Symposia, Sept. 2013, Potsdam, Germany, submitted

Seitz M., Angermann D., Drewes H.: *Accuracy assessment of the ITRS 2008 realization of DGFI: DTRF2008*. In: Altamimi Z., Collilieux X. (Eds.) Reference Frames for Applications in Geosciences, IAG Symposia 138: 87–93, DOI:10.1007/978-3-642-32998-2_15, 2013

Seitz, M., Steigenberger, P., Artz, T.: *Consistent Adjustment of Combined Terrestrial and Celestial Reference Frames*. In: Rizos, C., Willis, P. (eds.) Earth on the Edge: Science for a Sustainable Planet, IAG Symposia, 139:215–221, DOI: 10.1007/978-3-642-37222-3_28, 2014

2 Gravity Field

The Earth's gravitational field serves on the one hand as a reference surface for many dynamic processes in the Earth system, while on the other hand the observation of the gravitational field itself together with its variations in time characterize mass distribution and mass transport, which in turn describe geophysical processes. Typical examples of research areas for which the gravitational field is of importance are geodesy, geophysics, oceanography, and navigation. A central theme is therefore the observation, modelling and determination of the Earth's mean and time-variable gravitational field at all temporal and spatial scales.

In 2013, we focussed on three main topics related to the gravitational field. The first topic dealt with refinements in our regional gravity field analysis, exploiting satellite altimeter and airborne gravity data (Sect. 2.1). The time-variable gravity field (Sect. 2.2) was studied at different spatial scales using a combination of satellite laser ranging (SLR) and Gravity Recovery And Climate Experiment (GRACE) data, as well as combining GRACE and gravity gradients from the Gravity field and steady-state Ocean Circulation Explorer (GOCE). A final topic was height systems and their application (Sect. 2.3). Highlights of these three topics are discussed below.

2.1 Regional gravity fields

Regional gravity field modelling with altimeter data

Measurements from radar altimetry missions are the primary source for high-resolution marine gravity field modelling. Particularly, the geodetic mission phases with their dense ground track pattern can provide valuable information. In addition to the older data from GEOSAT and ERS-1, new measurements are available today: Jason-1 was flying on a geodetic orbit between May 2012 and July 2013; Cryosat-2 was launched in 2010 with a long repeat cycle of 369 days. Using these multi-mission data, a spatial resolution of about 6 km can be achieved.

The model approach we use for regional gravity modelling is set up as a series expansion in spherical basis functions, i.e. spherical scaling functions to describe disturbing potential differences with respect to a given background model. The unknown coefficients are estimated in an adjustment procedure, and variance component estimation is used to ensure an appropriate relative weighting between the different altimeter missions (and other input data types, if applicable).

The scaling functions are defined by their level j and a base b whose relation to the maximum spherical harmonic degree $l_{\max}$ is given by $l_{\max} = \text{int}[b^j - 1]$. The higher j, the sharper the scaling function and the higher the spatial resolution of the model. Until recently, we used a fixed base $b = 2$. Now, we allow different bases $b \leq 2$, which improves separation of frequency bands as they become smaller. This is particularly important in the high-frequency parts. For the results presented here, the model parameters were set to level $j = 20$ with base $b = 1.5$ (resulting in $l_{\max} = 3324$ and a spatial resolution of about 6 km), as this resolution fits best to the observation distribution. The estimated gravity anomalies in our test region, a 5° by 5° area in the Antarctic Ocean south of Australia, are plotted in the left graph of Fig. 2.1; the right plot shows the differences with respect to EGM2008.

The choice of level and base defines the spatial resolution of the gravity model and influences the consistency with EGM2008 (which is developed up to $l_{\max} = 2190$). The smallest differences compared to EGM can be achieved with $j = 18$ ($b = 1.545$), since the resolution ($l_{\max} \approx 2500$) of both models is similar in this case (keeping in mind the spatial smoothing characteristics of the Blackman functions that are used to reconstruct the gravity anomalies from the estimated series coefficients). The differences with respect to EGM reach 3.8 mGal RMS for such a model (cf. Fig. 2.2).

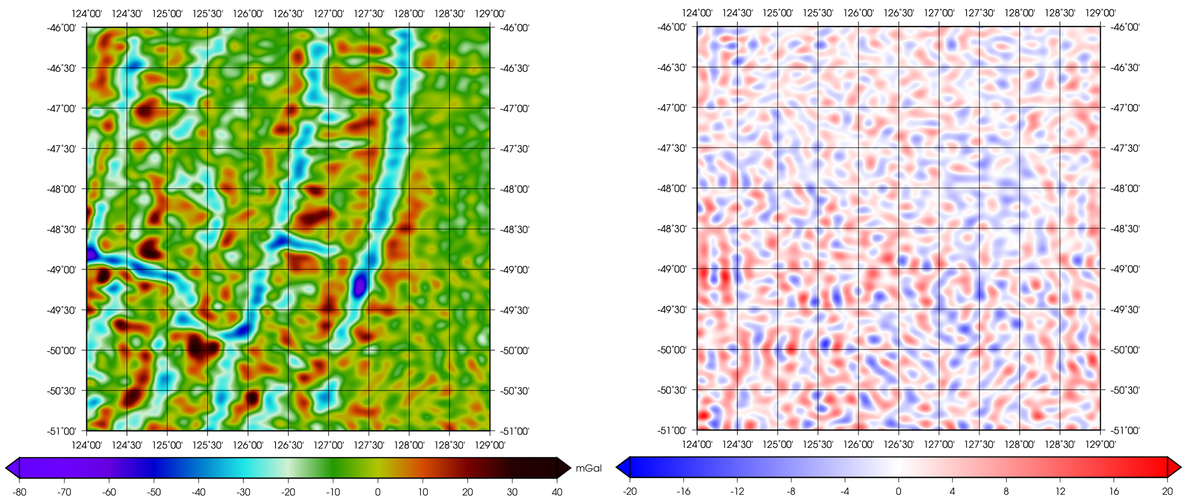
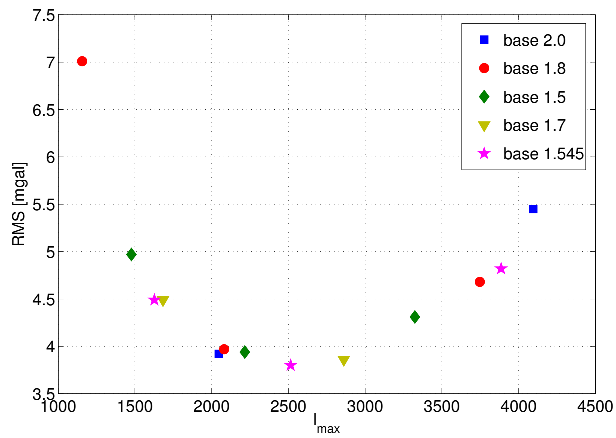


Fig. 2.1: Left: Gravity anomalies in mGal for level j=20 (b=1.5) estimated from altimeter SSH (sea surface height) of three different missions (ERS-1, Cryosat-2, and Jason-1 GM); Right: Differences wih respect to EGM2008 (d/o 2190). The model differences are randomly distributed with an RMS of 4.3 mGal and a maximum of 35 mGal. In the central part of the area the consistency is better: 3.6 mGal RMS and a maximum difference of 15 mGal.

Fig. 2.2: Influence of the model resolution on differences with respect to EGM2008 (d/o 2190). The smallest differences can be achieved for similar spatial resolutions.



Extended modelling for passes of geodetic altimeter missions

While multiple observations of altimeter profiles of repeat missions ensure noise reduction (due to averaging) and are free of radial offsets (due to cross-calibration), individual passes of a geodetic mission may be offset due to ocean variability, mismodelled inverted barometer effects or a hidden storm surge. Thus, the standard approach for estimating geopotential from altimeter data has been extended by considering a potential constant T_p as additional unknown for every single pass p, such that the (sub-)system of observation equations for those passes becomes

$$\mathbf{v} = \mathbf{s}T_p + \mathbf{A}\mathbf{x} - \mathbf{l} = \left[\mathbf{s} \mid \mathbf{A}\right] \cdot \begin{bmatrix} T_p \\ \mathbf{x} \end{bmatrix} - \mathbf{l} \tag{2.1}$$

with $\mathbf{x}$ being the vector of unknowns (coefficients of spherical base functions), $\mathbf{l}$ the observation vector of pass p (sea surface heights reduced by the dynamic ocean topography), $\mathbf{A}$ the design matrix and $\mathbf{s}' = (1, 1, ..., 1)$ a summation vector.

Accumulating the normal equations of many (hundred or thousand) passes would significantly increase the size of the normal equation system as a new T_p had to be introduced for every pass p of a geodetic mission. To avoid this, the pass-specific unknown T_p can be eliminated in advance. If the partitioning right hand of Eq. (2.1) is carried over to the normals and a weight matrix $\mathbf{W}$ is introduced for the observations, this yields

$$\begin{bmatrix} \mathbf{s'Ws} & \mathbf{s'WA} \\ \mathbf{A'Ws} & \mathbf{A'WA} \end{bmatrix} \cdot \begin{bmatrix} T_p \\ \mathbf{x} \end{bmatrix} = \begin{bmatrix} \mathbf{s'Wl} \\ \mathbf{A'Wl} \end{bmatrix} \tag{2.2}$$

Note that $c = \mathbf{s'Ws}$ and $\mathbf{s'Wl}$ are scalars while $\mathbf{s'WA}$ is a row vector with the same length as $\mathbf{x}$. Equation (2.2) can be reduced to block triangular form by left multiplying the first row with $\frac{1}{c}\mathbf{A'Ws}$ and subtracting this from the second row. This gives

$$\begin{bmatrix} \mathbf{s'Ws} & \mathbf{s'WA} \\ 0 & \mathbf{A'WA} - \frac{1}{\mathbf{c}}\mathbf{A'Wss'WA} \end{bmatrix} \cdot \begin{bmatrix} T_p \\ \mathbf{x} \end{bmatrix} = \begin{bmatrix} \mathbf{s'Wl} \\ \mathbf{A'Wl} - \frac{1}{\mathbf{c}}\mathbf{A'Wss'Wl} \end{bmatrix} \tag{2.3}$$

Now, the lower part is only related to the global unknowns $\mathbf{x}$ and can be solved independently of T_p.

The extended approach has been implemented within the scope of a master thesis [Pimenova 2013]. Test computations with data of the geodetic phases of ERS-1 and GFO as well as with Cryosat-2 data and validation against marine gravity data demonstrate a general improvement for the extended approach which is incorporated into the operational software.

Analysing DGFI's regional gravity modelling approach using airborne data

As many high-resolution gravity field observations, e.g. from terrestrial and airborne gravimetry, are not available globally, regional gravity field modelling is an important additional tool besides the global modelling of the Earth's gravitational potential. Airborne gravimetry observations, for example, may contain precise information of the Earth's gravitational potential at a spatial resolution of approximately 10 km (see Fig. 2.3) and, thus, deliver a valuable contribution to other gravity measurement techniques.

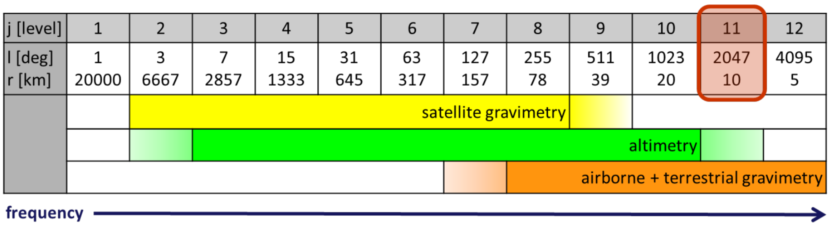


Fig. 2.3: Extract of the frequency spectrum which is split into resolution levels j: the upper boundary corresponds to a maximum degree l related to the spatial resolution r at the Earth's surface. The BKG/DNSC airborne data have their highest sensitivity at level $j = 11$. Sensitivities of other measurement types are also related to the level classification.

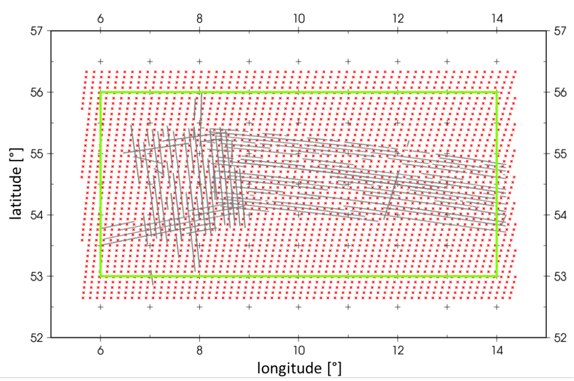


Fig. 2.4: Study area over the North and the Baltic Sea: the output area is shown in green, the locations of the airborne gravimetry measurements are plotted in gray, and the red crosses symbolise the computation grid.

In order to analyse DGFI's regional gravity modelling approach we used a data set from BKG/DNSC (Bundesamt für Kartographie und Geodäsie/Danish National Space Center) based on two different flight campaigns over the North and Baltic Sea in 2006 and 2007/08. The measurements have different accuracies and data gaps due to flight turbulences. In addition, the spatial distribution is heterogeneous. The effect of these data characteristics has been studied with DGFI's regional gravity modelling approach. We use series expansions in terms of spherical localising basis functions acting as low-pass filters related to the resolution levels j (see Fig. 2.3). Figure 2.4 shows the investigation area over the North and the Baltic Sea (green), the locations of the basis functions (red crosses) and the positions of the airborne gravimetry measurements from both flight campaigns.

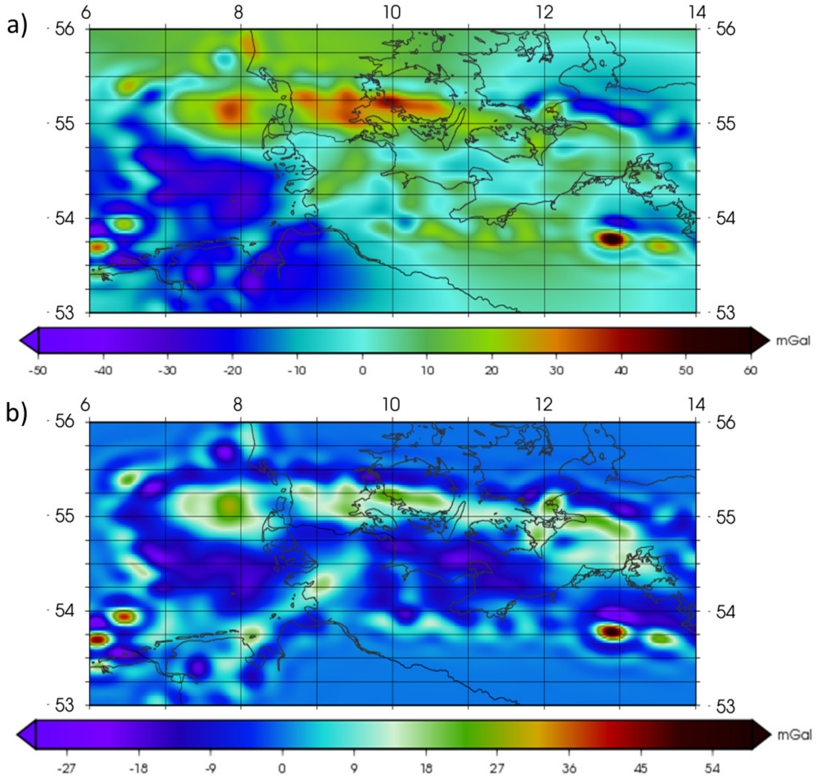


Fig. 2.5: *Modelled gravity anomalies for the full signal (a) and for the difference signal (b) related to a reduced data set from which the global background model GOCO03s up to degree/order 150 was subtracted.*

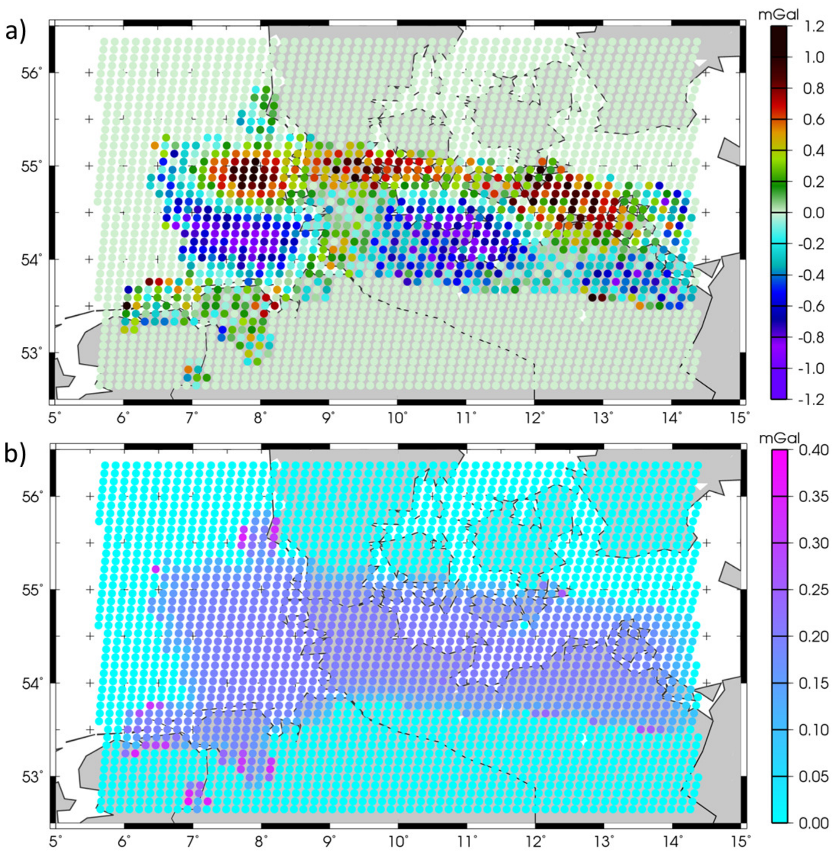


Fig. 2.6: *Estimated scaling coefficients (a) and their standard deviations (b).*

Table 2.1: Signal variations and standard deviations of regionally modelled gravity anomalies using airborne gravity measurements (air), terrestrial (ter) or altimetry (alti) data.

observations	signal [mGal]	max. std. [mGal]	mean std. [mGal]	mean std. [%]
air	$-30.1\ldots+55.2$	12.4	1.1	1.3
air + ter	$-47.8\ldots+55.2$	12.0	0.8	0.8
air + ter + alti	$-46.9\ldots+53.4$	11.3	0.7	0.7

We developed the series expansion up to a maximum degree $l' = 2047$ in terms of Blackman scaling functions (Lieb et al., accepted). The resulting full signal is displayed by means of gravity anomalies in Fig. 2.5a. Hereby we estimated scaling coefficients with respect to the background model GOCO03s (up to degree/order 150) and restored this background model. The amplitudes of the differential signal can be seen in Fig. 2.5b. They vary from -30.1 to $+55.2$ mGal with standard deviations between 0.04 and 12.39 mGal. The largest standard deviations occur along isolated flight tracks and close to the border of the observation area, i.e. in regions with inadequate data coverage. As expected, the central area which is covered by dense flight tracks contains the largest signal. The gravitational structures are directly modelled from the estimated coefficients defining the height of the scaling functions. Thus, the coefficients themselves already represent the gravitational structures (see Fig. 2.6a) with standard deviations of up to 0.37 mGal (Fig. 2.6b). The maxima of the structures are located along a latitude of approximately 55°. The two dominating minima are within the German part of the North and the Baltic Sea. They are clearly visible in the coefficients (Fig. 2.6a) as well as in the resulting differential signal (cf. Fig. 2.5b). In areas without airborne measurements we introduced the background model as a priori information with expectation values equal to zero. Thus, the estimated coefficients and the appropriate standard deviations converge to zero. In the flight area the standard deviations show homogeneous values that are independent from data gaps or the varying accuracy of the measurements. However, along isolated flight tracks the standard deviations reach maximum values, especially in the south- and north-west of the study area. We conclude that data gaps and less accurate measurements in the central area have hardly an effect on the accuracy, but coefficients along isolated flight tracks might be erroneously determined. In general, the coefficients are estimated properly and can be interpreted physically since they reflect the energy content of the signal.

The mean standard deviation of the resulting gravity anomalies accounts for 1.1 mGal, i.e. 1.3% of the signal amplitude in Fig. 2.5b. We further combined the high-resolution airborne gravimetry measurements with partly overlapping terrestrial data from BGI (Bureau Gravimétrique International). The resulting gravity anomalies show variations from -47.8 to $+55.2$ mGal related to the larger extent of the observation area (see Table 2.1). Despite larger signal amplitudes, the standard deviations are reduced. The mean value accounts for 0.8% of the signal variation. As expected, the achievable accuracy directly depends on the number of observations. Finally, a combination with altimetry data from the geodetic missions of ERS-1e and 1f over the North Sea provides the best result with a mean standard deviation of smaller than 0.7 mGal that corresponds to 0.7% of the signal amplitude. Besides a larger number of observations and a better spatial coverage of the study area, the mid-frequency domain is stabilised by the altimeter data in this combined solution.

2.2 Time-variable gravity field

Low-degree spherical harmonics from multi-mission SLR

SLR observations can be used to determine the time-variable part of the Earth's gravity field. Due to the limited number of globally distributed telescopes and the high altitude of the tracked satellites (for this study only passive satellites with spherical shape were used), SLR observations are mainly sensitive to

long-wavelength variations (low degree spherical harmonics).
As an official ILRS analysis centre, DGFI processes SLR observations to various satellites at altitudes between 690 and 20000 km using weekly arcs. These observations are combined using variance component estimation (VCE) on the level of normal equations (NEQs). The resulting weekly multi-satellite NEQs can be stacked to monthly NEQs or directly solved for orbit parameters, station coordinates, Earth orientation parameters and gravity field coefficients (GFCs). The obtained GFCs are compared with state-of-the-art time series provided by, e.g., the Center for Space Research (CSR). Figure 2.7 (Bloßfeld et al., submitted) shows the computed geoid errors of degree two for three different DGFI solutions. The weekly 4-satellite solution (blue) contains only observations to the satellites LAGEOS 1/2 and Etalon 1/2 with orbit altitudes of 6000 and 20000 km, respectively. Due to the applied VCE and the refined orbit modelling, even the weekly 4-satellite solution shows smaller geoid errors of degree two than the two CSR solutions (see Fig. 2.7). The long-term behaviour of the geoid error is caused by changes in the global SLR observation network. The weekly DGFI 7-10 satellite solution (red) contains additional observations to 3-6 LEO satellites which increase the sensitivity of the solution to the Earth gravity field significantly. In addition, the observation network is stabilized since observations to more satellites result in a denser station network. This can be demonstrated by comparing the global observation coverage (see Fig. 2.8) for the two certain epochs (red) from Fig. 2.7. For the monthly DGFI solution (green), 4-5 weekly arcs (depending on the beginning and the end of each month) of the 7-10 satellite solution are stacked. From Fig. 2.7 it is clearly visible that the monthly DGFI solution exhibits the smallest geoid errors that show hardly any variation with time.

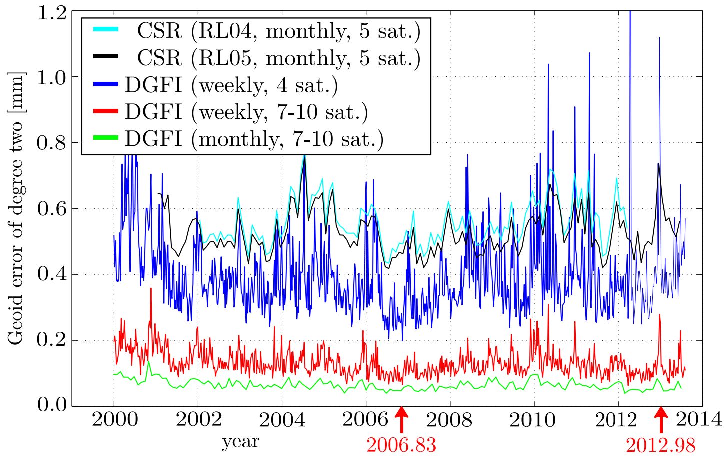


***Fig. 2.7:** Geoid errors of degree two for three DGFI and two CSR solutions (from Bloßfeld et al., submitted).*

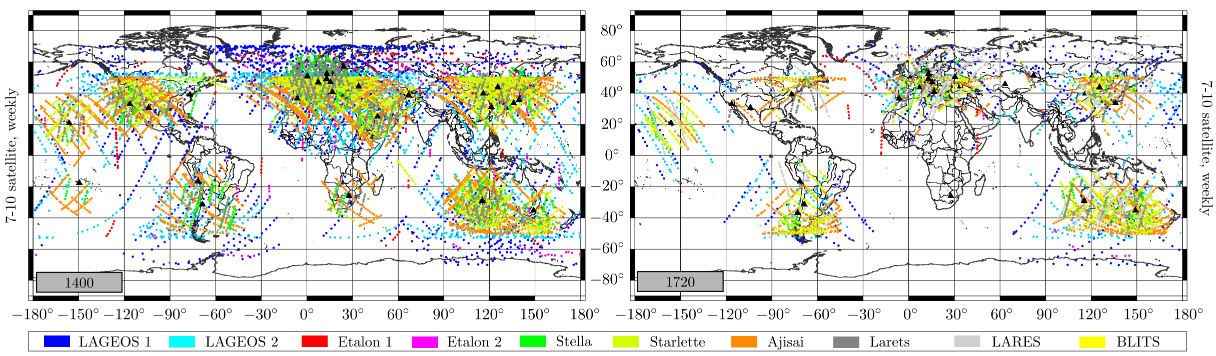


***Fig. 2.8:** Global distribution of observations for the 7-10 satellite solution of GPS week 1400 (2006.83) and 1720 (2012.98) (from Bloßfeld et al., submitted).*

Combined estimation of the Earth's gravity field using GRACE and SLR data

Since 2002, the satellite mission GRACE observes the Earth's static and time-variable gravity field with a spatial resolution of about 150 km for the static and of up to 300 km for a monthly field. However, the estimation of low degree coefficients is difficult with GRACE, especially as regards the flattening coefficient $C_{2,0}$. Therefore, in GRACE gravity field models, this coefficient is often replaced by a value based on SLR measurements. In addition, unfiltered GRACE global gravity field solutions show typical stripes which are related to the dominant sensitivity in north-south direction.

In our study, we combine both techniques to get a consistent set of spherical harmonic coefficients. Data of four weeks in March 2007 are used to calculate two independent results for GRACE and SLR, based on the same reference field (EIGEN-6C2). The GRACE computation is based on the integral equation approach (IEA). For SLR four one-week solutions containing data from 8 satellites are combined to one four-week solution. From the GRACE data, we estimate a gravity field containing coefficients from degree 2 up to degree 60. As SLR is mainly sensitive to the lower coefficients, the estimated gravity field is limited to a maximum degree of 20. For each technique, we get the NEQ matrix $\mathbf{N}_i$ and the vector of the right-hand side $\mathbf{n}_i$ that are combined using an iterative VCE. For this purpose, the smaller NEQ matrix $\mathbf{N}_{SLR}$ has to be extended to the size of $\mathbf{N}_{GRACE}$ by filling the coefficients of higher degree and order with zeros. From each iteration step, updated corrections with respect to the initial reference field and new values for the next iteration step are obtained. The iteration process is terminated as soon as the difference between two consecutive steps is below the computation precision.

Figure 2.9 shows the standard deviations (STDs) of the estimated spherical harmonic coefficients after the combination. Improvements due to the combination can be expected up to degree 20, as this is the highest degree estimated from SLR data. To reveal the benefit of SLR in the combination, the STDs of the combined solution are subtracted from the STDs of the GRACE-only solution (see Fig. 2.10). This procedure shows that the formal error of the coefficients improved, as no negative values occur. The largest improvements can be achieved for the coefficients of degree 2. Due to the various inclinations of the 8 SLR satellites, enhancements can also be detected for the sectorial coefficients. Furthermore, the estimation of coefficients of order 14 to 16 is improved because of resonance frequencies of the SLR satellites. Comparing Figures 2.9 and 2.10, the combined STDs are at maximum 10 % lower than the GRACE-only STDs.

The effects of the combination on the SLR-only solution are shown in Fig. 2.11. Due to the additional GRACE data in the combination, the estimation of the zonal and neighbouring coefficients is improved, starting from degree 5. For SLR, the combined STDs are even at maximum 90 % lower than that of the SLR-only solution. This is due to the large amount of GRACE data which reduces the variance factor of the combined solution.

Inversion of GPS, gravity and tsunami data in a distributed fault slip model for the Japan 2011 Tohoku-Oki 9.0 Mw earthquake

The Japan Tohoku-Oki 9.0 Mw earthquake had a devastating impact on the eastern coastal area of Japan. After the main shock in March 2011 several aftershocks took place leading to a vast deformation of the continental plate. With the dense GPS network of Japan it is possible to monitor such deformation processes over periods of seconds to years (see Fig. 2.12). Daily RINEX GEONET GPS time series were provided by the Geospatial Information Authority (GSI) of Japan, which were processed with Jet Propulsion Laboratory's GIPSY/OASIS-II software, using a single-station bias-fixing point positioning strategy, and provided by the ARIA (Advanced Rapid Imaging and Analysis) team from JPL and Caltech.

Since the deformation caused by the main shock, various aftershocks and after-slip events led to an additive displacement and, therefore, to temporal driven movement resulting in uplift and subsidence of the continental plate. The resulting mass displacements are mapped in Earth's gravity field and,

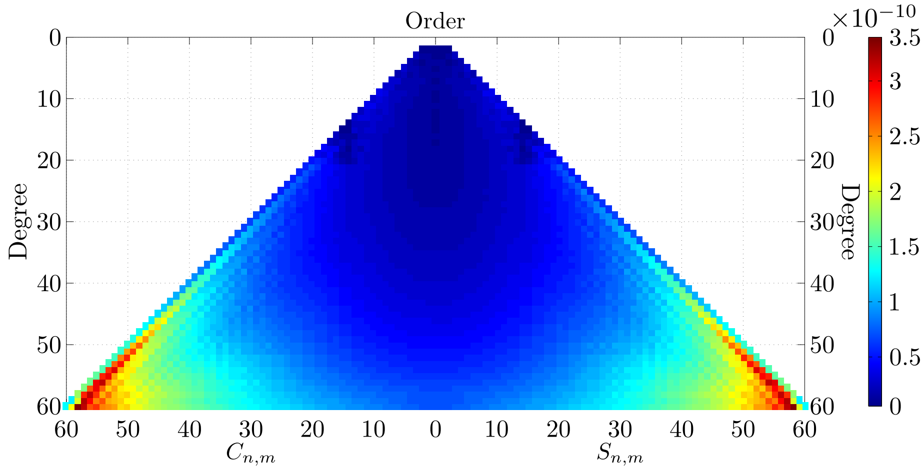


Fig. 2.9: *STDs of the combined estimated spherical harmonic coefficients up to degree and order 60.*

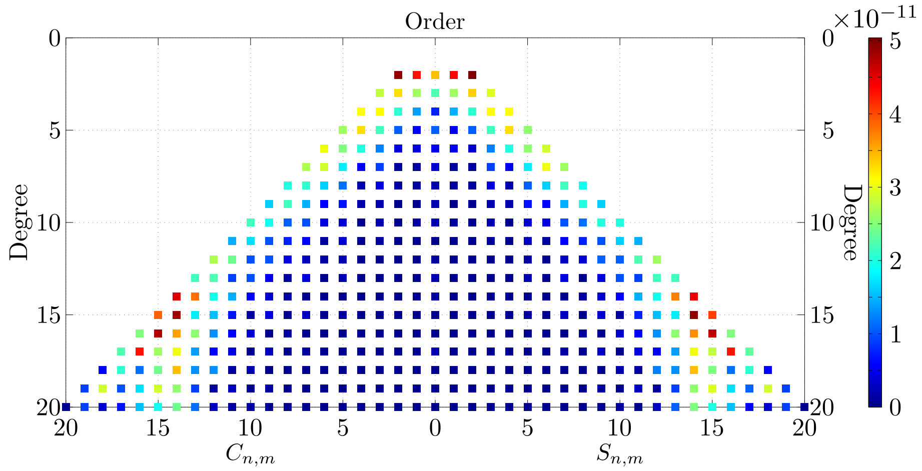


Fig. 2.10: *STDs of the GRACE-only solution minus STDs of the combined solution up to degree and order 20.*

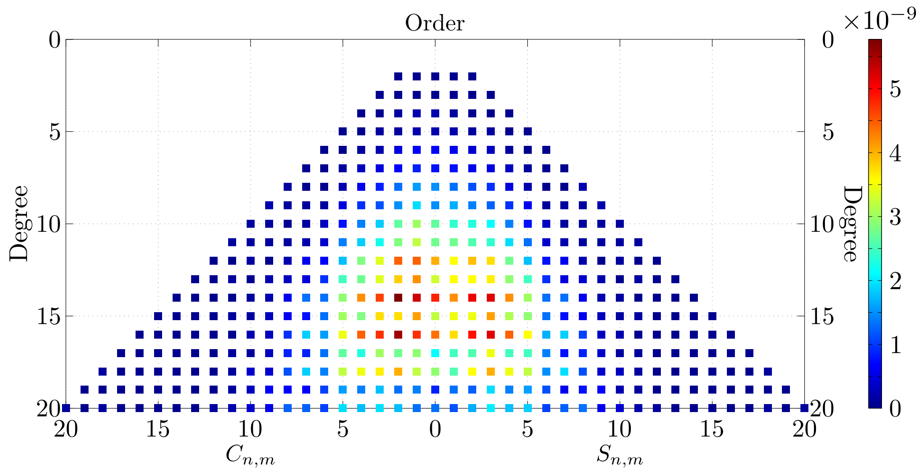


Fig. 2.11: *STDs of the SLR-only solution minus STDs of the combined solution up to degree and order 20.*

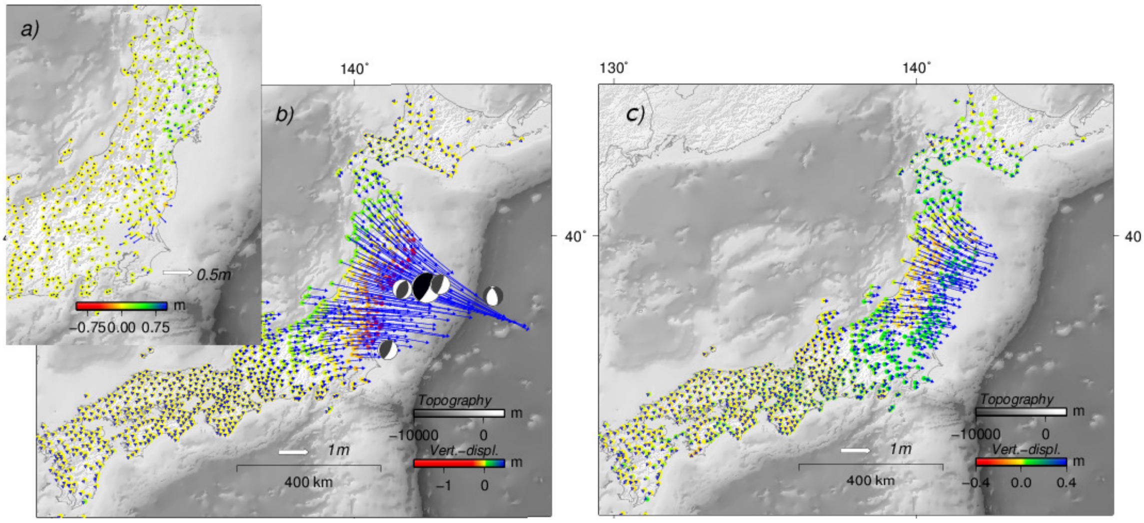


Fig. 2.12: Vertical and horizontal displacement of GPS stations in Japan. Image b) shows the coseismic change including the first aftershock (Mw 7.9 at 06:15:39 UTC). Image c) represents the post-seismic displacement two years after the earthquake. Figure a) shows the coseismic residuals between the model and the measurements.

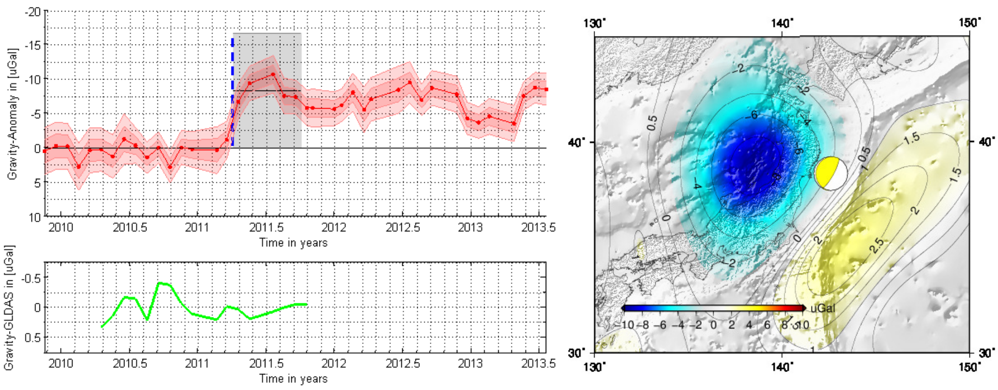


Fig. 2.13: Time series of the gravity change in the vicinity of the maximum gravity drop (top left) and the corresponding hydrological correction (bottom left). Coseismic gravity change evaluated with a 300 km Gaussian smoothing (right).

thus, are visible for the GRACE satellite mission. By combining the GPS deformation with monthly GRACE solutions of the CSR series, it is possible to estimate a revised slip distribution on a monthly basis. The input data for that approach are the temporal gravity changes caused by the Japan-Tohoku-Oki earthquake. The gravity change in the vicinity of the maximum gravity drop is shown in Fig. 2.13 (top panel) applying a Gaussian filter of 300 km. In addition, temporal corrections must be applied to the gravity measurements. For example, a hydrological correction derived from GLDAS, as shown in the bottom panel of Fig. 2.13 has been applied.

For a combined estimation of the slip distribution, the trench geometry has been resembled in 161 sub fault patches where a strike and dip-slip component has been estimated in a Bayesian inversion approach. The trench geometry represents the fault plane reconstructed by seismic reflection study[1]. The gravity change is computed from a semi-analytical normal mode model including sea water correction where realistic coast lines and self-gravitation are applied. The revised slip distribution shows, compared with common fault slip models based on GPS or seismic-only data, a higher slip located at the trench. In a direct comparison with a GPS-only solution the shifted slip-pattern indicates also the importance of gravity

[1]Fujie, G., Ito, A., Kodaira, S., Takahashi, N., Kaneda, Y., 2006. Confirming sharp bending of the Pacific plate in the northern Japan trench subduction zone by applying a travel time mapping method. Phys. Earth Planet. Inter. 157 (1-2), 72-85. doi:10.1016/j.pepi.2006.03.013

data in the inversion and the weakness of GPS-only data which map the displacement asymmetric based on continental surface deformation. Moreover deep slip might be resolved more accurate using gravity measurements. A similar result can be obtained by adding tsunami or geodetic sea floor measurements to a GPS-only inversion[2]. In a joint inversion of geometric, gravimetric and oceanic tsunami data, a detailed mapping of the coseismic displacement can be achieved (see Fig. 2.14, right panel). The combined model approves, for this case, the theoretical assumption that the Japan-Tohoku-Oki earthquake ruptured all the way through the trench.

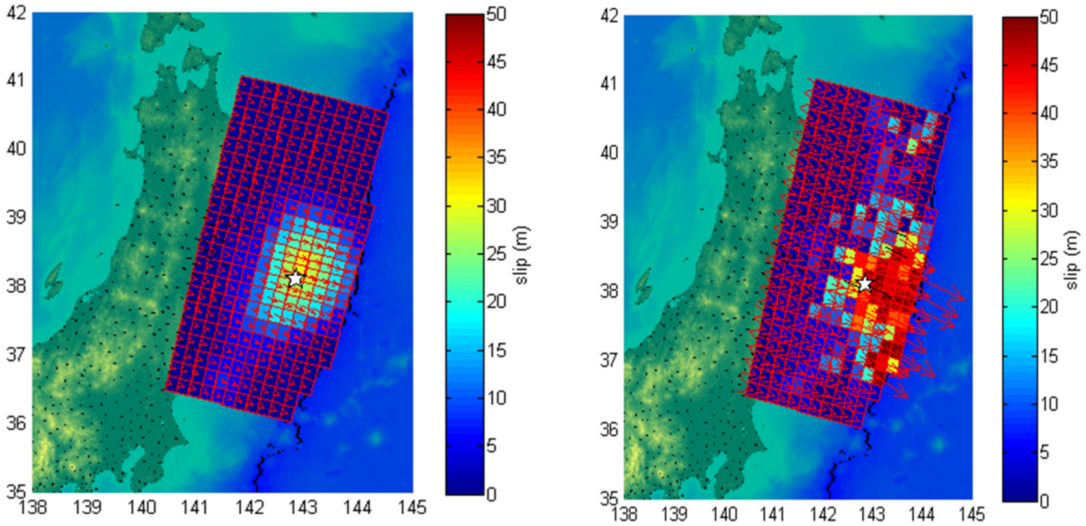


Fig. 2.14: (left) Coseismic fault slip model for a GPS-only model where regularization has been applied. (right) Coseismic slip pattern for a joint inversion of GPS, gravity and tsunami data. Due the joint inversion of different observation types the inversion is much better constrained and reveals more details.

A long-term analysis was performed on semi-annual and annual basis using the joint-inversion approach. Since GOCE gravity gradients show sensitivity to coseismic gravity changes in yearly averages (Fuchs et al., 2013), we evaluated whether long-term averages can improve the geophysical modelling in terms of spatial resolution and in terms of an additional independent and complementary measurement. Therefore, GOCE gravity gradients were combined with GRACE monthly solutions, where the GRACE information is used to restore the long wavelength content of GOCE measurements in the spectral domain since the GOCE measurements are less accurate there. To avoid any signal loss of the GOCE gravity gradients measured in the gradiometer reference frame, V_{XX}, V_{YY}, V_{ZZ} and V_{XZ} were combined in a regional gravity field analysis and used at orbit height (to avoid downward continuation) similar as stated in (Ebbing et al., 2013). The gradient analysis shows consistency with the forward model within the error bounds. Analyzing the temporal deformation behaviour on time scales of years it will be possible to determine geophysical parameters related to the material properties of Earth's mantle and crust such as, e.g., related to the viscoelastic rebound, rheology and afterslip which are subject to current investigations.

Ice mass loss in West Antarctica from a combination of GRACE and GOCE

The dramatic ice mass loss in West Antarctica, in particular for the Amundsen Sea sector, is visible in the GRACE monthly gravity field solutions. Although GOCE was not meant and not expected to sense related changes, it turns out that it does. We combined existing GRACE monthly solutions with a spatial resolution of about 350 km with GOCE gravity gradients for the period 2009–2012. For this time period we estimated equivalent water height (EWH) trends using 4-monthly gravity field solutions.

[2]Hooper, A., J. Pietrzak, W. Simons, H. Cui, R. Riva, M. Naeije, A. Terwisscha van Scheltinga, E. Schrama, G. Stelling, and A. Socquet (2012), Importance of Horizontal Seafloor Motion on Tsunami Height for the 2011 Mw=9.0 Tohoku-Oki Earthquake, Earth Planet. Sci. Lett., 361, 469-479, doi: 10.1016/j.epsl.2012.11.013

Figure 2.15 displays these trends at a spatial resolution of 350 km (left panel) and 200 km (right panel). The most negative EWH trends are roughly related to the Pine Island glacier (eastern minimum) and the Smith/Haynes/Kohler glaciers (western minimum). The solution may contain systematic errors, but it seems to be possible to separate different basins studying the GOCE data.

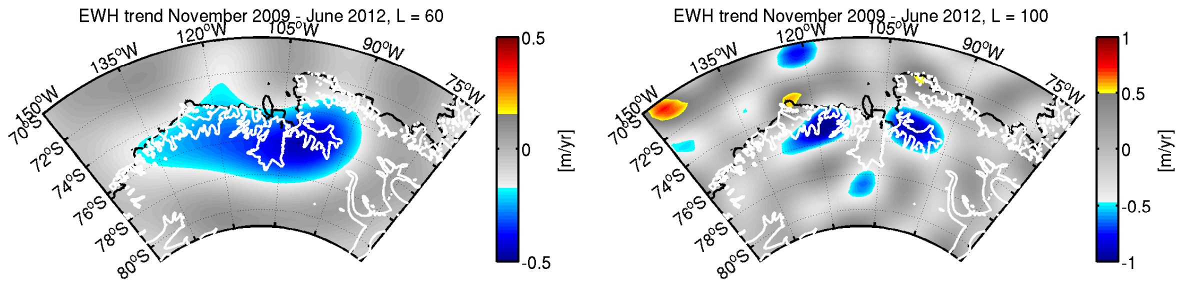


Fig. 2.15: *Equivalent water height trend in the Amundsen Sea sector for 2009-2012 from a combination of GRACE and GOCE. The left panel shows the EWH trend with a spatial resolution of 350 km, the right panel with a spatial resolution of 200 km*

2.3 Height systems

Towards a global vertical reference system in the frame of GGOS

The Global Geodetic Observing System (GGOS) promotes via Theme 1 (Unified Height System) the definition and realisation of a vertical reference system with homogeneous consistency and reliability worldwide (the same accuracy everywhere) and with long-term stability (the same accuracy at any time). DGFI supports this initiative by coordinating the Working Group "Vertical Datum Standardisation" (*http://whs.dgfi.badw.de*) which directly depends on GGOS Theme 1 and is supported by the IAG Commissions 1 (Reference Frames) and 2 (Gravity Field) as well as by the International Gravity Field Service (IGFS). The main purpose of this working group is to provide a reliable value for the geopotential W_0 to be adopted as the conventional reference level for the realisation of a global unified height system. Although any geopotential value could be arbitrarily chosen, this value has to be consistent with other defining parameters of geometric and physical models of the Earth.

In previous steps, it was possible to elaborate an inventory of the existing W_0 computations and to establis connections between individual initiatives for a homogeneous W_0 determination. In this way, four different groups performed new W_0 calculations using their own methodologies and applying recent geodetic models (e.g., GOCE/GRACE gravity models, sea surface models derived from calibrated and combined satellite altimetry observations, etc.). A comparison of these results with the reference potential value U_0 of the GRS80 ellipsoid and the W_0 value recommended by the IERS conventions showed that the first one corresponds to an equipotential surface located about 67 cm below the sea surface currently scanned by satellite altimetry, whereas the second one is about 17 cm further below. These discrepancies do not allow a precise realisation of these two levels and, therefore, it is necessary to introduce a new value for W_0 that agrees with current geodetic observations and models. Based on this conclusion, in 2013 the working group concentrated on outlining detailed standards for the computation of a "new W_0 best estimate".

Considerations for a new W_0 reference value

The adoption of a W_0 value to be the reference level is equivalent to appoint one of the infinite number of equipotential surfaces of the Earth's gravity field to be the zero-height surface, i.e. the geoid. Therefore, it is useful to adopt a W_0 value derived from the same observations and models applied for the geoid determination. Thus, the vertical reference level is defined by the W_0 value and is realised by the geoid computation. According to this, we recommend:

1. An empirical estimation of W_0 to facilitate its (reliable) realisation;
2. W_0 should be commensurate with present models for the geometry and gravity field of the Earth;
3. A known relationship between the equipotential surface defined by W_0 and the mean sea level to facilitate the integration of the classical height systems and to support oceanographic applications;
4. Estimation of W_0 from satellite-only gravity data to avoid uncertainties caused by the terrestrial gravity anomalies associated to the local height datum;
5. Evaluation over ocean areas only because:
    - Geometry of the sea surface is known with higher accuracy than that of the continental surfaces;
    - Geoid and quasi-geoid are the same (identical reference level for normal and orthometric heights);
    - Gravity effects of topographical features not scanned by satellite gravimetry are minimized;
    - Usual procedure for the determination of an Earth's best fitting ellipsoid (semi-major axis a).

Empirical estimation of a new W_0 reference value

To support these recommendations, the following evaluations were performed:

- Dependence of the W_0 estimate on the geographical coverage of the mean sea surface model;
- Dependence of the W_0 estimate on the spatial resolution of the mean sea surface model;
- Dependence of the W_0 estimate on spectral resolution of the global gravity model;
- Dependence of the W_0 estimate on temporal changes of the mean sea surface and of the global gravity model.

The computations were carried out using the mean sea surface models MSS_CNES_CLS11 (Schaeffer et al. 2012), DTU10 (Andersen 2010), as well as mean yearly models computed by Dayoub et al. (2012), Burša et al. (2012), and Savcenko and Bosch (2012). Besides, the following global gravity models (GGM) were applied: EGM2008 (Pavlis et al. 2012), EIGEN-6C2 (Förste et al. 2012), GOCO03S (Mayer-Gürr et al. 2012), GO_CONS_GCF_2_DIR_R4 (Bruinsma et al. 2013).

The main conclusions are:

- Models including GRACE, GOCE and SLR data are preferred since they deliver maximum differences of 0.06 m^2s^{-2} (6 mm vertical distance). The estimation based on the EGM2008 model differs by 0.14 m^2s^{-2} (1.4 cm) from the other GGM.
- The use of a satellite-only gravity model is suitable. Above degree and order 200, the largest differences are 0.001 m^2s^{-2} which are totally negligible.
- The W_0 estimates based on the models MSS_CNES_CLS11 and DTU10 differ by 0.31 m^2s^{-2}. They reflect the mean discrepancy of about 3 cm between both sea surface models, which are possibly caused by the different strategies to process the altimetry data, the different reductions taken into account, and the different time periods considered (i.e., different inter-annual ocean variability).
- The use of yearly mean sea surface models allows to refer the sea surface heights to a certain reference epoch. However, the resulting W_0 estimates reflect (with opposite sign) the sea level rise measured by satellite altimetry: extreme values occur in 1993 (maximum) and 2010 (minimum), with a difference of 0.46 m^2s^{-2}. These differences shall not be understood as a change in W_0, but in the sea level, as the geoid does not rise/decline with the mean sea level. It only means that, depending on the period utilized for the average of the sea surface heights, the mean sea level coincides with a different equipotential surface.

Related publications

Bloßfeld M., Müller H., Gerstl M., Štefka V., Bouman J., Göttl F.: Improved monthly Earth's gravity field solutions using multi-satellite SLR. Journal of Geophysical Research, submitted

Bouman J., Ebbing J., Fuchs M.: Reference frame transformation of satellite gravity gradients and topographic mass reduction. Journal of Geophysical Research 118(2): 759-774, American Geophysical Union, DOI:10.1029/2012JB009747, 2013

Bouman J., Ebbing J., Meekes S., Fattah R.A., Fuchs M., Gradmann S., Haagmans R., Lieb V., Schmidt M., Dettmering D., Bosch W.: GOCE gravity gradient data for lithospheric modeling. International Journal of Applied Earth Observation and Geoinformation, Elsevier, DOI:10.1016/j.jag.2013.11.001, 2013

Bouman J., Dettmering D., Fuchs M., Lieb V., Schmidt M., Seitz F.: Le monde est bleu comme une pomme de terre. Akademie Aktuell 02/2013: 23-27, Bayerische Akademie der Wissenschaften, ISSN 1436-753X, 2013

Bouman J., Floberghagen R., Rummel R.: More than 50 years of progress in satellite gravimetry. Eos Transactions 94(31): 269-270, American Geophysical Union, DOI:10.1002/2013EO310001, 2013

Dettmering D., Schmidt M., Bosch W., Lieb V.: Modelling marine gravity potential with satellite altimetry data. In: Ouwehand L. (Ed.) Proceedings of the ESA Living Planet Symposium, Sept. 2013, Edinburgh, UK, ESA SP-722 (CD-ROM), ISBN 978-92-921-286-5, 2013

Ebbing J., Bouman J., Fuchs M., Lieb V., Haagmans R., Meekes J.A.C., Fattah R.A.: Advancements in satellite gravity gradient data for crustal studies. The Leading Edge 32(8): 900-906, Society of Exploration Geophysicists, DOI:10.1190/tle32080900.1, 2013

Fuchs M.J., Bouman J., Broerse T., Visser P., Vermeersen B.: Observing coseismic gravity change from the Japan Tohoku-Oki 2011 earthquake with GOCE gravity gradiometry. Journal of Geophysical Research 118(10): 5712-5721, American Geophysical Union, DOI:10.1002/jgrb.50381, 2013

Lieb V., Bouman J., Dettmering D., Fuchs M., Schmidt M.: Combination of GOCE gravity gradients in regional gravity field modelling using radial basis functions, IAG Proceedings, Hotine Marussi Symposium 2013, Rome, accepted

Pimenova O.: High resolution gravity field modelling using satellite altimetry data of geodetic mission phases. Master Thesis, DGFI/TUM, 2013

Sánchez L.: *Towards a vertical datum standardisation under the umbrella of Global Geodetic Observing System*. Journal of Geodetic Science 2(4): 325-342, Versita, 2013

3 Geodetic Earth System Modelling

The main components of the Earth system are the atmosphere (containing the neutrosphere and the ionosphere), the hydrosphere (consisting of the oceans and the continental hydrology), the geosphere, i.e. the solid Earth, the cryosphere and the biosphere. The topics of this research field aim on improving the understanding of the dynamic processes and their interactions within these components observed by geodetic measurement techniques. Due to the close connection to other geoscience disciplines, such as geophysics, meteorology, oceanography or hydrology, complementary data from other sensors are integrated into the modelling process. The combination of all data allows for a reliable estimation of the dynamic processes, which are of great importance for monitoring climate change.

In 2013, we focussed on creating a database for hydrological time series of inland waters. For ionosphere modelling, we analysed and preprocessed DORIS data and extended the four-dimensional model of the electron density. Furthermore, we evaluated polar motion excitation functions, studied dynamic ocean topography profiles and improved the 30 m vertical pendulum in Berchtesgaden by technical modifications.

3.1 Geodetic Earth system models

Combination of geodetic space observations to separate individual polar motion excitation mechanisms

Redistribution and motion of masses within and between the subsystems of the Earth cause Earth rotation variations. Whereas the integral effect of the Earth rotation is precisely measured by geometric space techniques (SLR, VLBI, GNSS, DORIS), the separation into the individual excitation mechanisms remains a challenge. Usually, individual geophysical excitation mechanisms of the Earth rotation are derived from geophysical models which are afflicted with large uncertainties. Therefore, we have developed an adjustment model which allows to combine precise observations from space geodetic observation systems such as SLR, VLBI, GNSS, DORIS, satellite altimetry and satellite gravimetry in order to separate geophysical excitation mechanisms of the Earth rotation. Details on the preprocessing strategies and the combination were presented in the DGFI Annual Report 2011 and by Göttl (2013). Here, we present a detailed validation of the adjusted geodetic results that are based on updated time series.

We used the following equatorial excitation functions, denoted as χ_1 and χ_2, derived from polar motion, time variable gravity field models, sea level anomalies and atmospheric models for the combination:

- $\chi_{1,2}$ (integral effect): IERS EOP 08 C04, ITRF2008, DTRF2008;
- $\chi_{1,2}^{mass}$ (integral mass effect): CSR RL05, GFZ RL05, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010, CSR SLR RL04, DGFI SLR;
- $\chi_{1,2}^{O}$ (oceanic mass effect): CSR RL05, GFZ RL05, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010, AVISO/WOA09, AVISO/Ishii, DGFI/WOA09, DGFI/Ishii;
- $\chi_{1,2}^{H}$ (hydrological mass effect): CSR RL05, GFZ RL05, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010;
- $\chi_{1,2}^{A}$ (atmospheric mass effect): NCEP, ECMWF.

The adjusted geodetic results for the atmospheric, oceanic and hydrological mass effects and for the integral motion effect $\chi_{1,2}^{\mathrm{motion}}$ are compared with geophysical model results (NCEP, ECMWF, ECCO, OMCT, GLDAS, LSDM). In Table 3.1 the RMS differences and correlation coefficients are shown. Due to the combination of geodetic excitation functions the agreement with geophysical model results can be

***Table 3.1:** RMS differences [mas] / correlation coefficients [ ] between geodetic solutions for geophysical excitation functions and model results. The integral motion effect $\chi^m_{1,2} = \chi^{motion}_{1,2}$ can be estimated from the model combinations NCEP and ECCO (NE) as well as ECMWF and OMCT (EO). Furthermore, the integral motion effect can be determined from the integral effect (EOP) by reduction of the atmospheric, oceanic and hydrological mass effects from the model combinations NCEP, ECCO and GLDAS (NEG) or ECMWF, OMCT and LSDM (EOL).*

	mean grav.	mean alti.	combination		mean grav.	mean alti.	combination
χ_1^A NCEP			0.39/1.00	χ_2^A NCEP			0.86/1.00
χ_1^A ECMWF			0.54/1.00	χ_2^A ECMWF			2.23/1.00
χ_1^O ECCO	4.23/0.54	4.63/0.37	2.53/0.73	χ_2^O ECCO	6.06/0.59	5.37/0.66	4.31/0.82
χ_1^O OMCT	5.34/0.49	5.77/0.37	4.22/0.65	χ_2^O OMCT	4.90/0.66	5.66/0.50	4.06/0.73
χ_1^H GLDAS	3.47/0.65		3.18/0.67	χ_2^H GLDAS	4.73/0.25		4.54/0.23
χ_1^H LSDM	4.23/0.51		4.06/0.51	χ_2^H LSDM	7.73/0.66		7.10/0.77
χ_1^m NE			6.31/0.68	χ_2^m NE			7.92/0.76
χ_1^m EO			7.65/0.52	χ_2^m EO			10.69/0.49
χ_1^m EOP-NEG			3.34/0.95	χ_2^m EOP-NEG			5.74/0.88
χ_1^m EOP-EOL			4.88/0.91	χ_2^m EOP-EOL			7.70/0.77

significantly improved. This demonstrates that due to the combination the weaknesses of the individual processing strategies can be compensated and the technique-specific strengths can be fully exploited. Furthermore, we found that the reduced geodetic solutions for the integral motion effect are more realistic than the model results. This means that the modelling of winds and currents is afflicted with larger uncertainties than the modelling of mass displacements within atmosphere, oceans and continental hydrosphere. The RMS differences of the geophysical model results are significantly higher than the formal errors of the combined geodetic solutions. Thus, the individual geophysical excitation mechanisms of polar motion can be estimated more precisely by combination of geodetic space observations than from geophysical models:

- $\chi^A_{1,2}$: factor of 1.1 better than model estimates,
- $\chi^O_{1,2}$: factor of 1.8 better than model estimates,
- $\chi^H_{1,2}$: factor of 3.0 better than model estimates,
- $\chi^{\text{motion}}_{1,2}$: factor of 2.2 better than model estimates.

The presented approach is suitable for the computation of enhanced excitation time series and will improve the understanding of individual contributions of the subsystems to Earth rotation variations.

3.2 Ionosphere

Using DORIS measurements for ionosphere modelling

Nowadays, most of the ionosphere models used in geodesy are based on terrestrial GNSS measurements and define the vertical total electron content (VTEC) depending on longitude, latitude, and time. The accuracy of the VTEC maps is inhomogeneous for different regions of the Earth, because the GNSS stations are unevenly distributed and, therefore, some regions, especially the ocean areas, are not very well covered by observations. To overcome this unsatisfying measurement geometry of the terrestrial GNSS measurements for inosphere modelling and to take advantage of the different sensitivities of other space geodetic observation techniques, we work on the development of multi-dimensional models of the ionosphere from the combination of modern space geodetic satellite techniques. Currently, the capability of DORIS observations to derive ionospheric parameters such as VTEC is investigated.

Observations from all 52 active DORIS beacons received by the DGXX receiver on board Jason-2 during the CONT08 time period (from 12 August to 25 August 2008) were used. Since many DORIS beacons are located on islands, the global coverage is better than for GNSS.

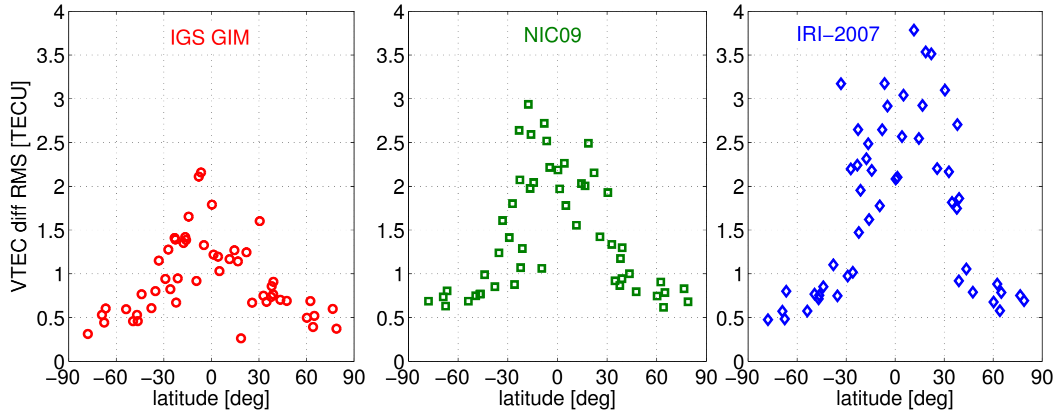


Fig. 3.1: *VTEC RMS differences [TECU] between DORIS and three global models for CONT08 time period per station; stations sorted by latitude.*

An important processing step is the data preprocessing, i.e. the derivation of VTEC values from the original phase measurements. Since the derived slant TEC (STEC) values are biased and the pseudo-range observations cannot be used to level the phase data as in the case of GNSS, external models such as the IGS Global Ionosphere Maps (GIM) are used to determine the absolute STEC level.

In order to map STEC to VTEC we use a single-layer model with fixed height and a simple cosine-dependent mapping function. The computed DORIS VTEC values show differences of up to 2 TECU RMS with respect to IGS GIMs, mainly in equatorial regions and probably related to higher absolute VTEC values in these areas. Differences with respect to other models, e.g. NIC09 and IRI-2007, reach values of up to 4 TECU RMS (cf. Fig. 3.1).

The DORIS VTEC observations were then used to compute global VTEC maps with our standard B-spline approach for 12 August 2008. In addition to DORIS, the following measurements were considered:

- VTEC observations from 67 GPS permanent stations,
- altimetry-based VTEC measurements from Jason-2,
- VTEC derived from radio occultation measurements (COSMIC and CHAMP),
- NIC09 as background model.

The different observation techniques were automatically weighted be means of a variance component estimation (VCE). Figure 3.2 shows the mean variance components (VC) for all data groups resulting from the VCE. DORIS observations get the lowest VCs corresponding to the highest weights.

If only GPS measurements are used, the mean formal errors (from 1.5 to 3.0 TECU) and also the differences with respect to external models (from ±5.4 to ±7.8 TECU for IGS GIM) increase significantly.

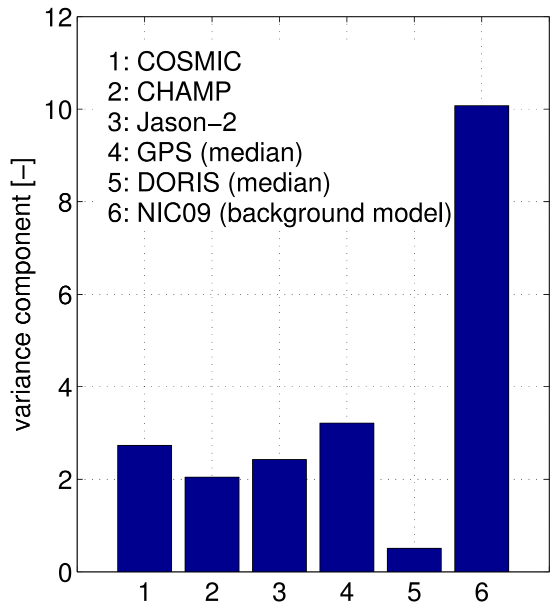


Fig. 3.2: *Variance components for different observation groups contributing to the estimation of a daily global VTEC map.*

Multi-dimensional ionosphere model from the combination of space geodetic techniques (MuSIK)

In 2013, we continued modelling the four-dimensional (4-D) electron density within the ionosphere. Associated tasks within the DFG project MuSIK have been carried out by the cooperation partners at the Institut für Astronomische und Physikalische Geodäsie (IAPG) of the Technische Universität München (TUM) and the German Aerospace Center (DLR) in Neustrelitz.

As already described in previous annual reports, we combine the physics-motivated Chapman function $N_e^{F2}(h)$ describing the ionospheric F2-layer with an additional plasmasphere layer $N_e^P(h)$ to represent the vertical distribution of the electron density $N_e(h)$ with h being the height above the Earth's surface. This results in the profile function

$$\begin{aligned} N_e(h) &= N_e^{F2}(h) + N_e^P(h) \\ &= N_m^{F2} \cdot \exp\left[0.5 \cdot \left(1 - z - \exp(-z)\right)\right] + N_0^P \cdot \exp\left[-|h - h_m^{F2}|/H^P\right] \end{aligned} \tag{3.1}$$

with $z = (h - h_m^{F2})/H^{F2}$ and $H^P = 10$ km for $h < h_m^{F2}$. It contains five key parameters, namely the F2-layer peak density N_m^{F2}, the corresponding peak height h_m^{F2}, the scale height H^{F2}, the plasmasphere basis density N_0^P and the plasmasphere scale height H^P. To model the spatio-temporal variations of the key parameters, they are represented as series expansions in terms of tensor products of three 1-D B-spline functions depending on longitude, latitude and time, with unknown series coefficients. As the B-spline functions are used as scaling functions, they can also be used for the generation of wavelet functions, thus, a multi-scale representation (MSR) can be established.

In our model, various observation techniques are combined to benefit from different signal characteristics, sensitivities and spatio-temporal resolutions. In particular, terrestrial GPS measurements and electron density profiles derived from ionospheric GPS radio occultations (RO) are of major importance, since they complement each other:

1. GPS RO measurements provide electron density observations which are sensitive to the vertical electron density structure, but rather sparse with respect to the spatio-temporal availability;
2. terrestrial GPS observations are densely distributed, but they provide the integrated ionospheric information in terms of STEC which is insensitive to the height.

Our model was applied exemplarily to solve for the three ionospheric key parameters (N_m^{F2}, h_m^{F2} and H^{F2}) in the region of South and Central America, in a first step from the combination of electron density profiles retrieved from ionospheric GPS RO measurements of the satellite missions FORMOSAT-3/COSMIC, GRACE and CHAMP. The spatial variations of the reconstructed key parameters for a specific epoch are depicted in Fig. 3.3. In the top row the estimated corrections for the key parameters with respect to the initial values derived from the background model, i.e. the IRI-2007 are shown for 12:00 UT. The colour bars are adapted to the respective minimum and maximum correction values. It is obvious that key parameters are only corrected in areas where observed density profiles support the estimation of the corresponding coefficients. Three selected profiles which have a strong impact on the estimated corrections are given along the bottom row where observations (blue), initial (green) and estimated values (red) are illustrated. The positions of these profiles are indicated by arrows on the correction maps in the top row. The graph in the middle shows a profile observed at longitude $\lambda = 289°$ and latitude $\varphi = -52°$ that affects mainly h_m^{F2}. Apart from that, N_m^{F2} exhibits a decrease visible in the corresponding ΔN_m^{F2} correction map. The changes with respect to H^{F2} can be explained by the profile on the right ($\lambda = 286°, \varphi = -25°$) where the estimated (red) and the observed curve (blue) are very close to each other. The profile on the left ($\lambda = 320°, \varphi = 5°$) has a strong influence on the estimation of N_m^{F2}, but also causes a slight decrease of h_m^{F2}. In particular, N_m^{F2} is reduced by almost $2 \cdot 10^5$ el/cm^3 which is mainly due to the impact of a lower atmospheric layer, maybe the E-layer. In this case, the Chapman profile is not able to approximate the observed profile correctly resulting in a systematic bias in the estimated key parameters. This situation

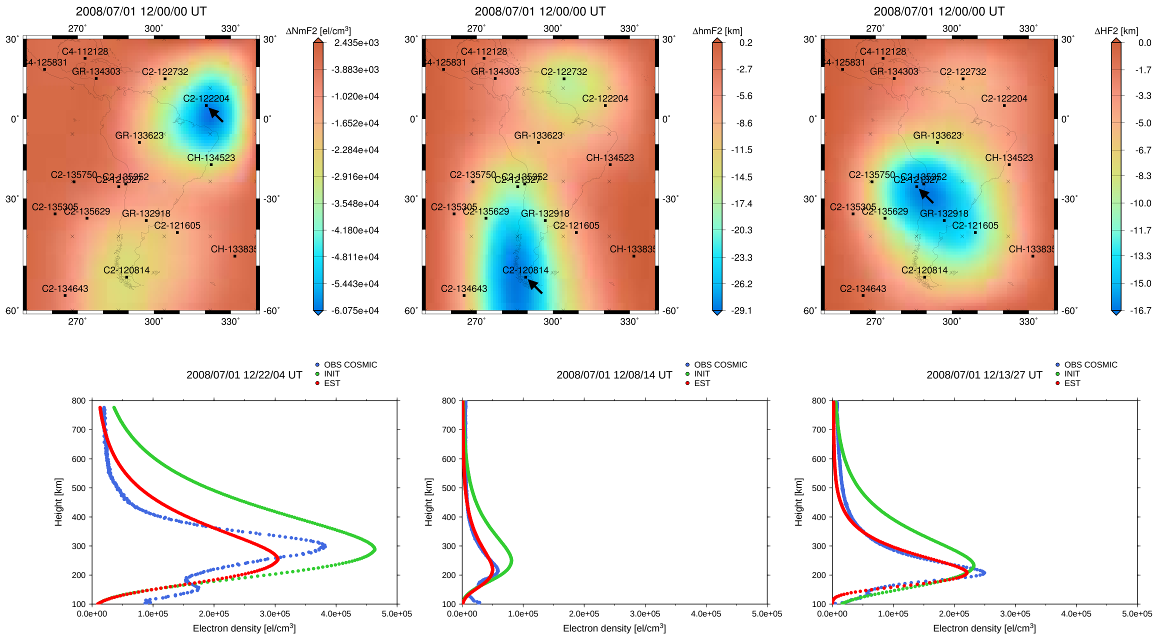


Fig. 3.3: *top row: estimated $\Delta\widehat{N}_m^{F2}$, $\Delta\widehat{h}_m^{F2}$ and $\Delta\widehat{H}^{F2}$ for a fixed epoch at 12:00 UT on 2008-07-01, with B-spline levels $J_1 = J_2 = 2$ for longitude and latitude, respectively, and $J_3 = 3$ for the time; bottom row: selected FORMOSAT-3/COSMIC profiles that have an impact on the key parameter estimation. These profiles are indicated by arrows on the corresponding correction maps above; for details see Limberger et al. (2013).*

could be improved by rejecting observations at lower atmospheric layers or by implementing an additional E-layer into the model. In this specific case, the E-layer is very dominant and forces the model to adjust the Chapman layer as a compromise between the F2- and E-layers.

In a second step, terrestrial GPS data are combined with electron density profiles (neglecting the profiles with dominant E-layer). Due to correlation issues, we deal with the two most important parameters, namely N_m^{F2} and h_m^{F2}. A time span from 13 UT to 15 UT during a low solar activity day (1 July 2008) was chosen; the distribution of all available data is shown in Fig. 3.4. The initial values $N_m^{F2}|_0$ and $h_m^{F2}|_0$ derived from the background model IRI-2007 are shown in the first column of Fig. 3.5. In the second column the estimated corrections $\Delta\widehat{N}_m^{F2}$ and $\Delta\widehat{h}_m^{F2}$ are displayed, and in the third one the estimated final parameter values $\widehat{N}_m^{F2}$ and $\widehat{h}_m^{F2}$ (i.e., $\widehat{N}_m^{F2} = N_m^{F2}|_0 + \Delta\widehat{N}_m^{F2}$, $\widehat{h}_m^{F2} = h_m^{F2}|_0 + \Delta\widehat{h}_m^{F2}$) are visualized. Since GPS data have better spatial coverage than electron density profiles, B-spline levels of $J_1 = J_2 = J_3 = 3$ for longitude, latitude and time could be selected. Significant corrections can only be obtained in areas with input data available (compare Fig. 3.4). The final estimated parameters describe small-scale structures compared to the initial parameters derived from IRI-2007. For most regions, N_m^{F2} gets relatively large negative corrections up to $2 \cdot 10^5$ el/cm^3, which indicates that IRI-2007 overestimates N_m^{F2} for the selected scenario, whereas $\Delta\widehat{h}_m^{F2}$ does not show a systematic bias but an absolute maximum of 57 km.

The estimated standard deviations of the parameters (last column of Fig. 3.5) show a higher precision of $\Delta\widehat{N}_m^{F2}$ in regions with input data available. There the precision reaches values of about $2.5 \cdot 10^3$ el/cm^3, whereas the precision is only around $5 \cdot 10^4$ el/cm^3 over the oceans. The precision of $\Delta\widehat{h}_m^{F2}$ reaches a value of about 2.7 km over the coastline of Chile with one density profile available at 13:54 UT; usually, $\Delta\widehat{h}_m^{F2}$ reveals a precision of about 13 km over the continents. The achieved precision is as expected: STEC is insensitive to h_m^{F2}, whereas electron density profiles are sensitive, but only pointwise; accordingly, the highest precision is achieved in regions with both STEC and density profiles available, followed by the areas with profiles only and the locations with terrestrial GPS only.

Based on the estimates $\widehat{N}_m^{F2}$ and $\widehat{h}_m^{F2}$, VTEC maps can be constructed according to the formula $\widehat{VTEC} = \int N_e(\widehat{N}_m^{F2}, \widehat{h}_m^{F2})\, dh$ by integrating the electron density from 80 to 2000 km height. Those can be compared with IRI-2007 and IGS GIMs. The latter are a combination of several ionosphere models provided

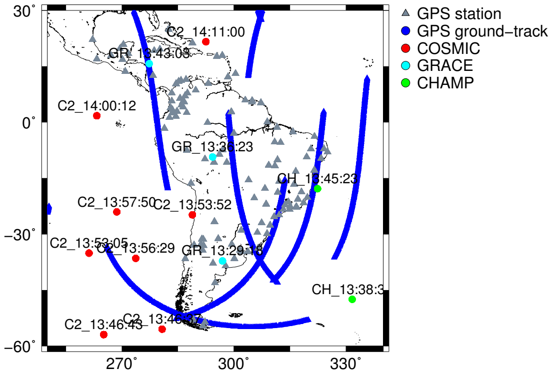


Fig. 3.4: *Data distribution within the study area for the time interval from 13 UT to 15 UT on 1 July 2008. Groundtracks (blue) of several GPS satellites observed by the permanent reference stations (gray triangles) of the SIRGAS-CON network; locations of electron density profiles derived from FORMOSAT-3/COSMIC (red dots), GRACE (cyan dots) and CHAMP (green dots), with observation time labeled in UT.*

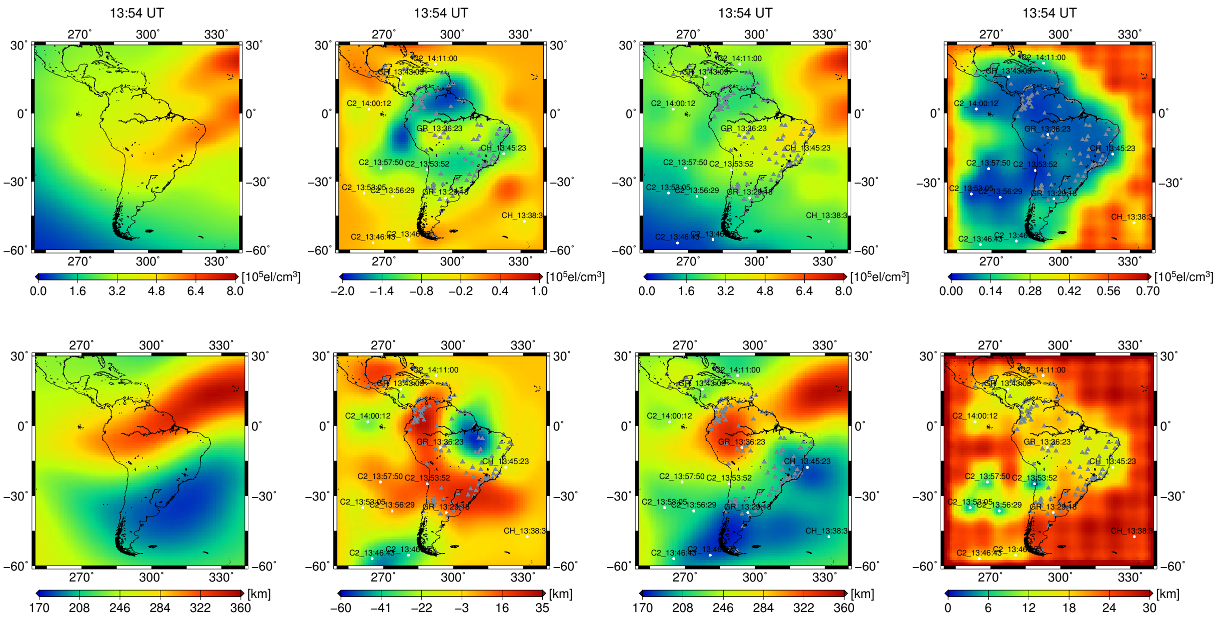


Fig. 3.5: *1st column: initial values* $N_m^{F2}|_0$ *and* $h_m^{F2}|_0$ *from IRI-2007; 2nd column: estimated corrections* $\Delta\widehat{N}_m^{F2}$ *and* $\Delta\widehat{h}_m^{F2}$*; 3rd column: estimated final parameters* $\widehat{N}_m^{F2}$ *and* $\widehat{h}_m^{F2}$*; 4th column: estimated standard deviations of* $\Delta\widehat{N}_m^{F2}$ *and* $\Delta\widehat{h}_m^{F2}$ *with B-spline levels* $J_1 = J_2 = J_3 = 3$.

by different IGS Associate Analysis Centers based on GNSS observations of the IGS ground network. Figure 3.6a shows the difference between IRI-2007 VTEC and the IGS GIM at 13:54 UT with an RMS value of 3.42 TECU. Figure 3.6b displays the difference between the estimated $\widehat{\mathrm{VTEC}}$ and the IGS GIM with an RMS value of only 2.80 TECU. Over the continent our estimation is closer to the GIM than the IRI model. Significant improvements can also be achieved in the areas with electron density profiles. Especially in the South Pacific Ocean around the magnetic equator, IRI shows large deviations (dark red in the left panel) that could be considerably improved (light red in the middle panel). It is worth mentioning that the quality of our model depends on the distribution of the observations as well as on the quality of the background model used to derive prior information.

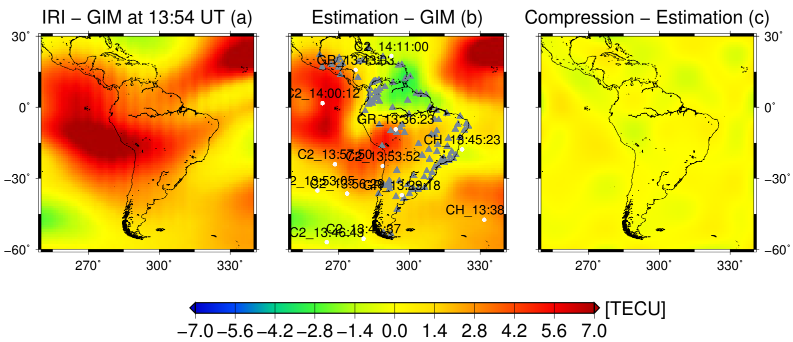


Fig. 3.6: *VTEC comparison: IRI-2007 – GIM (a);* $\widehat{\mathrm{VTEC}}$ *– GIM (b);* $\widehat{\mathrm{VTEC}}$ *from compressed* N_m^{F2} *–* $\widehat{\mathrm{VTEC}}$ *(c).*

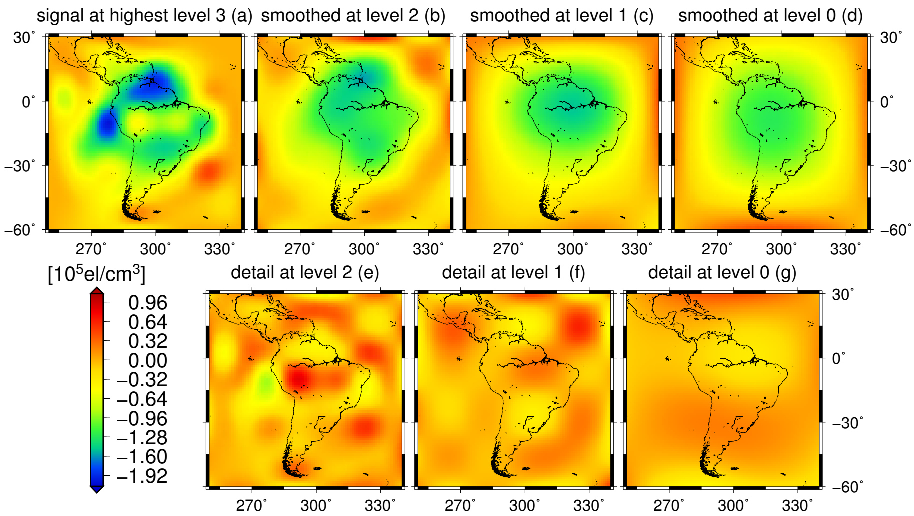


Fig. 3.7: *MSR of estimated* $\Delta\widehat{N_m^{F2}}$ *at 13:54 UT (1 July 2008): low-pass filtered smoothed signals (top: from left to right), estimated band-pass filtered detail signals (bottom: from left to right).*

From the unknown coefficients for the parameters an MSR can be performed. Figure 3.7 presents a graphical demonstration of the MSR exemplarily applied to the estimated $\Delta\widehat{N}_m^{F2}$ at 13:54 UT shown in Fig. 3.7a. The panels b-d depict the low-pass filtered smoothed signals, whereas the band-pass filtered detail signals are shown in the panels e-g, which contain the information of the difference of the smoothed signals with two adjacent levels in Fig. 3.7a-d. Hence, the sum of the smoothed signal at the lowest level (Fig. 3.7d) and the three detail signals (Fig. 3.7e-g) yields the signal at the highest level (Fig. 3.7a) which reflects the principle of the MSR. It is obvious that the structures become less detailed with decreasing level. Since more small-scale structures are contained in the higher-level detail signals, we apply level-dependent thresholds to neglect non-significant wavelet coefficients. Since more wavelet coefficients can be neglected in case of large thresholds, higher compression rates are achieved and more information might get lost. The difference between the compressed VTEC (282 coefficients) and the constructed VTEC without compression (1000 coefficients) is displayed in Fig. 3.6c; no significant difference can be seen, and the RMS value is around 0.35 TECU. Therefore, just a small number of wavelet coefficients needs to be stored without degrading the quality.

3.3 Continental hydrology

Database for hydrological time series of inland waters (DAHITI)

Since many years satellite altimetry gets more and more important for continental hydrology. The fact that altimetry – originally designed for open ocean applications – can also provide reliable results over inland waters makes it a very useful tool for continental hydrology, as it helps to understand the water cycle of the Earth system.

The new Database for Hydrological Time Series of Inland Waters (DAHITI) developed at DGFI provides time series for about 200 inland water targets (lakes, rivers, and wetlands) from multi-mission satellite altimetry. DAHITI is part of DGFI's Open Altimeter Database (OpenADB) which is available at *http://openadb.dgfi.badw.de*. All data sets are freely available, but they are provided without guarantee.

The methodology applied for DAHITI includes a new approach for the estimation of water level time series. In contrast to other groups such as LEGOS (Hydroweb), ESA (River and Lakes), or the US Department of Agriculture (Global Reservoir and Lake Elevation Database) we do not only use one single altimeter track per water body, but all multi-mission altimeter data available over the inland water

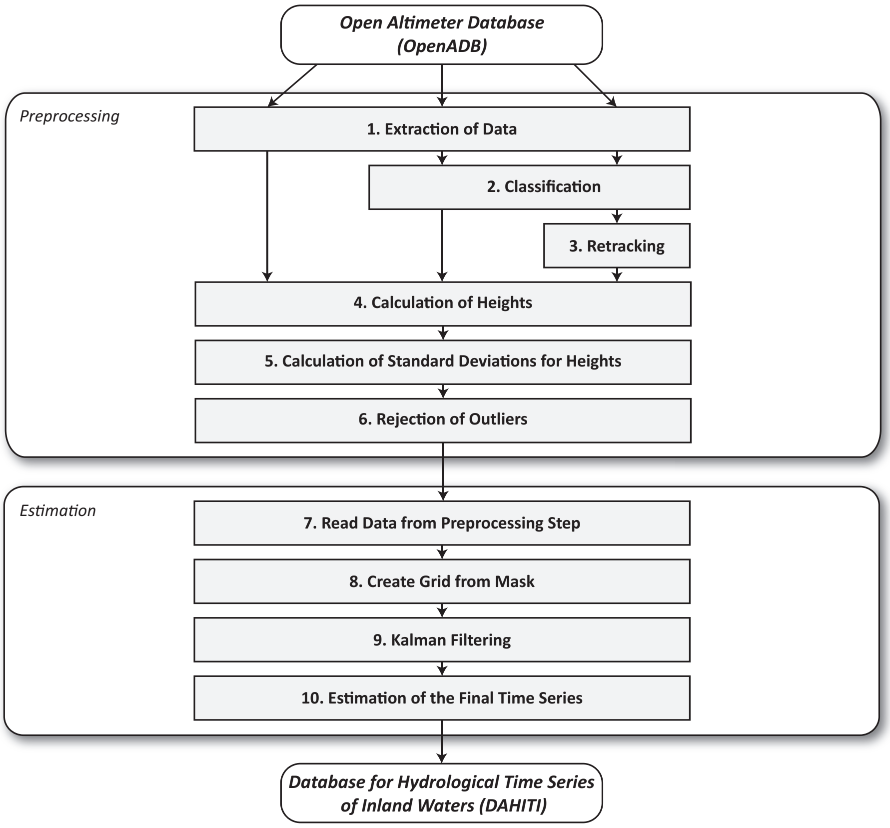


Fig. 3.8: *Flowchart for the estimation of water level time series from satellite altimetry.*

target. Moreover, a Kalman filter approach is applied for the estimation of water level heights for a certain time period. Figure 3.8 shows the processing strategy of DAHITI.

The initial step for the estimation of the water level time series is to extract all necessary altimeter data such as position, satellite height, range, geophysical corrections, time, geoid and waveforms from OpenADB for each water body. In case of small water bodies we can improve the original altimeter range by a retracking algorithm which is performed after a waveform classification. At the moment, three different classes are used: 'linear brown', 'linear exponential', and 'single peak'. The classification is done automatically by means of the so-called Support Vector Machine. Each waveform is assigned to a certain retracking algorithm which is used to estimate improved altimeter ranges. The final heights are computed considering original or retracked ranges (depending on data quality and water body extent), geographical corrections, geoid, and corrections for relative range biases between different missions. In addition, along-track standard deviations for each height are estimated. In the last preprocessing step, outliers are rejected. For this purpose, we use criteria such as location, maximum standard deviation, height thresholds, along-track Support Vector Regression (SVR), SVR for the whole missions, and waveform classes from the classification.

In the estimation procedure, the preprocessed water level heights are used for the computation of the final water level heights by applying a Kalman filter approach. For this approach, a spatial grid is derived from a land/water mask. The Kalman filter enables to compute values of water level heights for every epoch and grid node of the water body. Time-dependent heights derived from altimeter data, together with their standard deviations are used as input. In order to consider the evolution of the water level height before and after a certain epoch, a forward and backward Kalman filtering is applied. In a final processing step, an average height of all grid nodes is estimated for each epoch considering the error limit.

Figure 3.9 shows water level time series for three lakes of different size, namely Lake Michigan (USA), Lake Turkana (Ethiopia, Kenya), and Lake of the Woods (Canada, USA). Due to the different shape and size of the lakes, different altimeter data were used as input. For large lakes such as Lake Michigan, 1 Hz altimeter data are sufficient. For smaller lakes, high-frequent (10 Hz, 20 Hz) data are necessary because no (or not enough) 1 Hz data are available, as altimeter data close to the lakeshore are often contaminated by land reflections. Depending on the quality of the altimeter data, retracking of the altimeter waveforms can improve the existing ranges to achieve better results. Retracking of the altimeter data was performed, e.g., for Jason-1 and Jason-2 over the Lake of the Woods.

The resulting time series are highly consistent with in-situ data. Comparing the time series with tide gauges (red curves in Fig. 3.9), correlations of 0.95 (Lake Michigan) and 0.81 (Lake of the Woods) can be achieved. Thus, DAHITI provides smooth and reliable time series for inland waters which are valuable for many hydrological applications, mainly for areas without in-situ measurements. In future, DAHITI should also consider smaller water bodies. Therefore, an improved classification and retracking strategy will be necessary to achieve reliable time series. For this purpose, additional retrackers will be implemented and investigated and the number of waveform classes will be extended.

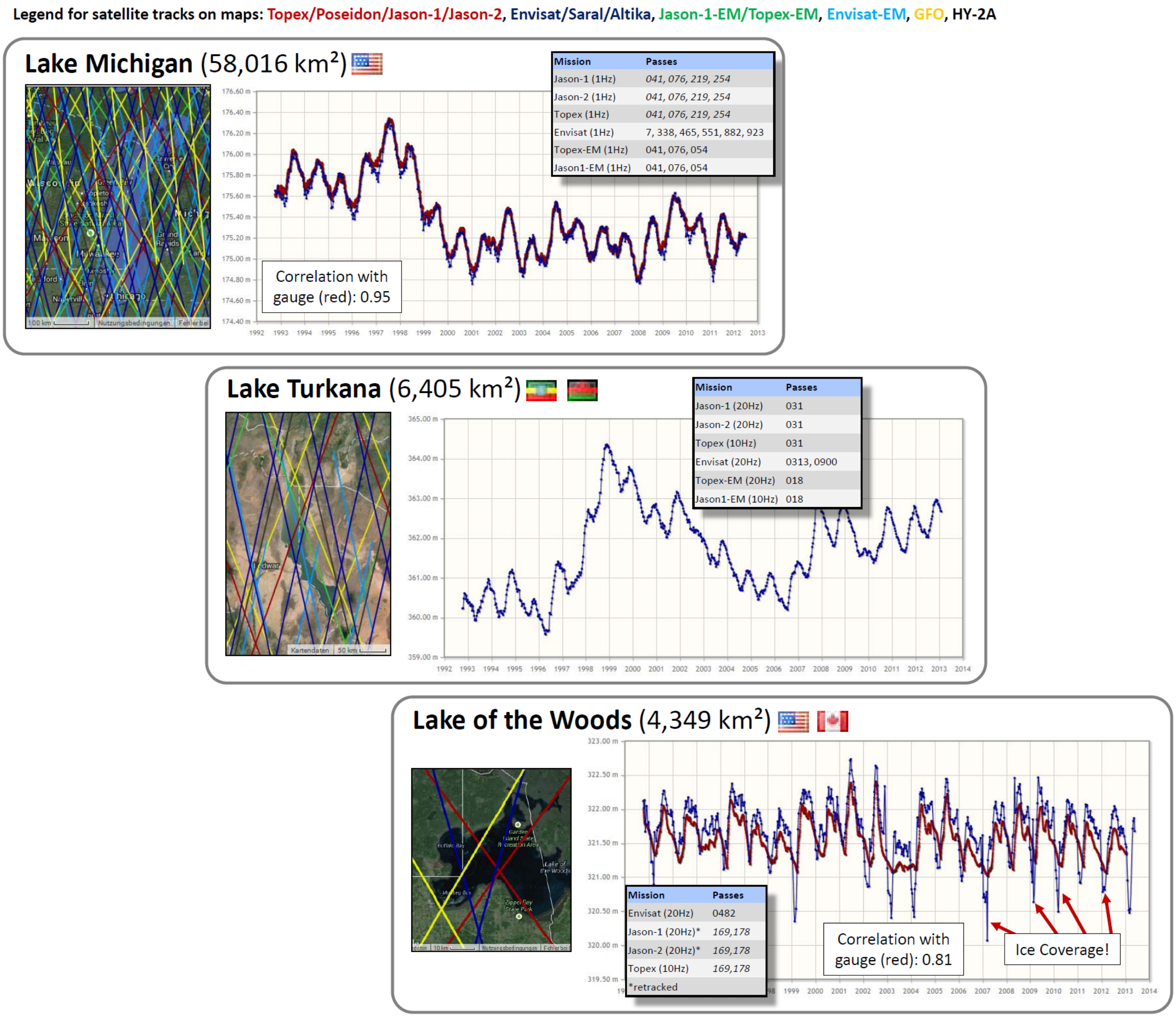


Fig. 3.9: Water level time series for Lake Michigan, Lake Turkana, and Lake of the Woods.

3.4 Ocean

Gridding of dynamic ocean topography profiles

In the context of the GEOTOP project of the DFG SPP1257 priority program ”Mass transport and mass distribution in the Earth system” a specific approach has been developed to estimate instantaneous profiles of the dynamic ocean topography (iDOT profiles). This so-called profile approach evaluates differences between multi-mission along-track sea surface height measurements and geoid heights derived from a satellite-only gravity field model (e.g., GOCO03S), both of them filtered by the same Gaussian filter to ensure spectral consistency. The advantage of the iDOT profiles is obvious: for the first time a two-decade time series of the dynamic ocean topography could be provided (Bosch et al., 2013). Moreover, the short length of about 70 km for the Gaussian filter does not only allow to identify eddies in the strong western boundary currents, but also to trace them as long as their amplitude with respect to a mean dynamic topography is significant. As an example, the DGFI Annual Report 2012 illustrated how the Gulf Stream position seasonally varies with the most southern (northern) position in winter (late summer).

On the other hand, also gridding of the iDOT profiles is desirable. By finite differences, it allows to infer the geostrophic surface velocities, to identify areas with strong eddy formation and to compute the eddy kinetic energy. A long-term mean dynamic ocean topography (MDOT) is required in order to use the geodetic mission phase of Geosat for marine gravity field recovery. The gridding of available iDOT profiles is simplified by the fact that since the end of 1992 the multi-mission altimeter scenario provides a sufficient spatial sampling, e.g. for a $1^\circ \times 1^\circ$ grid. For a dedicated MDOT estimate we considered the period from October 2002 to September 2005 with five altimeter systems observing simultaneously (TOPEX-EM, Jason-1, ERS-2, ENVISAT, and GFO). Thereby, even a grid of $30' \times 30'$ could be resolved. First, the iDOT profiles were used to generate a time series of 10-day DOT snapshots. Then, 110 of those snapshots were averaged to the MDOT. Finally, the residuals between individual 10-day snapshots and the MDOT were used to derive the MDOT standard deviation.

Figure 3.10 (top) shows the three-year MDOT estimate with the twofold typical positive topograpy pattern in the Pacific related to the large-scale basin-wide circulation, clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere. The bottom panel of Fig. 3.10 indicates, by means of the standard deviation, those areas with intensive formation of eddies (circular pattern with a diameter of 50-200 km).

The gridding of profiles with partly irregular distribution requires particular attention: even though the profiles of different missions were cross-calibrated, there are a few passes which are offset by a few decimeters and cause ’trackiness’ in the mean topography. For the present investigation any ’trackiness’ was absorbed by comparing each profile with a smooth topography and by skipping profiles with the magnitude of differences exceeding a threshold of 0.3 m.

3.5 Solid Earth

30 m vertical pendulum in Berchtesgaden

Since 2007 DGFI operates a 30 m vertical pendulum in the salt mine of Berchtesgaden. In 2013, two technical main modifications were made in order to ensure more reliable and stable operations of the pendulum.

In the original setup (Fig. 3.11), two mounting angles were attached on floating bearings to the ground plate. On each angle, a measurement spool was mounted. The angles were perpendicular to each other and could be aligned by servomotors automatically. The alignment was necessary due to a small drift

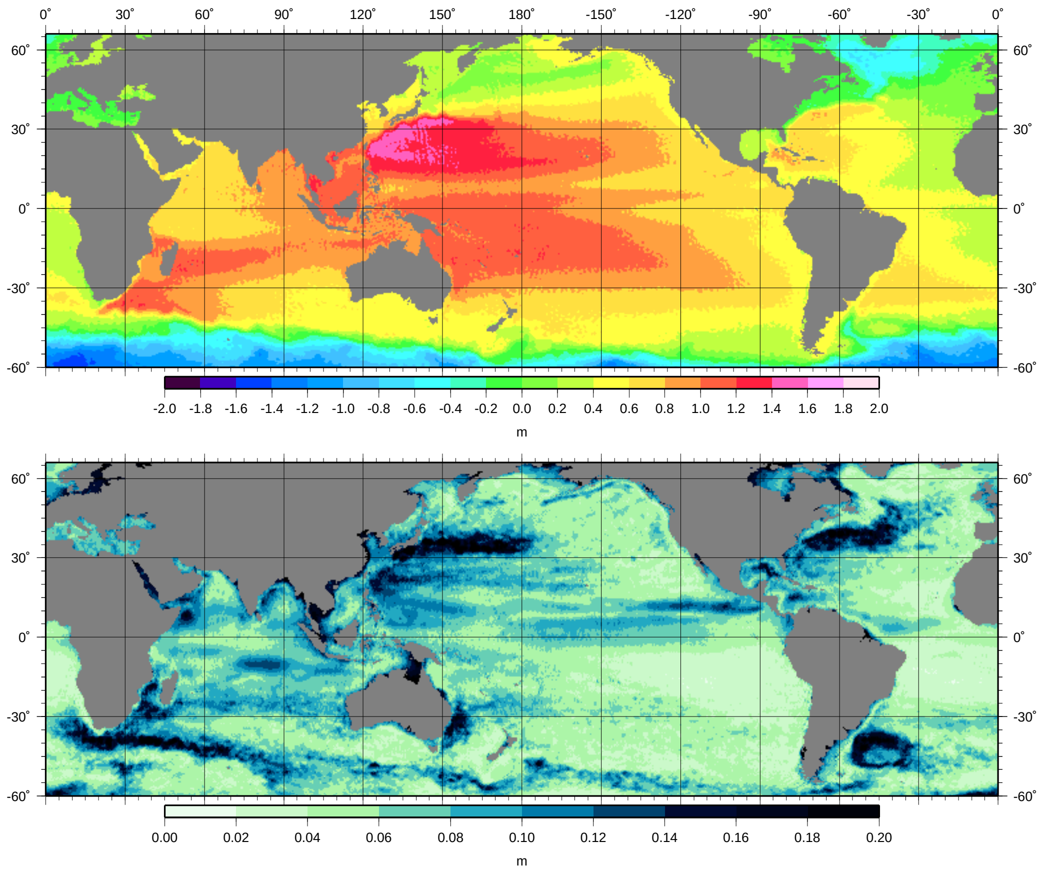


Fig. 3.10: *Top: Three-year mean [m] of the dynamic ocean topography (MDOT) for the period 10/2002 – 09/2005. Bottom: Standard deviation [m] of the MDOT estimate. High standard deviations can be detected for the western boundary currents where intensive eddy formation takes place.*

of the pendulum mass with respect to the measurement unit. Since the reactivation of the pendulum in 2007, the situation changed. An increased drift required a manual alignment every 7 to 8 weeks at maximum. For each aligment, the ferrite cores in the spools had to be dismounted from the pendulum mass. This procedure was a very invasive interference in the whole system and caused both temperature rise and a possible disalignment since the alignment depends strongly on the subjective sensation. The new measurement setup consists of two secondary plates which are mounted on floating bearings on the original ground plate and can be aligned automatically via servomotors (Fig. 3.12). On the upper plate, the original mounting is fixed. The whole measurement unit was demounted and brought to Munich for reconstruction. There, the plates were installed and nickeled. To the new construction, several perforations were added and all plates were connected. Finally, the measurement unit was reinstalled at the salt mine in Berchtesgaden. Now, the necessary realignment to compensate the drift is possible from Munich via remote control.

The system installed for data logging in 2007 is called 'LogMessage' (Delphin company). It allows a high recording rate even for a high data resolution (24 bit). Therefore, no electric filters are necessary. With the new software, the data processing, recording and transferring could be realized. Furthermore, the servomotors for the realignment can be controlled. Due to a LAN connection (10 Base-T), the whole system is directly placed at the measurement unit and, thus, disturbing signals (temperature, etc.) can be avoided. The controlling of the whole pendulum could be significantly simplified through the remote control. In November 2013, the measurement and the remote control unit were reinstalled in the salt mine. Since December 2013, the pendulum operates in the normal measurement mode.

Fig. 3.11: Measurement unit with pendulum mass before update.

Fig. 3.12: Measurement unit with pendulum mass after update.

Related publications

Bosch W., Savcenko R., Dettmering D., Schwatke C.: A two-decade time series of eddy-resolving dynamic ocean topography (iDOT), In: Ouwehand L. (Ed.) Proceedings of "20 Years of Progress in Radar Altimetry", Sept. 2012, Venice, Italy, ESA SP-710 (CD-ROM), ISBN 978-92-9221-274-2, ESA/ESTEC, 2013

Dettmering D., Schmidt M., Limberger M.: Contributions of DORIS to ionosphere modeling. In: Ouwehand L. (Ed.) Proceedings of "20 Years of Progress in Radar Altimetry", IDS Workshop, Sept. 2012, Venice, Italy, ESA SP-710 (CD-ROM), ISBN 978-92-9221-274-2, ESA/ESTEC, 2013

Göttl F.: Kombination geodätischer Raumbeobachtungen zur Bestimmung von geophysikalischen Anregungsmechanismen der Polbewegung. Deutsche Geodätische Kommission, Reihe C, Heft 714, Verlag der Bayerischen Akademie der Wissenschaften, ISBN 978-3-7696-5126-3, 2013

Liang W., Limberger M., Schmidt M., Dettmering D., Hugentobler U.: Combination of ground- and space-based GPS data for the determination of a multi-scale regional 4-D ionosphere model. IAG Symposia Series, Nov. 2013, Potsdam, Germany, submitted

Limberger M., Liang W., Schmidt M., Dettmering D., Hugentobler U.: *Regional representation of F2 Chapman parameters based on electron density profiles*. Ann Geophys 31(12): 2215–2227, DOI:10.5194/angeo-31-2215-2013, 2013

Seitz F.: *Geodätische Erdsystemforschung*. Akademie Aktuell 02/2013: 21-22, Bayerische Akademie der Wissenschaften, ISSN 1436-753X, 2013

Singh A., Seitz F., Schwatke C.: Application of multi-sensor satellite data to observe water storage variations. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 6(3): 1502–1508, DOI:10.1109/JSTARS.2013.2258326, 2013

4 Methodological Foundations

Research on methodology has been identified as a cross-sectional field of activities serving all other research areas. This includes the development of generic methods and algorithms, to be implemented in a numerically efficient way, to be tested, documented and maintained such that its application leads to robust results in short time allowing sound decisions in research and development. In addition, acquisition, backup, documentation and long-term storage of primary data must be taken into account in order to provide the longest possible time series of observations related to a reproducible geodetic reference frame for reliable findings in global change studies. Also current analysis methods are to be reviewed, the validity of their assumptions is to be verified in order to identify deficits or inconsistencies in the modelling and to deduce recommendations for an improved parameterisation.

In the following we report about current developments and updates within the DGFI Orbit and Geodetic parameter estimation Software (DOGS), about progress of the Bureau of Standard and Conventions (BSC), and the construction of a satellite altimeter data simulator.

4.1 Numerical methods and parameter estimation

DOGS-OC development

As an official analysis centre of the ILRS, DGFI maintains and develops a software called DGFI Orbit and Geodetic parameter estimation Software (DOGS). The library to analyze SLR observations is called 'Orbit computation'. The updates to the official software version which were made in 2013 are summarized in Table 4.1.

Table 4.1: *DOGS-OC software updates in 2013.*

date of change	update description
2013-05-13	Separation of non-tidal atmospheric pressure corrections for loading and gravity
2013-06-25	New derivatives of CRF-TRF rotation matrix
2013-06-26	Release of DOGS-OC 5.03
2013-06-28	Implementation of tidal atmospheric loading
2013-07-01	Improvement of tidal atmospheric loading
2013-07-05	New data format for atmospheric loading
2013-08-01	New input record ELIMTIME
2013-08-06	Station-dependent centre of mass corrections
2013-08-09	Parameter array containing satellite data
2013-09-20	Bug fix correcting the counter of observation and orbit files
2013-11-26	Implementation of ocean pole tide loading (*)
2013-12-05	Implementation of tidal admittance functions for ocean tides (*)
2013-12-12	Implementation of IERS 2013 Earth tide model (1st+2nd waves) (*)

(*) changes only implemented in developing version yet.

For the DOGS development, the version control program 'Subversion' (SVN) is used. Therefore, any prior version of DOGS could be recompiled, if necessary. Furthermore, we introduced an e-mail alert for each SVN change of DOGS to all developers and users of DOGS at DGFI.

The above summarized updates significantly improved the accuracy of the observation analysis in DOGS-OC at DGFI.

DOGS-RI development

Currently, the VLBI analysis software OCCAM is refined to become part of DOGS. The new module will be called DOGS-RI (radio interferometry). All routines are based on the IERS 2010 Conventions and the celestial intermediate pole (CIP). The theoretical models for the group delay need time derivatives and, in case of delay rate, also the second time derivatives of the input parameters. The OCCAM approach to approximate these derivatives by finite differences with a fixed time step of 2 s was superseded. Parameter and observation models were expanded to provide analytically calculated first and second time derivatives. This conversion is complete except for some routines calculating the equinox-based transformation matrix from the nutation parameters $\Delta\psi$ and $\Delta\varepsilon$. Thus, only the branch based on X_{CIP}, Y_{CIP} and the celestial intermediate origin (CIO) is operative. The correlations between $(X_{\mathrm{CIP}}, Y_{\mathrm{CIP}})$ and $(x_{\mathrm{pol}}, y_{\mathrm{pol}})$ are not yet theoretically modelled; condition equations to prevent subdiurnal retrograde motions still lack in the program.

4.2 Standards and conventions

The Bureau for Standards and Conventions (BSC) was established as a GGOS component in 2009. The BSC is hosted and supported by DGFI and the Institut für Astronomische und Physikalische Geodäsie (IAPG) of TU München, under the umbrella of the Forschungsgruppe Satellitengeodäsie (FGS).

Purpose

The work of the BSC is primarily focussed 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 purpose and major goal of the BSC is to ensure that common standards and conventions are adopted and implemented by the IAG components as a fundamental basis for the analysis of geodetic observations to ensure consistent results for the geometry, rotation and gravity field of the Earth along with its variations in time.

Objectives

The BSC supports GGOS in its goal to obtain products of highest accuracy, consistency, and temporal and spatial resolution, which refer to a unique reference frame, stable over decades in time.

According to the Terms of Reference the objectives of the BSC are:

- To keep track of the strict consideration of adopted geodetic standards, standardized units, fundamental physical constants, resolutions and conventions in the generation of IAG/GGOS products.
- To review, examine and evaluate all standards, constants, resolutions and conventions adopted by IAG or its components and recommend their use or propose the necessary updates.
- To identify gaps, inconsistencies and deficiencies in standards and conventions and to initiate steps to remove them.
- To propose the adoption of new standards where necessary.
- To propagate standards and conventions to the wider scientific community and promote their use.

Major activities in 2013

The major BSC activities were focussed on the compilation of an inventory of standards and conventions used for the generation of the IAG/GGOS products, such as the celestial and terrestrial reference frames, the Earth orientation parameters, orbits for GNSS satellites, global and regional gravity fields as well as

Table 4.2: *Representatives of IAG Services, IAU and other entities in the BSC (status: December 2013).*

G. Petit, France	International Earth Rotation and Reference Systems Service (IERS)
U. Hugentobler, Germany	International GNSS Service (IGS)
E. Pavlis, USA	International Laser Ranging Service (ILRS)
J. Gibson, USA	International VLBI Service for Geodesy and Astrometry (IVS)
F. Lemoine, J. Ries, both USA	International DORIS Service (IDS)
R. Barzaghi, Italy	International Gravity Field Service (IGFS)
F. Barthelmes, Germany	International Center for Global Gravity Field Models (ICGEM)
S. Bonvalot, France	International Gravimetric Bureau (BGI)
R. Heinkelmann, Germany	International Astronomical Union (IAU), Working Group "Numerical Standards for Fundamental Astronomy"
M. Craymer, Canada	Chair of Control Body for the ISO Geodetic Registry Network
J. Ádám, Hungary	Chair of the IAG Communication and Outreach Branch
J. Ihde, Germany	IAG representative to ISO/TC211
J. Kusche, Germany	Representative of gravity community

vertical reference frames. This includes an evaluation of the standards and conventions currently in use in the geodetic community such as the Geodetic Reference System 1980, the IERS Conventions 2010 and the standards for gravity missions (e.g, CHAMP, GRACE, GOCE). Relevant are also resolutions of IUGG, IAG and IAU as well as standards and fundamental physical constants adopted by external bodies (e.g., ISO, BIPM, CODATA). The BSC evaluates the status as regards standards and conventions for the mentioned IAG/GGOS products, identifies gaps and inconsistencies as well as interactions between different products. A publication of such a product-based inventory is in progress and will be entitled: "*GGOS Bureau for Standards and Conventions: Inventory of standards and conventions used for the generation of IAG/GGOS products*". The current status of numerical standards, including the definition of time and tide systems is given as an example of this inventory (see Table 4.3).

The compilation of such an inventory requires the participation of the IAG Services and interaction between the BSC and IAG, IAU and the other entities involved in standards and conventions. These links could be established by including representatives from these entities as Associated Members of the BSC (Table 4.2).

Numerical standards, time and tide systems

The IUGG resolution No. 7 (1979) and the IAG resolution No. 1 (1980) recommend the Geodetic Reference System 1980 to be used as the official reference for geodetic work. GRS80 is defined by four conventional constants GM, a, J_2 and ω which are given with their numerical values in Table 4.3. In addition, this table shows the consistent set of fundamental parameters, the numerical standards of the IERS Conventions 2010 and those of the Earth Gravitational Model 2008 (EGM2008).

Table 4.3 demonstrates that the numerical standards given in the four sources are quite different for some parameters. Apart from that, some of the values such as the equatorial radius of the Earth a and for the dynamical form factor J_2, are expressed in different tide systems and GM depends on the definition of the time system. Confusion may also be caused within the IERS Conventions itself, since the GRS80 ellipsoid parameters are recommended for the transformation of Cartesian to ellipsoidal coordinates, while other values are given for the numerical standards in the IERS Conventions 2010 (Table 4.3). Also the time and tide systems as used by the different geodetic communities are a potential source of confusion and inconsistency. The IUGG resolutions from 1991 require units to be consistent with the Geocentric Coordinate Time (TCG) scale. In practice, however, Terrestrial Time (TT) scale is commonly used since all geodetic measurements are time tagged with a time scale consistent with TT. As mentioned, another source of inconsistency is the use of different tidal systems for geodetic applications and purposes. While the gravimetric services provide products mostly in the zero-tide system, in agreement with IAG resolution 16 of the 18^{th} General Assembly 1983, the geometric services provide their products, e.g., the ITRF,

Table 4.3: *Comparison of numerical standards. The IERS Conventions 2010 provide the TCG value for the gravitational constant (GM) in Table 1.1, in addition the TT-compatible value is given in Section 1.2 of that document.*

Quantity	**GRS80**	**Fundamental Parameters**[1]	**IERS2010**	**EGM2008**	**Unit**
Gravit. constant (GM)					
– TCG value	398.6005	398.6004418	398.6004418		[10^{12}m^{3}s^{-2}]
– TT value			398.6004415	398.6004415	
Equatorial radius (a)					
– zero-tide value	6378137.0		6378136.6		
– mean-tide value		6378136.7			[m]
– tide-free value				6378136.3	
Dyn. form factor (J_2)					
– zero-tide value	1082.63	1082.6359	1082.6359	1082.6361	[10^{-6}]
Ang. rot. velocity (ω)	7.292115	7.292115	7.292115	7.292115	[rad s^{-1}]

[1] Groten E., 2004. Fundamental Parameters and Current (2004) Best Estimates of the Parameters of Common Relevance to Astronomy, Geodesy, and Geodynamics. J Geod 77(10-11), 724-797, doi:10.1007/s00190-003-0373-y

in the tide-free system. In applications involving satellite altimetry, the mean-tide system is commonly used. All the geodetic products should be expressed in the same time and tide system before combining them. Using different numerical standards, time and tide systems is a potential source for inconsistencies and even errors of geodetic products. Particularly, users not specialized in geodesy may have difficulties in using geodetic products correctly due to their lack of knowledge about the properties of the products.

4.3 Satellite altimeter data simulator

The ability to simulate satellite altimetry data has been recognized as an important tool for investigating the space-time sampling capability of new single altimeter missions or multi-mission altimeter scenarios. For example, Sentinel-3, to be launched in 2014, will have a completely new orbit configuration with a 27-day repeat cycle. The impact of its ground track pattern on estimating ocean tides or monitoring ocean dynamics is not clear right from the start.

An altimeter data simulator should allow predicting the altimeter ranges for a given location and time as a function of atmospheric conditions and effects on the ocean surface like ocean tides, wind and waves, and seasonal as well as secular variations with geographically varying pattern. Given the orbital ephemeris of a satellite, it is straightforward to derive altimeter ranges that would be measured to a mean sea surface. Ocean tides can have coastal amplitudes of several meters and would be the second largest effect to be considered for simulated altimeter data. As models for the mean sea surface and the global ocean tide are available, these two simulator components are easy to implement. More critical is a realistic simulation of non-tidal, seasonal and aperiodic sea surface height variations. The forecasting of non-tidal sea surface height variations was investigated and prototyped within the scope of a master thesis.

From the experience of previous analyses, a combination of deterministic and stochastic approaches is best suited for predicting non-tidal sea surface height variations. The most efficient way to describe seasonal variations of sea surface heights is a Fourier series. Two historic data sets were analyzed: a 20-year multi-mission compilation with 0.5° spatial and monthly temporal resolution and a 10-year data set derived from TOPEX only, defined on a 1.875° grid, sampled every 10 days. The coefficients of annual and semi-annual periods were estimated by harmonic analysis and stored for simulation requests. The residual sea surface height variations (with periodic components removed) were then subject to a principal component analysis (PCA) describing the temporal evolution of the most dominant sea surface height variations. In order to approximate 80% of the residual signal, some 77 modes with their spatial pattern and temporal coefficients had to be stored. This concept and the relationship to other components of the simulator is illustrated by the flowchart in Fig. 4.1.

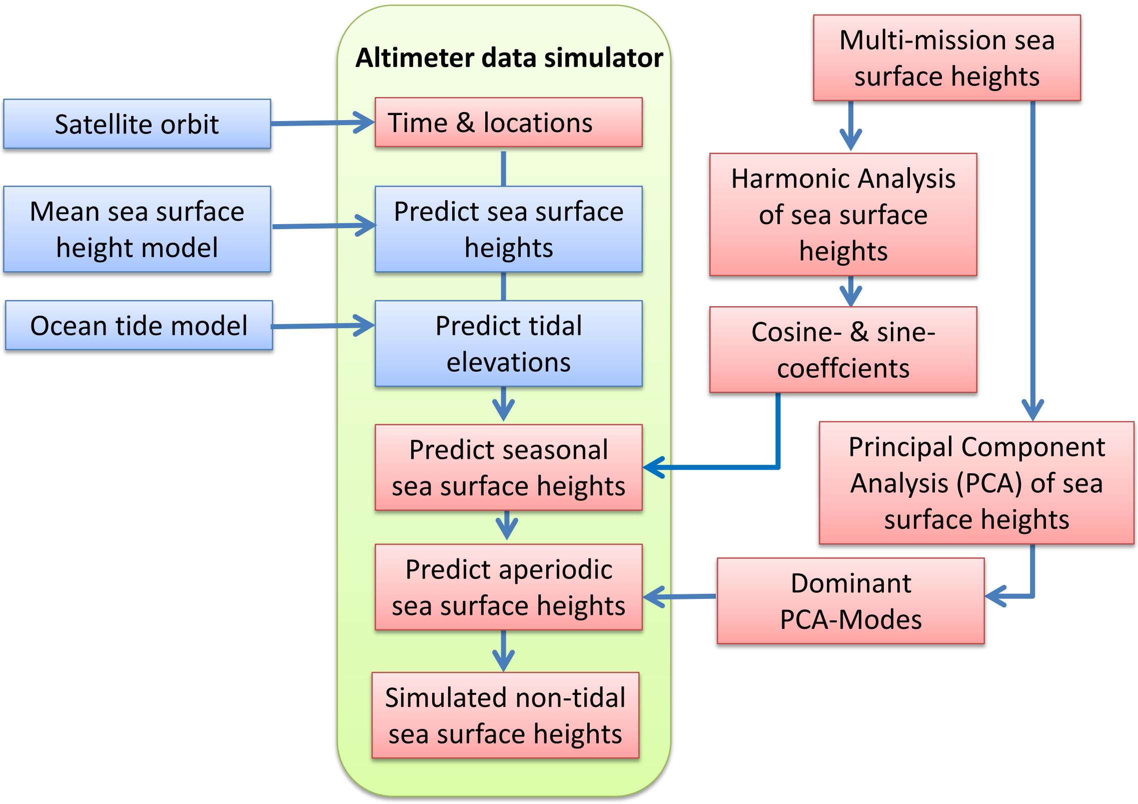


Fig. 4.1: *Flow chart for an altimeter data simulator with focus on non-tidal seasonal and a-periodic sea surface variations.*

The simulator was validated by reconstructing observed ERS-2 data for a 35-day cycle at the end of 1997. The differences between observed and simulated sea level anomalies showed RMS values of 10 and 8.5 cm for the 20-year and the 10-year data set respectively. With regard to the significant smoothing implied by approximation and interpolation those figures appear to be acceptable. A good balance between spatial and temporal resolution of the historic data has to be investigated.

Related publications

Angermann D.: *Bureau for Standards and Conventions*, Travaux, Vol. 38, Report of the International Association of Geodesy 2011-2013, 2013

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 Series, Sept. 2013, Potsdam, Germany, accepted

Ludwig W.: Vorhersage gezeitenfreier Meereshöhenvariationen – eine Komponente eines Altimetrie-Daten-Simulators. DGFI/TUM Master Thesis, 2013

5 Information Services and Scientific Transfer

It is of particular importance for fundamental research on geodesy (a rather unacquainted field in geosciences) to provide information on research projects, scientific results, value-added data and products to both the scientific community and the public. Exchange of knowledge and scientific results is a basic requirement for any research that is more and more based on international cooperation. Publications in peer-reviewed scientific journals are still the most acknowledged way of scientific transfer. Section 5.2 provides a list of the papers printed or published online in 2013. It is followed by a list of posters and oral presentations that wered presented by DGFI staff at numerous workshops, symposia and conferences.

Besides, the internet is intensively used as a platform for information exchange. DGFI maintains a homepage on which all research activities, projects and cooperations of the institute are described in detail. Under the heading of "hot stories" we call attention to the most recent results. Quite a number of additional web sites are maintained by DGFI, particularly those of the Office of the International Association of Geodesy (IAG) and of the German Geodetic Commission (Deutsche Geodätische Kommission, DGK) including an online catalogue with about 1000 publications (predominantly dissertations) published by the DGK. Further internet sites are set up and maintained for large projects, services and national research programmes.

5.1 Internet representation

The Internet has become an indispensable medium for the exchange of data and scientific information. The DGFI maintains several independent internet sites and wikis to meet growing demands for information about different scientific aspects.

Internet sites set up and maintained by DGFI

Internet sites maintained by the DGFI:

- Deutsches Geodätisches Forschungsinstitut (DGFI)
- Deutsche Geodätische Kommission (DGK)
- Office of the International Association of Geodesy (IAG)
- DFG priority programme "Mass transport and mass distribution in the Earth system" (SPP1257)
- Geocentric Reference System for the Americas (SIRGAS)
- EUROLAS Data Center (EDC)
- Open Altimeter Database (OpenADB)
- Geodesy Information System (GeodIS)
- International Altimetry Service (IAS)
- ESA projects
- IAG Working Groups
- IAG Joint Study Groups

DGFI

The DGFI home page, available at

http://dgfi.badw.de,

informs about the structure and results of the current research programme, ongoing research topics, the national and international projects DGFI is involved in and the multiple contributions of DGFI to international services. The web site (see Fig. 5.1) also provides a complete list of papers and reports published since 1994 by the employees as well as a compilation of all posters and oral presentations. Annual reports and DGFI reports are available in electronic form.

DGK

Another web site is maintained for the "Deutsche Geodätische Kommission" (DGK). It is available at

http://dgk.badw.de

and informs about the structure of the DGK, the membership, sections, geodetic research institutes in Germany, and the numerous publications of DGK. The complete catalogue of DGK publications can be downloaded as a pdf file or browsed by means of a user-friendly search function (see Fig. 5.1).

IAG Office

At the General Assembly of IUGG in Perugia, Italy, the IAG was reorganized. The position of the IAG Secretary General was handed over to the retired director of DGFI, and the IAG Office was established at DGFI. The web site

http://iag.dgfi.badw.de

was installed to support the work of the Office.

DGFI priority programme "Mass transport and mass distribution in the Earth system"

Another internet site for the DFG priority programme "Mass transport and mass distribution in the Earth system", SPP1257. It resides on a DGFI server, but has its own domain name

http://massentransporte.de.

The site (see Fig. 5.2) makes the SPP programme known to the public and other scientists (outreach), supports the organization of international symposia, and provides a basis for internal information exchange with links to data and products that are relevant for the priority programme.

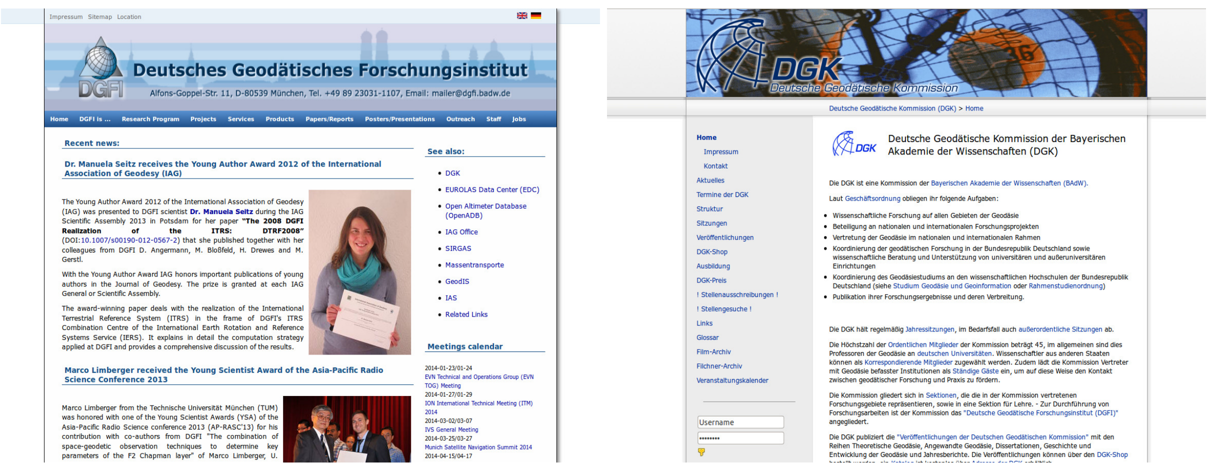


***Fig. 5.1:** Screenshots of the home pages of DGFI (left) and DGK (right)*

SIRGAS

SIRGAS is the Geocentric Reference System for the Americas. The web site is operated by the SIRGAS Vice-President at DGFI and located at

http://sirgas.org.

The SIRGAS web site comprises (see Fig. 5.2)

- a scientific description presenting definition, realization, and kinematics of the SIRGAS reference frame,
- an organizational summary showing the operational structure and functions of the different components of SIRGAS,
- a bibliographic compilation with reports, articles, presentations, and posters related to the SIRGAS activities.

EUROLAS Data Center (EDC)

The EUROLAS Data Center (EDC) provides access to the database of SLR observations and derived products (see Fig. 5.3). This web site informs about the data flow within the Operation Centre (OC) and the data holding of the Data Centre (DC). This site is available at

http://edc.dgfi.badw.de.

Open Altimeter Database (OpenADB)

OpenADB is a database for multi-mission altimeter data and derived high-level products. It is designed for users with little experience in satellite altimetry and scientific users evaluating data and generating new products, models and algorithms. OpenADB allows fast parameter updates and enables database extracts with user-defined formats and parameters. The usage of OpenADB is open after registration to anyone (see Fig. 5.3). This site is available at

http://openadb.dgfi.badw.de.

Fig. 5.2: Screenshots of the web sites of the DFG priority programme "Mass transport and mass distribution in the Earth system" (left) and SIRGAS (right)

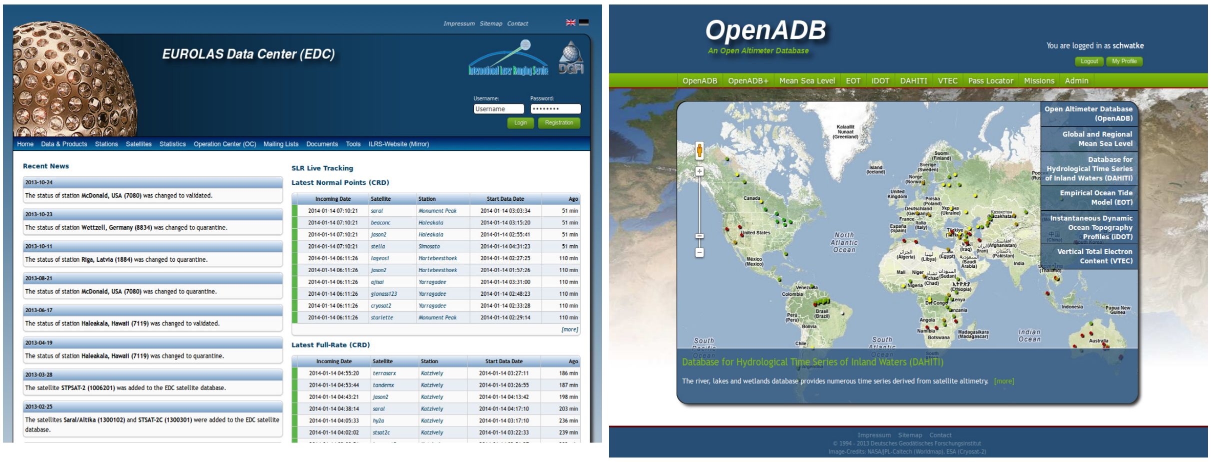


Fig. 5.3: Screenshots of the web sites of the EUROLAS Data Center (left) and the Open Altimeter Database (right)

GeodIS

The geodesy information system GeodIS, located at

http://geodis.dgfi.badw.de,

is maintained by DGFI with the objective to compile information about the most important areas of geodesy. The intention of GeodIS is to give support in finding information on and data relevant to geodesy. GeodIS provides also links to the home pages of international scientific organizations.

International Altimetry Service (IAS)

The home page of the International Altimetry Service

- provides a point of contact for general information on satellite altimetry and its applications;
- communicates and interfaces with altimeter mission data providers and with centres which process, archive and analyze altimeter data and other related services and organizations;
- promotes satellite altimetry as a core element of Global Earth Observing Systems;
- helps users to compile and analyze data and to respond to altimeter user requirements.

This site is available at

http://ias.dgfi.badw.de.

ESA projects

The web sites of the GOCE+ GeoExplore and the GOCE+ Time-Variations (see Fig. 5.4) are available at

http://goce4interior.dgfi.badw.de

and

http://gocedt.dgfi.badw.de.

Both web sites provide information about the progress of the projects. Presentations related to the projects are also available.

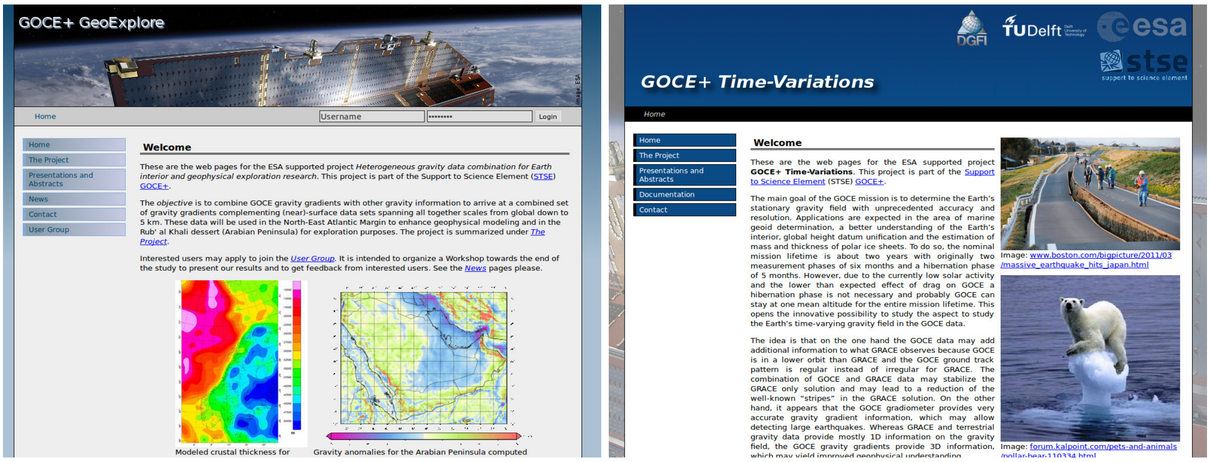


Fig. 5.4: Screenshots of the ESA project home pages of "GOCE+ GeoExplore" (left) and "GOCE+ Time-Variations" (right)

IAG Working and Joint Study Groups

The DGFI maintains web sites of three IAG Working (IAG-WG) and Joint Study Groups (IAG-JSG).

- IAG Joint Working Group 0.1.1 – "Vertical Datum Standardisation" (*http://whs.dgfi.badw.de/*)
- IAG Joint Working Group 1.3 – "Strategies for Epoch Reference Frames" (*http://erf.dgfi.badw.de/*)
- IAG Joint Study Group 0.3 – "Methodologies of Regional Gravity Field Modelling" (*http://jsg03.dgfi.badw.de/*)

Wikis mainted by DGFI

In addition to the different web sites, the DGFI currently maintains seven wikis which are used for information exchange within projects or working groups.

Mailing lists

Mailing lists are maintained by DGFI to fulfill the requirements for information exchange within the ILRS Global Data Centre, the Reference System SIRGAS and CGE. The mailing lists are realized by the 'mailman' program which transforms submitted e-mails to a specific format which can then be viewed by any internet browser sorted according to date, thread or author.

Intranet

Another server behind a firewall is used to provide Intranet functionality, on the basis of the Typo3 CMS. The internal information exchange is supported by a black board, a meeting calendar, the access to the library database, and numerous pages which can be created, modified or deleted by any of the employees. The pages compile internal information for the work of particular research topics, links to data sets, formats, internal documentation and the necessary meta data.

5.2 Publications

Abelen S., Seitz F.: *Relating satellite gravimetry data to global soil moisture products via data harmonization and correlation analysis*. Remote Sensing of Environment 136: 89-98, Elsevier, 2013

Angermann D., Seitz M., Drewes H.: *Global terrestrial reference systems and their realizations*. In: Xu G. (Ed.) Sciences of Geodesy II - Innovations and Future Developments, 97-132, Springer, 2013

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Bentel K., Schmidt M., Rolstad-Denby C.: *Artifacts in regional gravity representations with spherical radial basis functions*. Journal of Geodetic Science 3(3): 173-187, Versita, 2013

Bentel K., Schmidt M., Gerlach C.: *Different radial basis functions and their applicability for regional gravity field representation on the sphere*. GEM - International Journal on Geomathematics 4(1): 67-96, Springer, 2013

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Bosch W., Savcenko R., Dettmering D., Schwatke C.: *A two-decade time series of eddy-resolving dynamic ocean topography (iDOT)*. In: Ouwehand L. (Ed.) Proceedings of "20 Years of Progress in Radar Altimetry", Sept. 2012, Venice, Italy, ESA SP-710 (CD-ROM), ISBN 978-92-9221-274-2, ESA/ESTEC, 2013

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(Eds.) Reference Frames for Applications in Geosciences, IAG Symposia 138: 137-145, Springer, 2013

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Fuchs M.J., Bouman J., Broerse T., Visser P., Vermeersen B.: *Observing coseismic gravity change from the Japan Tohoku-Oki 2011 earthquake with GOCE gravity gradiometry*. Journal of Geophysical Research 118(10): 5712-5721, American Geophysical Union, 2013

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Seitz M., Haas R. *Terrestrial Reference Frames - Lecture*. VLBI school, Espoo, Helsinki, 2013-03-04

Seitz M., Steigenberger P., Artz T. *Consistent Realization of ITRS and ICRS*. IAU ICRF-3 WG & IAG SC 1.4 Splinter Meeting at the 21th EVGA Meeting, Espoo, Finland, 2013-03-07

Seitz M. *GPS und Geophysik*. Visit of the members of the W-seminar GEOPHYSIK of the Gymnasium Ottobrunn, DGFI, Germany, 2013-02-28

Seitz M., Steigenberer P., Artz T., Nothnagel A. *Konsistente Berechnung von TRF, CRF und Erdorientierungsparametern*. FGS-Workshop, Bad Kötzting, Germany, 2013-04-25

Seitz M., Steigenberer P., Artz T. *Consistent Realization of ITRS and ICRS*. IAU ICRF-3 WG & IAG SC 1.4 Splinter Meeting Espoo, Finland, 2013-03-07

Seitz M., Angermann D. *Rigorous Combined IERS Products - Introduction -*. IERS Retreat, Paris, France, 2013-05-23

Seitz M., Angermann D., Bloßfeld M., Gerstl M. *Report from the ITRS Combination Center at DGFI* . IERS Directing Board Meeting, San Francisco, USA, 2013-12-08

Singh A., Seitz F., Schwatke C., Güntner A. *Hydrological storage variations in a lake water balance, observed from multi-sensor satellite data and hydrological models*. EGU General Assembly 2013, Vienna, Austria, 2013-04-11

Visser P., van der Wal W., Schrama E., Bouman J. *Long-wavelength temporal gravity field variations: observable by GOCE?*. IAG Assembly, Potsdam, Germany, 2013-09-01/06

Visser P., van der Wal W., Bouman J. *GOCE GPS and accelerometer observations and Earth*. ESA Living Planet Symposium, 2013-09-09/13

5.4 Membership in scientific bodies

American Geophysical Union (AGU)

- Journal of Geophysical Research - Solid Earth,
  Associate Editor: Bouman J.

Centre National d‘Etudes Spatiales (CNES) / National Aeronautics and Space Administration (NASA)

- Ocean Surface Topography Science Team for Jason-2,
  Member: Bosch W., Dettmering D.

Deutsche Geodätische Kommission (DGK)

- *Member: Seitz F.*

Deutsche Gesellschaft für Geodäsie, Geoinformation und Landmanagement (DVW)

- Working Group 7: Experimentelle, Angewandte und Theoretische Geodäsie,
  Guest: Schmidt M., Member: Seitz F.

European Geosciences Union (EGU)

- Geodesy Division,
  President: Schmidt M., Vice president: Bouman J.

European Space Agency (ESA) / European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)

- Sentinel-3 Validation Team, Altimetry sub-group,
  Member: Dettmering D.

International Association of Geodesy (IAG)

- Commission 1 Sub-Commission 1.3b: Regional Reference Frame for South and Central America,
  Vice-Chair: Sánchez L.
- Commission 4 Study Group 4.2: Ionosphere modelling and analysis,
  Chair: Schmidt M., Member: Dettmering D., Liang W.
- GGOS Bureau for Standards and Conventions,
  Director: Angermann D.
- GGOS Consortium,
  Member: Angermann D.
- GGOS Coordinating Board,
  Member: Angermann D.
- GGOS Executive Committee,
  Member: Angermann D.
- ICCT Joint Study Group 0.1: Application of time series analysis in geodesy,
  Member: Schmidt M.
- ICCT Joint Study Group 0.3: Methodology of regional gravity field modelling,
  Chair: Schmidt M., Member: Haberkorn C., Lieb V.

- ICCT Joint Study Group 0.5: Multi-sensor combination for the separation of integral geodetic signals,
  Chair: Seitz F., Member: Schmidt M., Seitz M.
- ICCT Joint Study Group 0.6: Applicability of current GRACE solution strategies to the next generation of inter-satellite range observations,
  Member: Bouman J., Haberkorn C., Schmidt M.
- Joint Working Group 0.1.1: Vertical Datum Standardization,
  Chair: Sánchez L.
- Joint Working Group 1.1: Tie vectors and local ties to support integration of techniques,
  Member: Seitz M.
- Joint Working Group 1.3: Strategies for epoch reference frames,
  Chair: Seitz M., Member: Bloßfeld M., Sánchez L.
- Sub-Commission 1.4: Interaction of celestial and terrestrial reference frames,
  Member: Seitz M.
- Symposia Series,
  Associate Editor: Sánchez L.
- Working Group 1.3.1: Integration of Dense Velocity into the ITRF,
  SIRGAS representative: Sánchez L.
- Working Group 1.3.2: Deformation Models for Reference Frames,
  Member: Sánchez L.

International Astronomical Union (IAU)

- Commission 19, Rotation of the Earth,
  Secretary: Seitz F.
- Working Group: ICRF-3,
  Member: Seitz M.

International Earth Rotation and Reference Systems Service (IERS)

- ITRS Combination Centre,
  Chair: Seitz M.
- Working Group: Combination at the Observation Level,
  Co-Chair: Seitz M., Member: Bloßfeld M., Member: Angermann D.
- Working Group: SINEX format,
  Member: Seitz M.
- Working Group: Site coordinate time series format,
  Member: Seitz M.
- Working Group: Site survey and co-location,
  Member: Angermann D., Schmid R., Seitz M.

International GNSS Service (IGS)

- Antenna Working Group,
  Chair: Schmid R.

- Governing Board,
  Member: Schmid R.
- GPS Tide Gauge Benchmark Monitoring - Working Group,
  Member: Sánchez L.

International Laser Ranging Service (ILRS)

- Analysis Working Group,
  Member: Bloßfeld M., Müller H.
- Data Centre (EDC),
  Chair: Schwatke C., Member: Müller H.
- Governing Board,
  Member: Müller H.
- Operations Centre (EDC),
  Chair: Schwatke C.
- Program Committee of the 18th International Workshop on Laser Ranging,
  Member: Bloßfeld M.
- Working Group: Data Formats and Procedures,
  Chair: Müller H., Member: Schwatke C.

International VLBI Service for Geodesy and Astrometry (IVS)

- Operational Analysis Centre,
  Member: Schmid R., Seitz M.

Modelado de movimientos no lineales en el establecimiento de marcos de referencia

- *Member: Sánchez L.*

Sistema de Referencia Geocéntrico para las Américas (SIRGAS)

- *Vice president: Sánchez L.*
- Working Group 1: Reference frame,
  Member: Sánchez L.

5.5 Participation in meetings, symposia, conferences

2013-01-28/29 :

Projekttreffen der DFG-Forschergruppe FOR1503 (Reference Systems), Munich, Germany
Angermann D., Bloßfeld M., Mora-Diaz J., Panafidina N., Schmid R.

2013-01-29 :

Projekttreffen der DFG-Forschergruppe FOR584 (Earth Rotation), Munich, Germany
Angermann D., Bloßfeld M., Mora-Diaz J., Panafidina N., Schmid R., Schmidt M.

2013-02-14 :

GOCE+ GeoExplore, Progress Meeting #4, Munich, Germany
Bouman J., Fuchs M., Lieb V.

2013-03-01 :

Seminar des Instituts für Ostseeforschung (IOW), Warnemünde, Germany
Seitz F.

2013-03-12/14 :

Cryosat User Workshop, ESA, Dresden, Germany
Dettmering D.

2013-04-06 :

GGOS Coordinating Board Meeting, Vienna, Austria
Angermann D.

2013-04-07 :

ILRS Analysis Working Group Meeting, Vienna, Austria
Müller H.

2013-04-08/12 :

European Geosciences Union (EGU) General Assembly 2013, Vienna, Austria
Angermann D., Bloßfeld M., Bouman J., Fuchs M., Lieb V., Limberger M., Panafidina N., Schmidt M., Schwatke C., Seitz F., Seitz M.

2013-04-24/25 :

FGS Workshop 2013, Bad Kötzting, Germany
Angermann D., Bloßfeld M., Bosch W., Dettmering D., Fuchs M., Haberkorn C., Lieb V., Müller H., Panafidina N., Schmid R., Schmidt M., Schwatke C., Seitz F., Seitz M.

2013-05-03 :

Meeting of the IERS Working Group on Combination at the Observation Level (COL), Munich, Germany
Angermann D., Bloßfeld M., Seitz M.

2013-05-14/17 :

Meeting of the Americas, American Geophysical Union, Cancun, Mexico
Sánchez L.

2013-05-21/22 :

IERS Workshop on Local Surveys and Co-locations, Paris, France
Angermann D., Schmid R.

2013-05-22/25 :

IERS Retreat, Paris, France
Angermann D., Seitz F.

2013-06-05/06 :
DFG round table discussion 'Alp Array', Hofgeismar, Germany
Seitz F.

2013-06-19 :
VIII Hotine Marussi Symposium, Rome, Italy
Lieb V., Schmidt M.

2013-07-08/12 :
International Beacon Satellite Symposium 2013, Bath, United Kingdom
Liang W.

2013-07-16 :
GOCE+ Time Variations, Final Review, ESA, Noordwijk, Netherlands
Bouman J., Lieb V.

2013-09-01/06 :
IAG Scientific Assembly, Potsdam, Germany
Angermann D., Bloßfeld M., Bouman J., Drewes H., Fuchs M., Haberkorn C., Liang W., Panafidina N., Sánchez L., Seitz F.

2013-09-09/13 :
ESA Living Planet Symposium, Edinburgh, UK
Bouman J., Dettmering D.

2013-09-19/20 :
Projekttreffen der DFG-Forschergruppe FOR1503 (Reference Systems), Berlin, Germany
Angermann D., Panafidina N., Schmid R.

2013-09-24/27 :
Conference on Satellite Methods for Positioning in Modern Geodesy and Navigation, Cracow, Poland
Schmidt M.

2013-09-30/10-04 :
Semana Geomática Internacional 2013, Instituto Geográfico Agustín Codazzi, Bogotá, Colombia
Drewes H., Sánchez L.

2013-10-07/08 :
7th Coastal Altimetry Workshop, Boulder, USA
Dettmering D., Schwatke C.

2013-10-08/11 :
Ocean Surface Topography Science Team (OSTST) Meeting 2013, Boulder, USA
Dettmering D., Schwatke C.

2013-10-10 :
Geodätische Woche, Essen, Germany
Panafidina N., Schmid R.

2013-10-21/26 :
SIRGAS General Meeting 2013, Panama City, Panama
Drewes H., Sánchez L.

2013-11-05/06 :
GOCE+ GeoExplore, Progress Meeting #5, Munich, Germany
Bouman J., Ebbing J., Fuchs M., Haagmans R., Lieb V.

2013-11-09 :
ILRS Analysis Working Group Meeting, Fujiyoshida, Japan
Bloßfeld M., Müller H., Schwatke C.

2013-11-11/15 :
18th International Workshop on Laser Ranging, Fujiyoshida, Japan
Bloßfeld M., Müller H., Schwatke C.

2013-11-26/29 :
Sentinel-3 Validation Team (S3VT) Meeting, ESA/ESRIN, Frascati, Italy
Bosch W.

2013-11-27/29 :
Jahressitzung der Deutschen Geodätischen Kommission (DGK), Munich, Germany
Hornik H., Seitz F.

2013-12-02/03 :
Kick-Off Meeting of the IGSSE Focus Area 'Water', Garching, Germany
Seitz F.

2013-12-06 :
General Meeting of the Munich GeoCenter, Munich, Germany
Seitz F.

2013-12-07 :
GGOS Consortium Meeting, San Francisco, USA
Angermann D.

2013-12-07 :
GGOS Coordinating Board Meeting, San Francisco, USA
Angermann D.

2013-12-08 :
IERS Directing Board Meeting, San Francisco, USA
Angermann D.

2013-12-08/13 :
American Geophysical Union (AGU) Fall Meeting, San Francisco, USA
Angermann D.

5.6 Guests

2013-01-21 :	Dr. Annette Eicker, Universität Bonn, Germany
2013-01-30 :	Ole Roggenbuck, Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt/Main, Germany
2013-02-25 :	Prof. Dr. Maria Hennes, Karlsruhe Institute of Technology (KIT), Germany
2013-05-01/09-30 :	Jorge Bernales Concha, Universidad de Concepcion, Chile
2013-06-06 :	PD Dr. Klaus Börger, Amt für Geoinformationswesen der Bundeswehr (AGeoBw), Euskirchen, Germany
2013-06-06 :	Dr. Volker Bothmer, Institut für Astrophysik Göttingen (IAG), Göttingen, Germany
2013-06-11 :	Prof. Dr. Jörg Reinking and some students, Jade University, Oldenburg, Germany
2013-07-04 :	Prof. Dieter Bilitza, Goddard Space Flight Center (GSFC), Greenbelt, USA
2013-08-26/09-12 :	Prof. Claudio Brunini, Universidad Nacional de La Plata, La Plata, Argentina
2013-08-26/12-31 :	Romina de los Angeles Galvan, Universidad Nacional de La Plata, La Plata, Argentina
2013-09-09/10 :	Prof. Dr. Chengli Huang, Shanghai Astronomical Observatory, China
2013-09-09/11 :	Chunli Dai, Kun Shang, Ohio State University (OSU), Columbus, USA
2013-12-02/12-31 :	Dr. Murat Durmaz, Middle East Technical University, Ankara, Turkey
2013-12-12/13 :	Dr. Gunter Liebsch, Dr. Axel Rülke, BKG, Leipzig, Germany
2013-12-17/31 :	Prof. Claudio Brunini, Universidad Nacional de La Plata, La Plata, Argentina

6 Personnel

6.1 Number of personnel

Total staff of DGFI during the 2013 period (including DGK Office):

Regular budget

1	director; joint appointment with TUM (Chair of Geodetic Geodynamics)
12	scientific employees
6	technical and administrative employees
1	worker
6	student helpers with an average of 230 hours/year
3	part-time employee

Project funds

3 (4 till 2013-01-31)	junior scientists
3	postdoc scientists

6.2 Funding of the following projects is gratefully acknowledged:

COTAGA Combined ocean tide analysis by GRACE and altimetry data (DFG)

GEO-TOP Sea surface topography and mass transport of the Antarctic Circumpolar Current (DFG)

PROMAN Project management and scientific networking (DFG)

CEMIG Consistent estimation of water mass variations in different continental storage compartments by combined inversion of a global hydrological model with time-variable gravity and complementary observation data (DFG)

MuSIK Multi-scale model of the ionosphere from the combination of modern space geodetic satellite techniques (DFG)

FOR 584, P6 Integration of Earth rotation, gravity field and geometry using space geodetic observations (DFG)

FOR 584, P9 Combined analysis and validation of Earth rotation models and observations (DFG)

GOCE HPF Validation and frame transformation of GOCE gravity gradients (ESA/TUM)

GOCE+ GeoExplore Heterogeneous gravity data combination for Earth interior and geophysical exploration research (ESA)

GOCE+ Time Variations Feasibility study to the potential of GOCE data to detect temporal gravity field variations (ESA)

UHR-GravDat Consistent estimate of ultra-high resolution Earth surface gravity data (DFG)

RegGRAV Software application for high-resolution regional geoid models (ZGeoBw)

FOR 1503, PN5 Consistent celestial and terrestrial reference frames by improved modeling and combination (DFG)

FOR 1503, PN6 Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters (DFG)

AGGA Aeronomy and Geodesy in collaboration between Germany and Argentina (AvH)

CLIVAR-Hydro Signals of climate variability in continental hydrology from multi-sensor space and in-situ observations and hydrological modeling (DFG/IGSSE); at TUM Chair of Geodetic Geodynamics

MACOS Mass variations in continental surface water storage from heterogeneous space and in-situ observations (TUM Diversity); at TUM Chair of Geodetic Geodynamics

COMION Investigation of data compression techniques in a multi-scale representation of a regional ionosphere signal (TUM Diversity); at TUM Chair of Geodetic Geodynamics

CRUST-DEF Crustal deformation model in response to regional geophysical fluid variations determined by GRACE (Arcoiris/Erasmus Mundus); at TUM Chair of Geodetic Geodynamics

6.3 Lectures at universities

Bosch W. University lectures “Oceanography and Satellite Altimetry”, TUM, WS 2012/13 and WS 2013/14

Bouman J. University lectures “Gravity and Magnetic Field from Space”, TUM, WS 2012/13 and WS 2013/14

Schmidt M. University lectures “Numerical Modelling”, TUM, WS 2012/13 and WS 2013/14

Schmidt M. University lectures “Numerische Methoden in der Satellitengeodäsie”, TUM, SS 2013

Seitz F. University lectures “Earth System Dynamics”, TUM, WS 2012/13 and WS 2013/14

Seitz F. University lectures “Seminar ESPACE”, TUM, SS 2013

6.4 Lectures at seminars and schools

Sánchez L. Course “Precise processing of GNSS data for the establishment of a SIRGAS Processing Centre in Bolivia”, Instituto Geográfico Militar. La Paz, Bolivia, 2013-05-27/31

Drewes H., Sánchez L. Workshop on reference systems and satellite navigation systems, Instituto Geográfico Agustin Codazzi, Bogotá, Colombia, 2013-09-30/10-01

Sánchez L. Lecture “Vertical reference systems”, 11^{th} School of the International Geoid Service: Heights and height datum, University of Loja, Loja, Ecuador, 2013-10-11

Sánchez L. Lecture “Regional reference frames”, School on Reference Systems, Crustal Deformation and Ionosphere Monitoring, IUGG project “Monitoring crustal deformation and the ionosphere by GPS in the Caribbean”, 2013-10-22

Sánchez L. Lecture “Vertical reference systems”, School on Reference Systems, Crustal Deformation and Ionosphere Monitoring, IUGG project “Monitoring crustal deformation and the ionosphere by GPS in the Caribbean”, 2013-10-23

6.5 Thesis supervision

Master Theses

Ludwig W. Vorhersage gezeitenfreier Meereshöhenvariationen – eine Komponente eines Altimetrie-Daten-Simulators. (Supervisors: Seitz F., Bosch W.; institution: TUM)

Pimenova O. High resolution gravity field modelling using satellite altimetry data of geodetic mission phases. (Supervisors: Bosch W., Dettmering D.; institution: TUM)

Doctoral Theses

Alizadeh M. M. Multi-dimensional modeling of the ionospheric parameters, using space geodetic techniques. (Co-supervisor: Schmidt M.; institution: Vienna University of Technology)

Bentel K. Regional gravity modeling in spherical radial basis functions – on the role of the basis function and the combination of different observation types. (Co-supervisor: Schmidt M.; institution: Norwegian University of Life Sciences)

Naeimi M. Inversion of satellite gravity data using spherical radial base functions. (Co-supervisor: Schmidt M.; institution: Leibniz Universität Hannover)