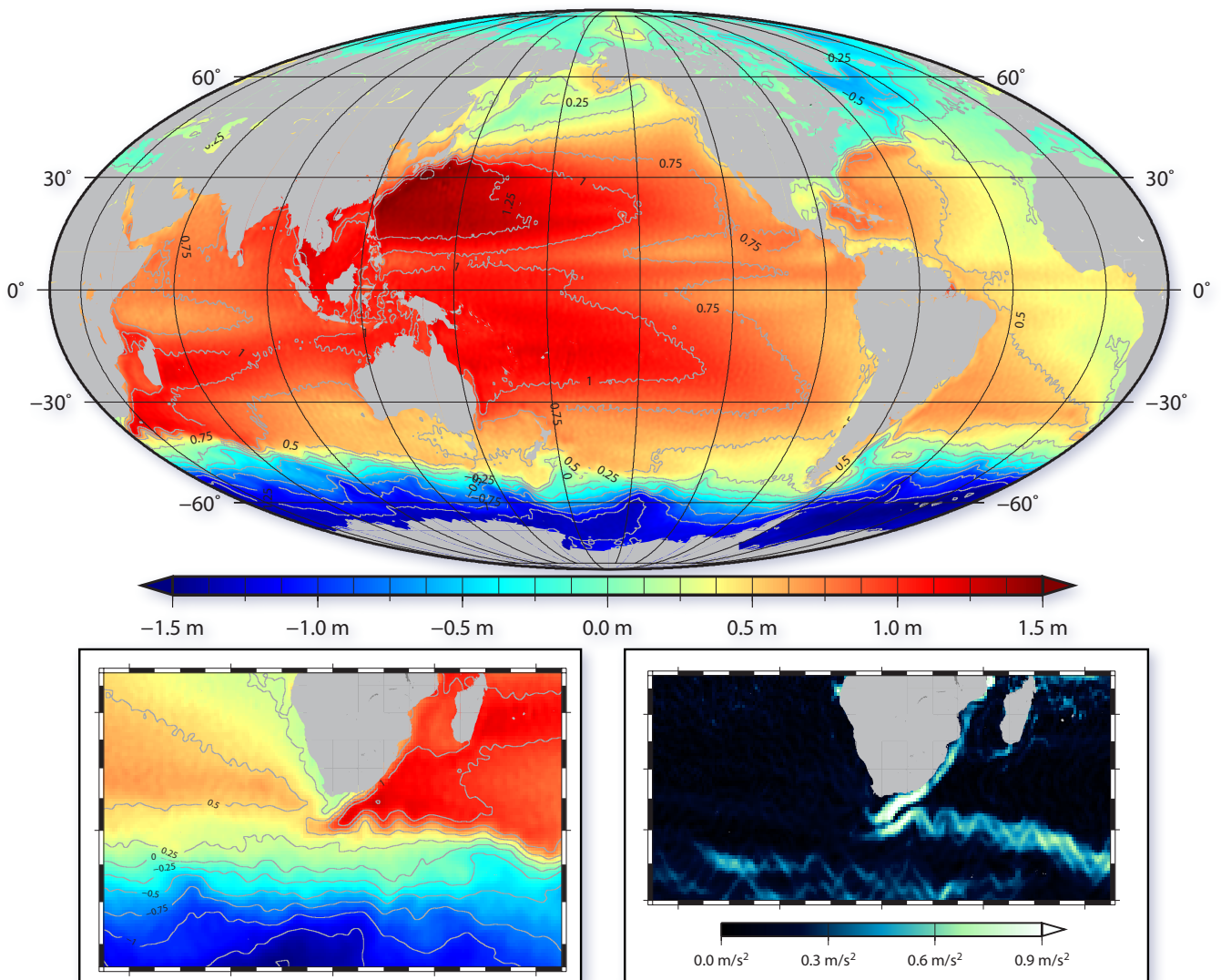


# ANNUAL REPORT 2011



Combining the most recent GOCE gravity fields and multi-mission satellite altimetry allows for the first time to resolve meso-scale features of the dynamic ocean topography (DOT). The plot on top shows a snapshot of the global DOT pattern caused by the large-scale ocean circulation. The plots below show DOT details (left) and the associated magnitude of geostrophic velocities (right) of the Agulhas counter current, South Africa, with a strong meandering and eddy formation (see section 3.3 and animations at <http://www.dgfi.badw.de/?333>).

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# ANNUAL REPORT 2011

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## The Institute



The *Deutsche Geodätische Forschungsinstitut* (DGFI) is nearly completing 60 years research on geodesy. Based on a decision of the *Deutsche Geodätische Kommission* (DGK e.V.) the State of Bavaria agreed in 1952 to the foundation of DGFI – after the financing was arranged between the federation and the states of Germany. Since then, DGFI contributed to numerous geodetic research fields and engraved on national and international level the development of geodesy to a science which contributes today not only to precise point positioning and gravity field determination but also to quite a number of processes of the Earth system whose states and changes are intensively sensed by the precise and highly redundant geodetic observations.

DGFI is accommodated at the *Bayerische Akademie der Wissenschaften* (BAW). Since many years the institute is fully funded by the State of Bavaria, it is nowadays affiliated to the section *Erdmessung* of DGK and regularly supervised by an international review board. The institute is acting as an autonomous research institute, covers a broad field of geodesy, participates in national and international research projects and has taken over various functions in international scientific bodies.

### DGFI, a member of CGE



Since October 2010 DGFI is a member of the “Centre of Geodetic Earth System Sciences (CGE)”, a close cooperation among the following geodetic research entities in Munich:

- *Institut für Astronomische und Physikalische Geodäsie* (IAPG) of the *Technische Universität München* (TUM)
- *Forschungseinrichtung Satellitengeodäsie* (FESG), also at TUM
- the section *Erdmessung* of the *Kommission für Erdmessung und Glaziologie* (KEG) of the BAW
- *Deutsches Geodätisches Forschungsinstitut* (DGFI)

The basic objective of CGE is to set up and realize a common research program, guided by the vision that geodesy can provide a high precision, consistent and long-term valid metric for Earth system sciences. CGE will identify and take advantage of synergies among its members, propose and execute common projects, give lectures and organize scientific meetings.

### Membership in FGS



Since many years DGFI is also member in the *Forschungsgruppe Satellitengeodäsie* (FGS), a follow-on cooperation of a former *Sonderforschungsbereich* SFB78, closely affiliated with the Geodetic Observatory Wettzell in the Bavarian Forest. Besides IAPG, FESG and DGFI the *Bundesamt für Kartographie und Geodäsie* (BKG) in Frankfurt a.M. and the *Institut für Geodäsie und Geoinformation* (IGG) of the University Bonn are members of FGS.

### Connections to Universities

Furtheron, DGFI has close cooperations with all German universities involved in geodetic education. This is realized under the umbrella of the DGK but also in bilateral arrangements. Members of

DGFI give lectures and courses at universities. Doctoral or Master theses are supervised by DGFI scientists. Interdisciplinary cooperation is installed with university institutes for Geophysics, Meteorology and Oceanography.

### **International Integration**

The research of DGFI is integrated within several international scientific services, programmes and projects, in particular of the *International Association of Geodesy* (IAG). DGFI recognizes the outstanding role of the IAG Services for science and practice, and cooperates in these services as data, analysis and research centre. Scientists of DGFI have taken leading positions and supporting functions in IAG's Commissions, Services, Projects, Working and Study Groups, and the *Global Geodetic Observing System* (GGOS). DGFI also participates in research programmes and bodies of the European Union (EU) and the European Space Agency (ESA). It cooperates in several United Nations' (UN) and inter-governmental institutions and activities.

### **DGFI research program and its structure**

The actual research program, set up for the period 2011-2014, has been evaluated and approved in November 2010 by an international scientific council (*Wissenschaftlicher Beirat*). As a result of preparatory discussions among the members of CGE the research program of DGFI already adapted the structure of the envisaged CGE research program, approved one year later in 2011. According to the central geodetic competence and the development towards a geodetic Earth system sciences (see yellow box vis-à-vis) the research program of DGFI (and CGE) was broken down to following research fields

1. Geometric techniques
2. Gravitational field
3. Geodetic Earth system modelling
4. Methodology

The first two research fields underpin the basic geodetic competence, related to precise point positioning and gravity field determination. The third research field is dedicated to geodetic studies on the Earth system, the most challenging subject of today's geodetic research. Methodology is a cross-cutting research area focussing on the development of tools and infrastructure supporting the other research areas. A fifth research field, new technologies, is not listed here as it is exclusively handled by FESG, working on the technological infrastructure of the Geodetic Observatory in Wettzell.

The above research fields are broken down into themes (see the table of contents) and further on in projects or tasks. Overall, the DGFI research plan identifies and describes 28 tasks or projects each one attributed to a theme of one of the research areas. Not all of these tasks or projects were (intensively) covered in 2011. Thus, the present report, dedicated to the activities in 2011, gives introductory descriptions of the four research fields and subsequently reports under the corresponding theme on the progress of those projects that were investigated in 2011.

## Geodesy on the move

Helmet's<sup>1</sup> (1880) understanding of geodesy as the science of measuring and mapping of the Earth surface has been significantly extended during the last decades through the development of satellite geodesy. Today the central task of geodesy is supported by geometric and gravimetric space techniques and consequently the research at DGFI focuses on

- the analysis and application of these space techniques, in order to create global and regional reference frames,
- the determination of the gravity field of the Earth to provide a global, unique reference for height systems, and on
- investigations related to orientation and rotation of the Earth.

<sup>1</sup> HELMERT F. R. (1880): *Die Mathematischen und Physikalischen Theorien der Höheren Geodäsie, Teil I*, Teubner, Leipzig

The results of these activities are relevant for land surveying, geo-information, navigation and other geosciences.

Beside these central tasks, the DGFI activities have been extended to a geodetic Earth system research. Nearly all geodetic observations are affected by processes within atmosphere, cryosphere, hydrosphere and the Earth interior. High precision and high redundancy of geodetic observation allow inferring the extent and metric of such processes in the Earth system. Examples are the time variable gravity field, ocean and solid Earth tides, sea level rise and sea level variations, the ocean dynamic topography, the deformation of the Earth surface, the global water cycle, the distribution and transport of masses as well as processes in ionosphere and troposphere.



*Components of the system Earth and geodetic observing systems (after ESA, modified and taken from the CGE research program).*

# 1 Geometric Techniques

*The space geodetic observation techniques Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) with the techniques GPS, GLO-NASS and in future GALILEO, Doppler Orbitography and Radiopositioning Integrated by Satellite (DO-RIS) as well as satellite altimetry provide the data basis for the work within this research field. These observation techniques allow a highly precise and continuous determination of the figure of the Earth along with its temporal variations.*

*This research field is focussing on acquisition, analysis and combination of the above mentioned space geodetic observations in order to determine geometric parameters describing the shape and orientation of the Earth. There are quite a number of tasks and projects, covering the full processing chain up to the generation of geodetic results and products. They are grouped into four themes defined for this research area, namely (i) observation systems, data acquisition and provision, (ii) model development and analysis of the space geodetic observations, (iii) analysis and refinement of combination methods, and (iv) computation of global and regional reference frames.*

## Engagement in IAG services

The research on space geodetic observations benefits from a significant engagement of DGFI in International Scientific Services of the International Association of Geodesy (IAG). The institute operates - mostly by long-term commitments - data centres, analysis centres, and combination centres and takes over various responsibilities and functions in the services listed on the right.

Participating in this IAG services implies a free access to globally acquired data, exchange of analysis methods, development and application of quality procedures, as well as access to and comparison of value-added products.

Thus, the engagement in IAG services is a backbone of the research field 'geometric techniques'.

- IGS Regional Network Associate Analysis Centre for SIRGAS (RNAAC-SIR)
- IGS Tide Gauge Benchmark Monitoring Analysis Centre (TIGA)
- ILRS Data- and Operations Centre
- ILRS Analysis Centre
- IVS Analysis Centre
- IVS Combination Centre (jointly with BKG Frankfurt am Main)
- ITRS Combination Centre within the International Earth Rotation and Reference Systems Service (IERS)
- IERS Working Group on Combination on the Observation level

## 1.1 Observation systems, data acquisition and provision

### Operation of permanent GNSS stations

In the framework of various international projects DGFI installed and operates permanent GNSS stations. The data of these GNSS stations are archived at DGFI and distributed to the processing centres. DGFI took over the responsibility as Regional Data Centre of SIRGAS, the Latin American reference frame. Within the International Laser Ranging Service (ILRS), the institute acts as a Global Data Centre and as an Operations Centre. These responsibilities are a continuous task and a regular update and refinement of the procedures has to be performed to satisfy the requirements.

Since 1998, DGFI has installed about 15 continuously operating GNSS stations in different regions of the world. Within the European Union's Territorial Cooperation (INTERREG III) Alpine Space Project for detection and control of crustal deformations in the Alpine region (ALPS-GPS QUAKENET), DGFI installed and operates five permanent GNSS stations. The project ended in

2007, but the German part is continued by DGFI. The other GNSS stations operated by DGFI (mostly in cooperation with local institutions) contribute to various international projects, such as the IGS Tide Gauge Benchmark Monitoring Project (TIGA) and the regional densification of the ITRF in Latin America, SIRGAS (see section 1.4). The data of some of these stations also contribute to the unification of local height datums (SIRGAS-WG III) and in a broader sense to GGOS theme 1 “Unified Height System”.

### ILRS Global Data and Operation Centre

Since the foundation of the International Laser Ranging Service (ILRS) in 1998, DGFI acts as one of two global ILRS data centres, the EUROLAS Data Center (EDC). The second global data centre is the Crustal Dynamics Data Information System (CD-DIS) at NASA. A complete re-organization of the data structure and the processing scheme started on new hardware, including a backup solution was completed in fall 2011.

In 2009, the EDC became an ILRS Operation Center (OC) after the implementation of the so-called Consolidated Ranging Data (CRD) format. The OC performs quality control procedures in order to ensure the correct conversion between the old NPT/FRD data format and the new CRD format. The ILRS planned the transition to the new format at March 1, 2012, provided that all SLR stations are ready to deliver their observation data in the CRD format. Until end of 2011, 13 out of 38 stations were not yet validated.

EDC is running several mail exploder for exchanging information, data and result among tracking stations, operation centres and users. The Consolidated Prediction Format (CPF) files (26382 in 2011) of 63 satellites are distributed automatically on a daily and sub-daily basis and stored at the FTP (<ftp://edc.dgfi.badw.de>) server. Mailing lists such as SLR-Mail (96 in 2011), SLR-Report (1521 in 2011), Urgent and Rapid-Service-Mail (17 in 2011) are maintained by EDC.

In 2011, 38 SLR stations observed 65 satellites. There were 10 new satellites tracked by SLR stations, namely Galileo124, Galileo125, GLONASS 125-130, HY-2A and Radio Astronomy. Figure 1.1.1 shows the data holding of NP and NPT data.

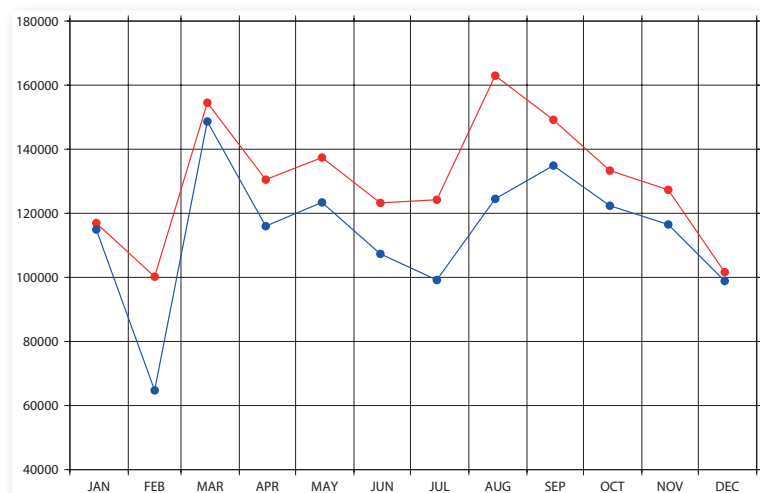


Fig. 1.1.1: The red line represents the number of monthly Normal Point observations in the old format (NPT/FRD) for the year 2011. The blue line shows the number of monthly Normal Point (NP) observations in the new CRD format.

## 1.2 Model development and analysis of the space geodetic observations

In its functions as ILRS Analysis Centre and IVS Analysis Centre, DGFI took over long-term activities that require a continuous analysis of SLR and VLBI data and the timely generation of geodetic products for these two services on a regular basis (e.g., daily or weekly). The activities also include a regular update of the software systems (DOGS-OC for SLR; DOGS-RI for VLBI) according to the processing standards defined by the ILRS and IVS and to the latest version of IERS Conventions. This theme also includes the activities within a Chilean and German cooperation project, funded since October 2010 by the International Bureau of the German ministry of education and research (IB-BMBF), with the primary goal of exchanging technology and providing software and experience for the processing of SLR and VLBI observations. Another subject is the harmonization and calibration of satellite altimetry data from various missions.

### ILRS Analysis Centre

An ongoing task is the weekly/daily processing of the SLR tracking data to the geodetic satellites Lageos-1/2 and Etalon-1/2. The solutions contain station positions, Earth orientation parameters and range biases for selected tracking stations. The results are delivered as SINEX files to the ILRS Data Centres CDDIS and EDC to be used for the computation of combined ILRS products. DGFI is also responsible for the detection and quantification of range and time biases of the SLR stations. In the framework of reprocessing 16.5 years of observations, DGFI detected a range bias for the station Shanghai, China (DOMES: 21605S010, ID: 7821) with a mean value of 20.02 cm for LAGEOS 1 and 18.48 cm for LAGEOS 2, respectively, between 2009-10-07 and 2010-01-27. Figure 1.2.1 shows the estimated station positions for the north, east and height component. The blue dots represent the coordinates when a range bias is estimated, whereas the red dots refer to a solution without estimating a range bias. The WRMS of the station coordinates is reduced significantly if a range bias is estimated.

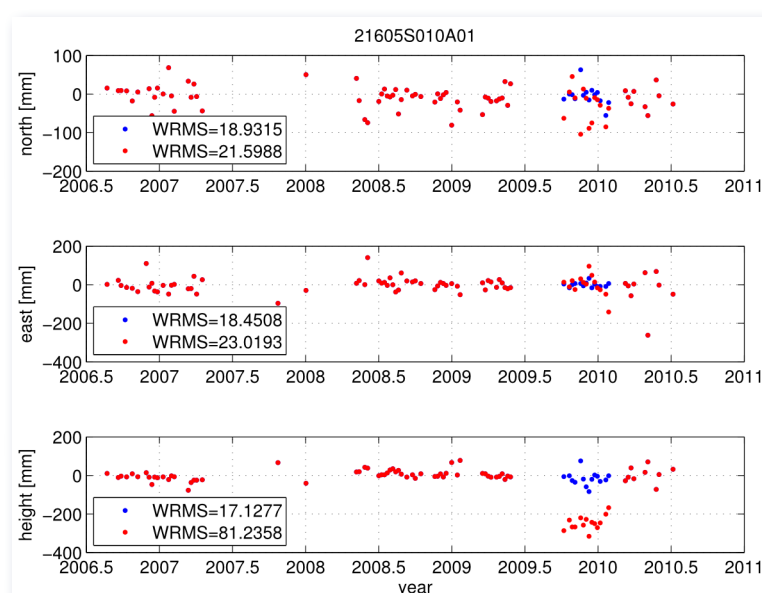


Fig. 1.2.1: Estimated coordinate time series of the SLR station Shanghai, China (7821) from 2006.5 to 2010.5. From 2009-10-07 to 2010-01-27, a range bias of about 20 cm for the LAGEOS satellites is estimated (blue dots); the red dots represent a solution without estimating range biases.

*Tab. 1.1.1: Estimated position and velocity vector for the SLR station Altay, Russia (1879, 12372S001) at epoch 2005.0.*

X [m]	Y [m]	Z [m]
543406.038	3955302.216	4957821.054
$V_x$ [m/a]	$V_y$ [m/a]	$V_z$ [m/a]
-0.045	0.014	-0.006

The new SLR station Altay, Russia (1879, 12372S001) starts their routinely operation at the end of 2008. Because of the fact that the ITRF2008 contains only input data until the end of 2008, the coordinates and velocities of this new station are not included in this reference frame solution. Within the SLR reprocessing at DGFI, a new multi-year solution was calculated. This solution contains data till the end of 2011. It includes about three years of data for the new Altay station, which were used to compute a set of coordinates and velocities for this SLR station. The obtained parameters at 2005.0 (J2000 epoch is 1826.5) are given in Table 1.1.1. The new coordinates will be delivered to the ILRS to update the SLRF2008 solution

### IVS Analysis Centre

In 2008, DGFI took over the responsibility as an operational Analysis Centre of the International VLBI Service for Geodesy and Astrometry (IVS). The institute processes and analyses the rapid turnaround IVS sessions (currently the IVS-R1 and IVS-R4 networks) and additional geodetic and astrometric sessions carried out by IVS and delivers datum-free normal equations in SINEX format. This task demands a continuously updating of files and software packages. This includes for instance, the addition of new sites into the catalogue of station coordinates and their respective information regarding atmospheric loading, ocean loading, antenna thermal deformation, etc. into the corresponding models.

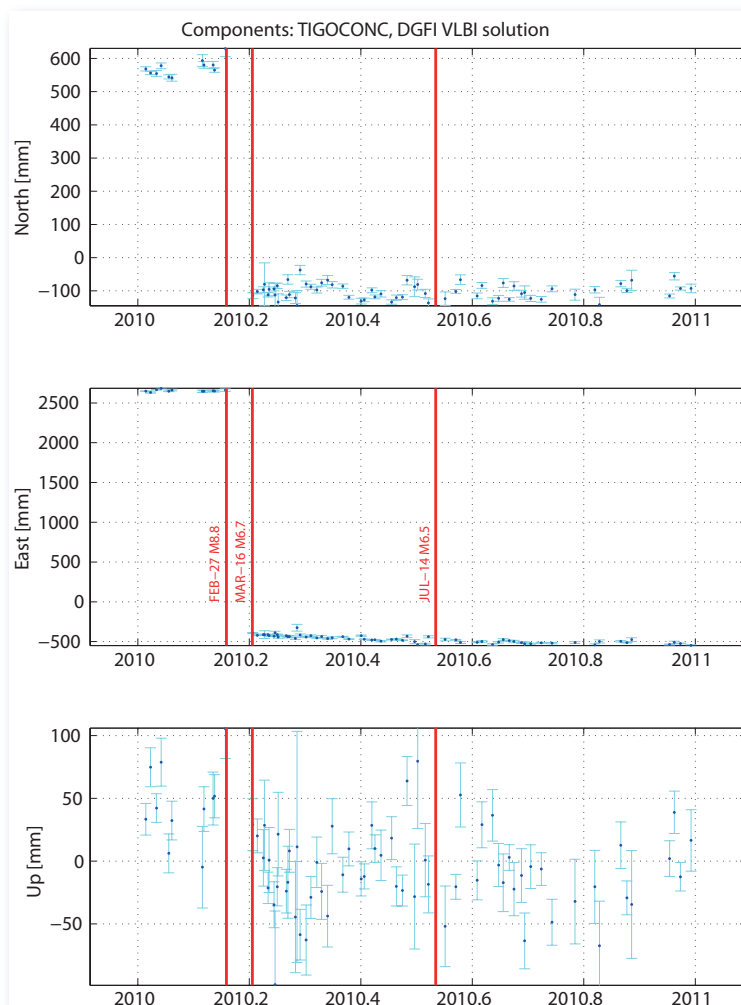
Another important issue is the modelling of the real clock breaks, some of which are reported by the correlator. These clock breaks are then semi-automatically detected and removed by a two step algorithm developed at DGFI. In a first least-squares adjustment, the clock breaks and offsets are considered. Then outliers are eliminated before a second least-squares adjustment. The outlier-free group delay observations corrected from clock breaks and from clock polynoms are then transformed into normal equations and written in SINEX format with the DOGS-CS software.

A still on-going activity during 2011 was the re-arrangement of the VLBI Analysis Software at DGFI. One of the main tasks was the conversion of the former OCCAM software into the radio interferometry part of the DGFI Orbit and Geodetic Parameter Estimation Software, DOGS-RI. This task also includes an update of the models according to the IERS Conventions 2010.

### German-Chilean Cooperation Project (IB-BMBF)

For a Chilean and German cooperation project DGFI funded by the International Bureau of the German ministry of education and research (IB-BMBF) since October 2010. Major tasks are the transfer of technology and the provision of software and experience for the processing of SLR and VLBI observations. This includes also the translation of the DOGS manuals and software documentation into English and the provision of software user manuals to the Chilean partners. The primary goal of the project is to enable the University of Concepcion (Chile) to analyse SLR and VLBI observations and to combine these results together with GPS observations, which are analysed at the Instituto Geographico Militar (IGM) in Santiago de Chile. These activities

Fig. 1.2.2: Time series of station positions for the VLBI telescope in Concepcion, Chile.



also support the TIGO Observatory in Concepcion, Chile, operated by BKG and Chilean institutions. Since the TIGO SLR tracking laser runs on a low energy budget the system can mainly track low earth orbiting satellites (LEOs). The processing of these LEO orbits requires the development of new models for the drag of the high atmosphere and the re-radiation of the Earth, which have to be implemented in the DOGS software.

### Harmonization and calibration of satellite altimeter measurements

In order to reach high temporal and spatial resolution in sea surface monitoring and mapping, the combination of multiple altimetry missions is mandatory. This requires a harmonized and consistent data set, which can be obtained by applying uniform correction models and a rigorous inter-mission calibration.

In 2011, the DGFI altimeter database has been updated with actual mission data of Jason-1, Jason-2, Envisat, and Cryosat-2. In addition, new data releases (Icesat R33, Cryosat-2 IPF2GDR\_2A/2.1, Envisat GDR-C) as well as new orbit products (REAPER orbits for ERS-1/2, ESOC EIGEN-6C orbits for Jason-1/2 and Cryosat) and new geographical correction models (EOT11a, SSB for Cryosat-2 ...) were incorporated. All these data sets – together with all other missions and models - have been used to compute a new multi-mission cross-calibration (MMXO, version 13) with the following main results: The new

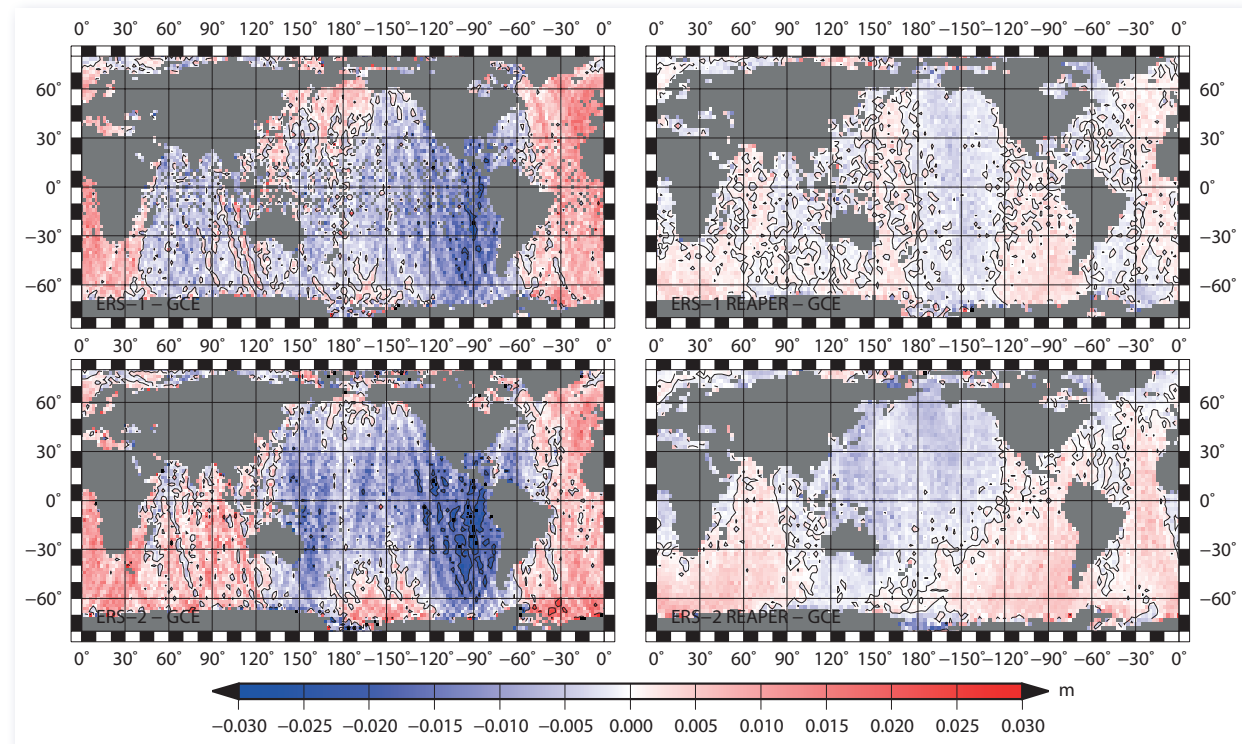


Fig. 1.2.3: Geographically correlated error (GCE) for ERS satellites. The left hand side is computed with old DEOS orbits and the right hand side with the new REAPER orbits. The RMS is improved from 7.7 mm to 2.8 mm for ERS-1 (top) and from 9.5 mm to 3.7 mm for ERS-2 (bottom).

### New orbits for ERS-1 and ERS-2

REAPER orbits for ERS-1 and ERS-2 improve the quality of the data for the first years of the time series. Mainly the geographically correlated error pattern (see Figure 1.2.3) and the differences in the realization of the geocentre are significantly improved. Now, the ERS orbit accuracy reaches the same order of magnitude than for TOPEX, Jason and Envisat. The Envisat GDR-C product replaces the old GDR product which was a combination of GDR-A, GDR-B and GDR-C standard. The offsets between the different GDR versions are not visible anymore; nevertheless, for some mission phases significant drifts in the time series of range biases remain (see Figure 1.2.4).

Fig. 1.2.4: Range biases for Envisat. The actual result from MMXO13 is plotted in red. Drifts of about -6 mm/year are visible for the first mission phase (till Jason Cycle 150) and the last mission phase (since Cycle 320). The offset of 1.7 cm around Cycle 160 is caused by a change to Envisat Side-B instrument in summer 2006.

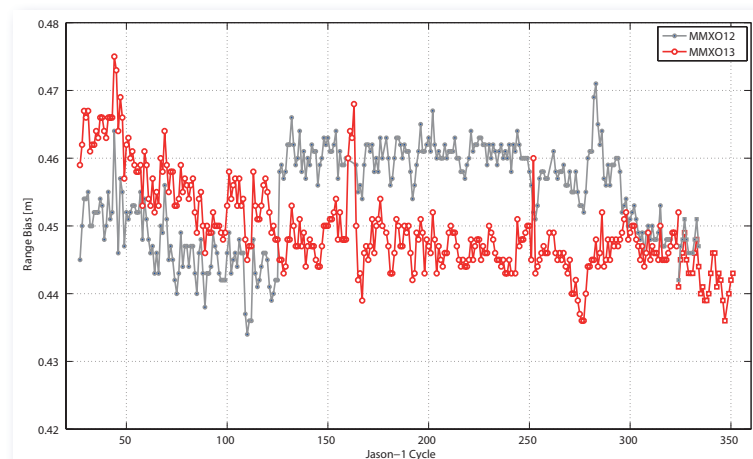
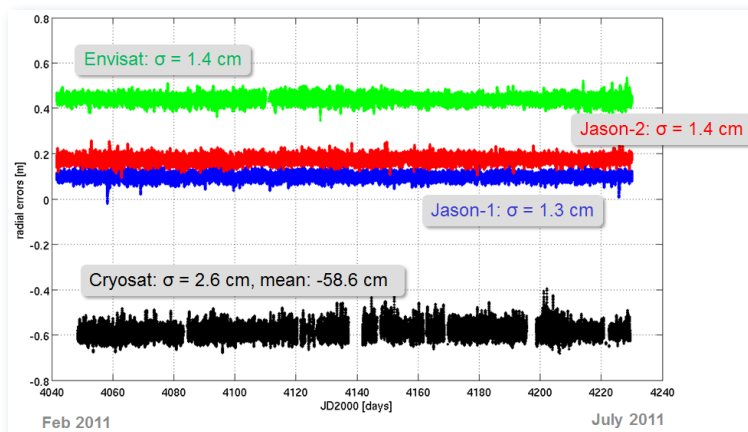


Fig. 1.2.5: Radial errors of Cryosat-2 LRM data with respect to TOPEX (a 11ms timing error has been corrected) in comparison to other altimeter missions.



The new processing chain for Cryosat-2 provides improved Level 2 data. The data for the three different measurement modes (LRM, SAR, and SARin) are now combined within one GDR product which is globally available. Nevertheless, up to now, there are still some known problems with the SAR and the SARin data part in the Level 2 product and actually, only L2 LRM data should be used. The global mean range bias of this data set has been reduced to -0.586 m (see Figure 1.2.5). A timing error of about 11 ms is still part of the data. To further improve the data, the use of external orbits (e.g. from ESOC) as well as the utilization of a hybrid sea state bias model provided by Altimetrics is recommended.

### 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 development of suitable combination methods also provides the basis for the computation of global and regional reference frames (see section 1.4). The combinations are performed on the level of datum-free normal equations with the DGFI software DOGS-CS, which is continuously updated. During 2011, DGFI performed the following major activities: Contributions to the IERS Working Group “Combination at the Observation Level”; the combination of VLBI data in its function as an IVS Combination Centre (jointly with BKG); the development of methods for the combination on an epoch basis (e.g., weekly, monthly); the common adjustment of the terrestrial and celestial reference frame and the EOP (see section 1.4).

#### IERS WG on Combination at the Observation Level

The IERS WG on Combination at the Observation Level (COL) was established in 2009. The major tasks of the Working Group are to develop strategies for the combination of space geodetic techniques at the observation level and to study the advantages of this combination method. DGFI contributes to the WG as an Analysis Centre for VLBI and SLR, as a Combination Centre and by co-chairing the WG. The main tasks in 2011 are given below.

A major effort was the homogenization of the software packages DOGS-OC (for SLR) and DOGS-RI (for VLBI) considering the COL processing standards and the IERS Conventions 2010. The homogenized DOGS software was then used to generate a new set of input normal equations. With the three new VLBI Analysis

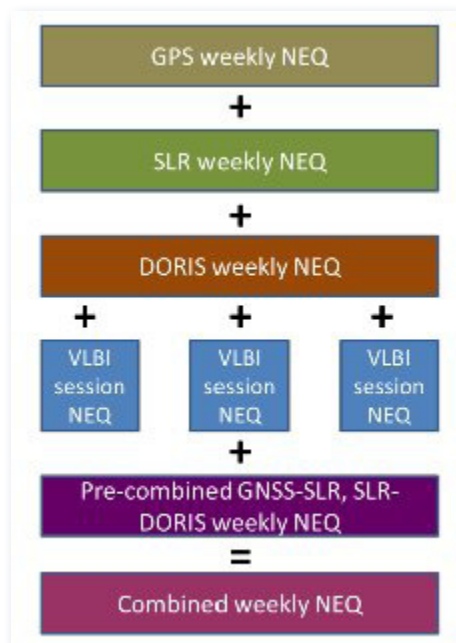


Fig. 1.3.1: Combination procedure applied for weekly combined solutions. The NEQ resulting from a common analysis of observations of different techniques (named pre-combined data) are generated by an integrated orbit determination using satellite collocations, e.g. GNSS-SLR co-locations at GNSS satellites or LEOs and SLR-DORIS at LEO satellites (e.g. Jason-2).

Centres (MAO, OPA, TUW), there are currently eight AC's that contribute to the WG COL (see Table 1.3.1). The AC's analyse the observation data of one or more techniques and provide the resulting NEQ in SINEX format.

Tab. 1.3.1: Analysis Centres (AC) contribution to the IERS WG COL in 2011

	AIUB	DGFI	ESOC	GFZ	GRGS	MAO	OPA	TUW
GNSS	x				x			
SLR	x	x	x		x			
VLBI		x			x	x	x	x
DPORIS					x			
GNSS-SLR			x	x				
SLR-DORIS			x					

The major task is the comparison and combination of the new generated NEQ provided by all AC. The individual contributions are analysed with respect to systematic differences and combined to weekly combined solutions (see Figure 1.3.1). The combination at the normal equation level is equivalent to the combination at the observation level, if (i) all common parameters are combined, (ii) common standards for modelling and parameterisation are applied for the data analysis and, if (iii) the same data editing is performed within a single or a common analysis of the observation data. Until now, station coordinates, terrestrial pole offsets and their rates, dUT, LOD, nutation offsets and their rates as well as tropospheric parameters (in case of micro-wave techniques) are considered as common parameters. In future also orbit and clock parameters shall be included.

A DGFI scientist acts as co-chair within the WG COL. The tasks include the organization of the WG meetings (e.g., 3<sup>rd</sup> WG meeting at the Observatoire de Paris in November 2011), presentations at scientific conferences and report to the IERS Directing Board.

### IVS Combination Centre

Since 2009, together with BKG, DGFI took over the responsibility as IVS Combination Centre. Major activities during 2011 were the maintenance of the DOGS-CS software for the combinations on the normal equation level carried out at BKG, the combination of tropospheric parameters and the delivery of reports to all associate analysis centres of the IVS. A typical result of the troposphere combinations are parameters of zenith wet delay and zenith total delay, which are frequently uploaded to IVS servers and graphically presented at the DGFI website. The improvement of the intra-technique combination method considering the multiple usages of identical observations and individual analysis noise depending on the specific AC is an ongoing research at DGFI.

### Combination on the epoch basis

The classical approach for the computation of reference frames based on the combination of multi-year solutions of the different space techniques is limited by the fact, that non-linear station motions (e.g., seasonal variations) currently not parameterized

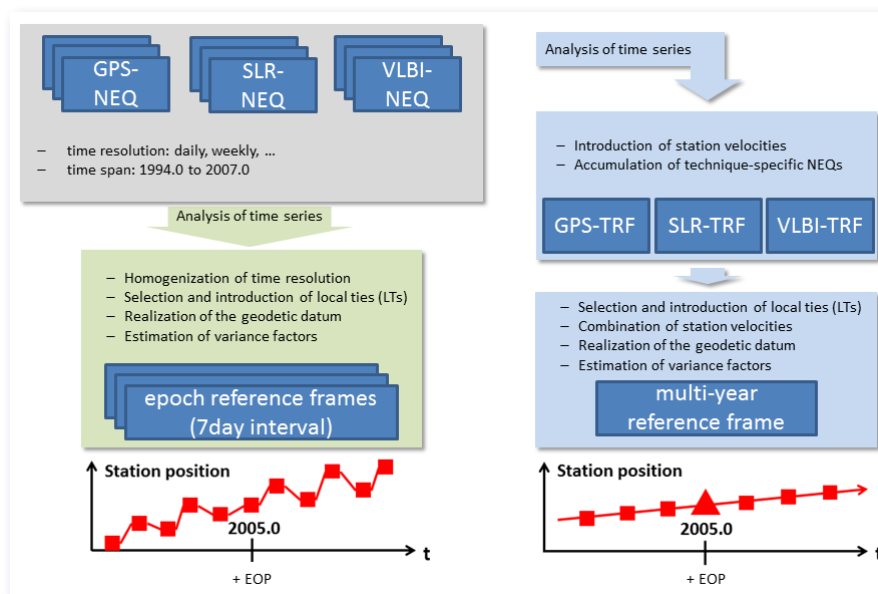


Fig. 1.3.2: Combination methodology for multi-year and epoch reference frames.

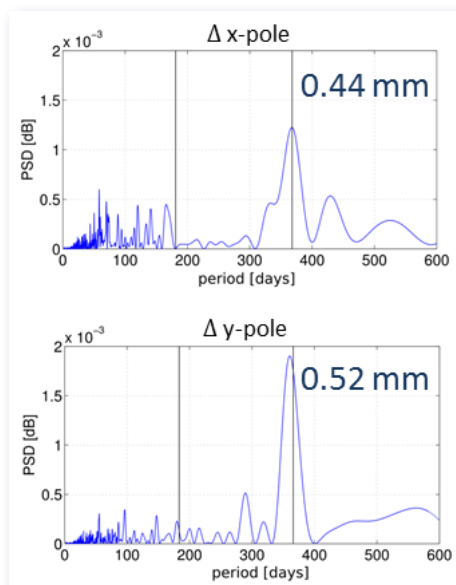


Fig. 1.3.3: Power spectra of the x- and y-component of the terrestrial pole.

(or modeled) affect the accuracy of the solutions. One possibility to overcome this problem is the combination of the space geodetic observations on an epoch basis (e.g., weekly or monthly). The development of suitable methods for the epoch combinations is a major goal of the project ‘Integration of Earth rotation, geometry and the Earth’s gravity field from observations of geodetic space techniques’ within the research group ‘Earth rotation and global dynamic processes’ of the German Science Foundation DFG. Figure 1.3.2 compares the processing scheme of epoch reference frames with the computation of multi-year reference frames. The new approach has been applied to estimate epoch reference frames from a combination of GPS, SLR and VLBI data with a weekly or monthly resolution (see section 1.4).

In order to quantify the effect of the different station parameterizations on the EOP, we compare the pole coordinates of the multi-year reference frame with the pole coordinates of the epoch reference frames and calculate the power spectra of the difference time series. Figure 1.3.3 shows the power spectra for the x-component (upper part) and for the y-component (lower part) of the terrestrial pole. The annual peaks in both spectra have a magnitude of 0.44 mm and 0.52 mm. These peaks are caused by annual site displacements which are not considered by multi-year reference frames.

## 1.4 Computation of global and regional reference frames

### Computation of global reference frames

In its function as an ITRS Combination Centre within the IERS, DGFI is responsible for a regular computation of global terrestrial reference frame solutions. The latest computations were finalized in 2010 resulting in the DTRF2008 solution. During 2011, the major focus was on a common adjustment of the terrestrial and celestial reference frames together with the EOP as well as the computation of epoch reference frames. Another focus was on regional reference frames, thereby the activities concentrate on the SIRGAS reference frame for Latin America and the Caribbean.

The present realizations of the International Terrestrial and the International Celestial Reference System, ITRF and ICRF, respectively, are performed separately as shown in Figure 1.4.1 (left). While the ICRF is derived from VLBI data only together with a VLBI only terrestrial reference frame and the linking EOP, the ITRF and the corresponding EOP are computed from a combination of GNSS, VLBI, SLR and DORIS data. The consequence of the independent realization is that the resulting reference frames and the EOP are not fully consistent. The computation of ITRF, ICRF, and EOP in a common adjustment would lead to consistency of the products (see Figure 1.4.1, right).

### Common adjustment of ICRF, ITRF and EOP's

A consistent solution of TRF, CRF and the EOP was performed and the effects of a common adjustment on the estimated parameters were analysed. It could be shown, that the local ties, in particular at stations in the southern hemisphere, lead to a very small but systematic shift of the source coordinates (0.03 mas in maximum). Additionally, we found that the combination of the EOP derived from the different techniques also has an impact on the ICRF. In particular, the positions of sources observed in regional VLBI sessions only (e.g. VLBA sessions), are changed (see Figure 1.4.2). The systematics between  $-40^\circ$  and  $30^\circ$  latitude can be related to sources observed by VLBA sessions only. The EOP benefit from a combination with respect to noise reduction and in case of dUT1 and nutation with respect to continuity, as

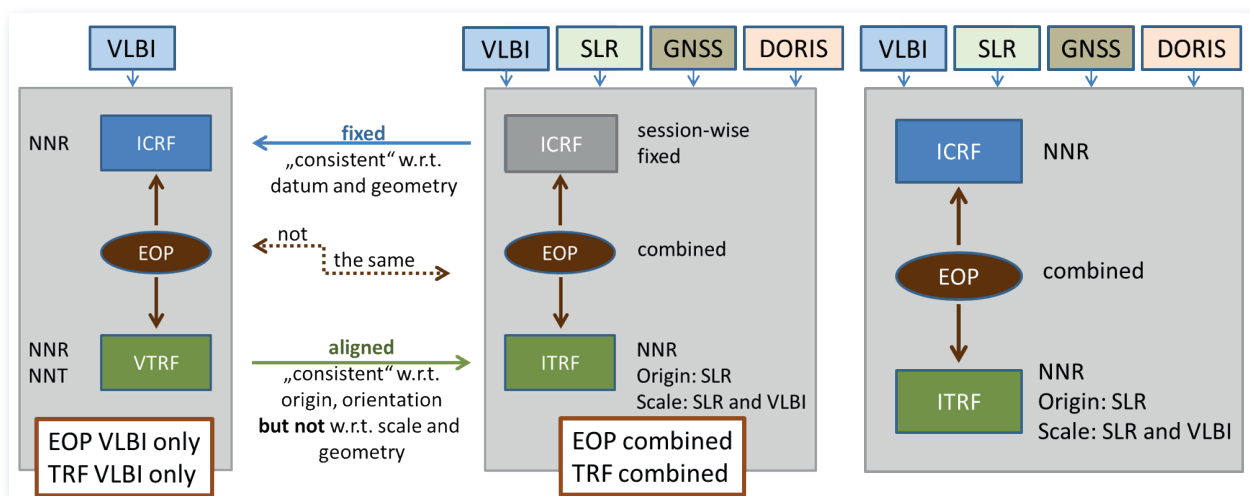
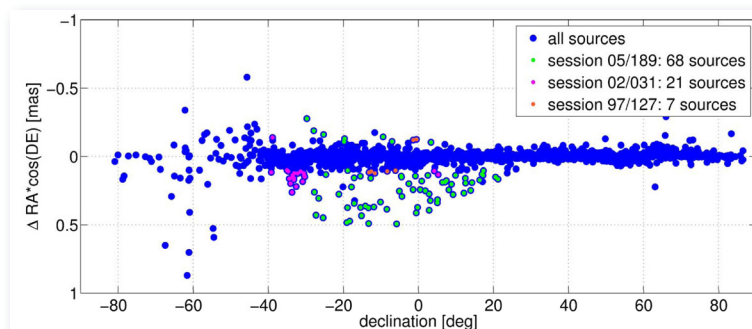


Fig. 1.4.1: Current situation for the computation of ITRF and ICRF (left) and a consistent computation of the two frames and the linking EOP (right).

Fig. 1.4.2: Difference in right ascension between VLBI only CRF and a CRF derived from a common adjustment of CRF, TRF and EOP.



the satellite techniques provide daily LOD values and GPS in addition nutation rates, which allow for a daily interpolation.

### Epoch reference frames

A second important topic is the computation of epoch reference frames (see section 1.3, Figure 1.3.2). Epoch reference frames approximate the station position variations (dominated by seasonal signals) very well, while in multi-year reference frames, like ITRF, station position variations are approximated by constant velocities. On the other hand, the long-term stability provided by the multi-year reference frames is much higher than for the epoch solutions. We computed epoch reference frames for the period of 1984.0–2007.0 with a weekly resolution as well as a multi-year reference frame based on the same homogeneously processed GNSS, SLR and VLBI data. From a frequency analysis of the EOP difference series, derived from both computations, annual signals and also frequencies related to the GPS orbit characteristics were detected. As shown in Figure 1.3.3, signals appearing in the station positions are partly mapped into the EOP series if the time variability is parameterized by a linear velocity, only. The improvement of epoch reference frames with respect to accuracy and stability is an important research topic in the near future.

### Regional reference frames

Regional densifications of the ITRF are necessary

- to provide accessibility to the global reference frame at continental and local levels;
- to ensure a precise basis for scientific and practical applications requiring high spatial and temporal resolutions; and
- to support the determination and utilization of geo-referenced data of high-quality, in particular, by means of GNSS techniques.

Usually, epoch solutions of regional reference networks (daily, weekly, multi-year) are aligned to the ITRF using a set of reference stations with given positions and constant velocities. The reliability of this procedure decreases due to the omission of non-linear movements of the reference stations in the ITRF; especially, seasonal position variations and co-seismic and post-seismic displacements. At present, DGFI concentrates on modelling these non-linear movements in order to improve the datum realization in regional networks.

### The SIRGAS reference frame

The present realization of SIRGAS is a network of about 250 continuously operating stations covering Latin America and the Caribbean. These stations are divided into different sub-networks being processed weekly by nine analysis centres: DGFI (Germany), CEPGE (Ecuador), CIMA (Argentina), CPAGS-LUZ (Venezuela), IBGE (Brazil), IGAC (Colombia), IGN (Argentina), INEGI (Mexico), and SGM (Uruguay). The distribution of the SIRGAS stations among the analysis centres guarantees that each station is included in three solutions. The weekly combination of the individual solutions is carried out by the SIRGAS Combination Centres at DGFI and IBGE. Main results of this processing are

- loosely constrained solutions of station positions for further combinations (e.g. integration into the IGS global polyhedron, computation of multi-year solutions), and
- weekly station positions aligned to the ITRF to be used as reference coordinates in GNSS positioning.

### SIRGAS weekly solutions delivered to IGS

In its function as an IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR), DGFI delivers the loosely constrained SIRGAS weekly combinations to the IGS. They are combined together with those generated by the other IGS global and regional Analysis Centres to form the IGS polyhedron. DGFI is also in charge of computing cumulative (multi-year) position and velocity solutions to estimate the kinematics of the network.



Fig. 1.4.3: Horizontal velocities of the SIR11P01 multi-year solution. Velocities of ITRF2008 stations are included for comparison.

### SIR11P01, the latest SIRGAS solution

Figure 1.4.3 shows the horizontal velocities of the latest computed solution: SIR11P01. It comprises weekly normal equations from 2000-01-02 (GPS week 1043) to 2011-04-16 (GPS week 1631), when the IGS08 reference frame was introduced, and includes 230 stations with 269 occupations. The final coordinates and velocities refer to the ITRF2008, epoch 2005.0. The precision is estimated to be  $\pm 1.0$  mm (horizontal) and  $\pm 2.4$  mm (vertical) for station positions, and  $\pm 0.7$  mm/a (horizontal) and  $\pm 1.1$  mm/a (vertical) for velocities. The consistency of the SIR11P01 solution with the ITRF2008 was evaluated by comparing positions and velocities of those stations which were not used as reference points. Results show mean discrepancies (offsets) under the millimetre level.

### Seasonal variations of SIRGAS stations

Most of the SIRGAS stations present significant seasonal position variations, which can reach several centimetres (up to 6 cm in the vertical component), especially in the Amazonas region (Figure 1.4.4 and 1.4.5). Additionally, estimated constant velocities depend highly on the considered time period.

The frequent occurrence of earthquakes in the SIRGAS region causes episodic station movements, which influence the long-term stability of the reference frame. Earthquakes of high magnitudes generate not only jumps in the station positions, but also change their “normal” movement (velocities). As an example, Figure 1.4.6 compares the constant velocities computed for the southern SIRGAS stations before and after the Maule earthquake in Chile on 2010-02-27.

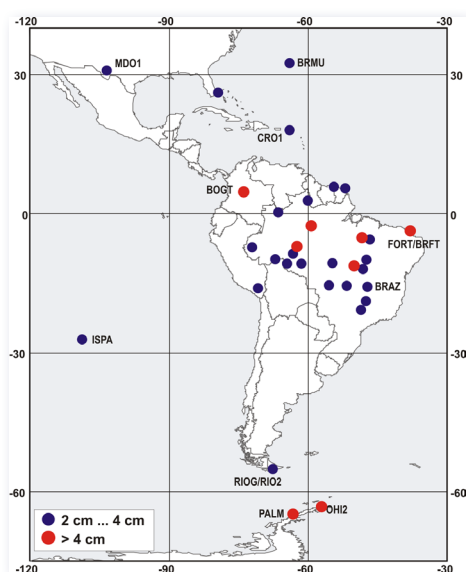


Fig. 1.4.5: SIRGAS stations with seasonal movements with amplitude larger than 2 cm.

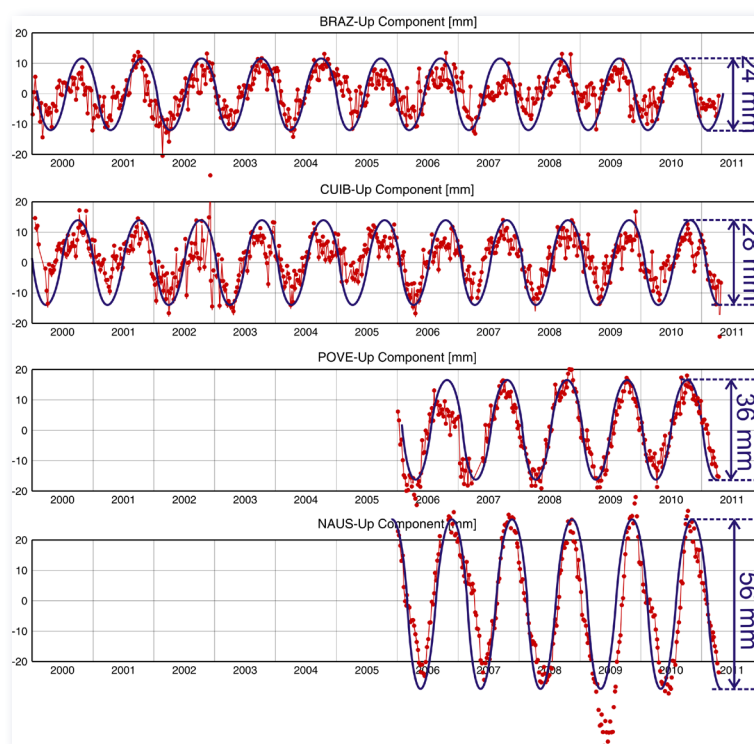
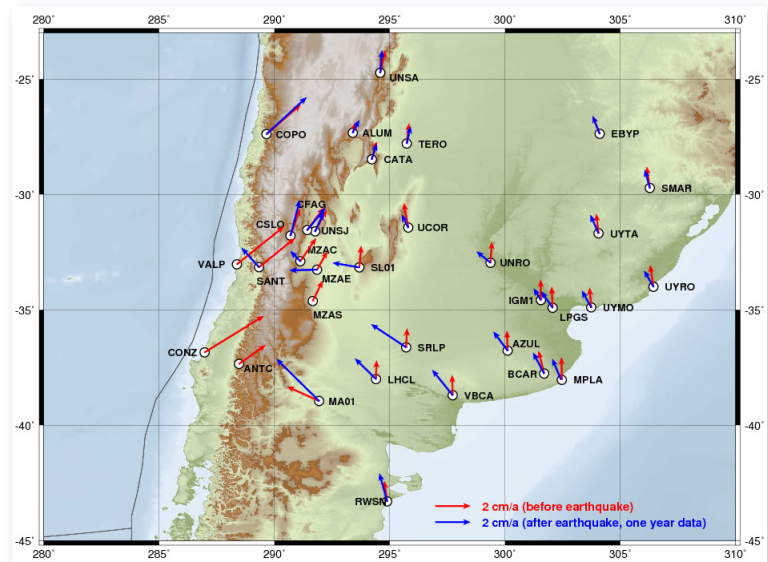


Fig. 1.4.4: Seasonal variations with seasonal movements larger than 2 cm.

Fig. 1.4.6: Comparison of pre-seismic and post-seismic (constant) velocities one year after the earthquake on 2010-02-27 in Chile (velocities for ANTC, CONZ, MZAS and VALP are intentionally not included, see Fig. 1.4.7).



### Modelling of non-linear station movements

The main drawback refers here to the modelling of non-linear station movements after an earthquake. Usually, a post-seismic period is split into short time intervals to represent the movement by a sequence of constant velocities. The transformation of the station positions before and after a seismic event is done by the sum of all the intervals. This approximation decreases the precision of the reference frame considerably, especially when the post-seismic movements occur very quickly. Figure 1.4.7 presents the post-seismic time series for the East component at the stations ANTC, CONZ, MZAS, and VALP. The station positions are changing rapidly, and a representation through constant velocities would imply the segmentation into very small time intervals (some weeks). However, the estimation of such short-term velocities is not reliable and thus it is not recommended for reference frame computations.

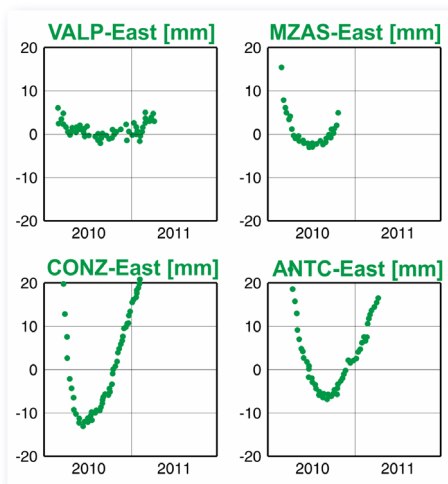


Fig. 1.4.7: Post-seismic time series for the East component at selected SIRGAS stations. Relative values with respect to constant velocities are presented.

One possibility to mitigate the impact of seismic events is the computation of short-period (e.g. weekly) crustal deformation models derived from the weekly reference station positions. The differences between the pre-seismic and post-seismic positions of arbitrary points can then be interpolated provided that the observed reference stations are sufficient in number and in spatial density. An example is shown in Figure 1.4.8. The displacements of SIRGAS stations during the Maule earthquake are interpolated in a  $1^\circ$ -grid by least squares prediction. The precision of the deformation model is not sufficient, because the spacing of the stations is too large ( $> 100$  km). The approach shall be improved by using additional stations from existing regional surveys in Chile. The cooperation with Chilean partners started in 2011.

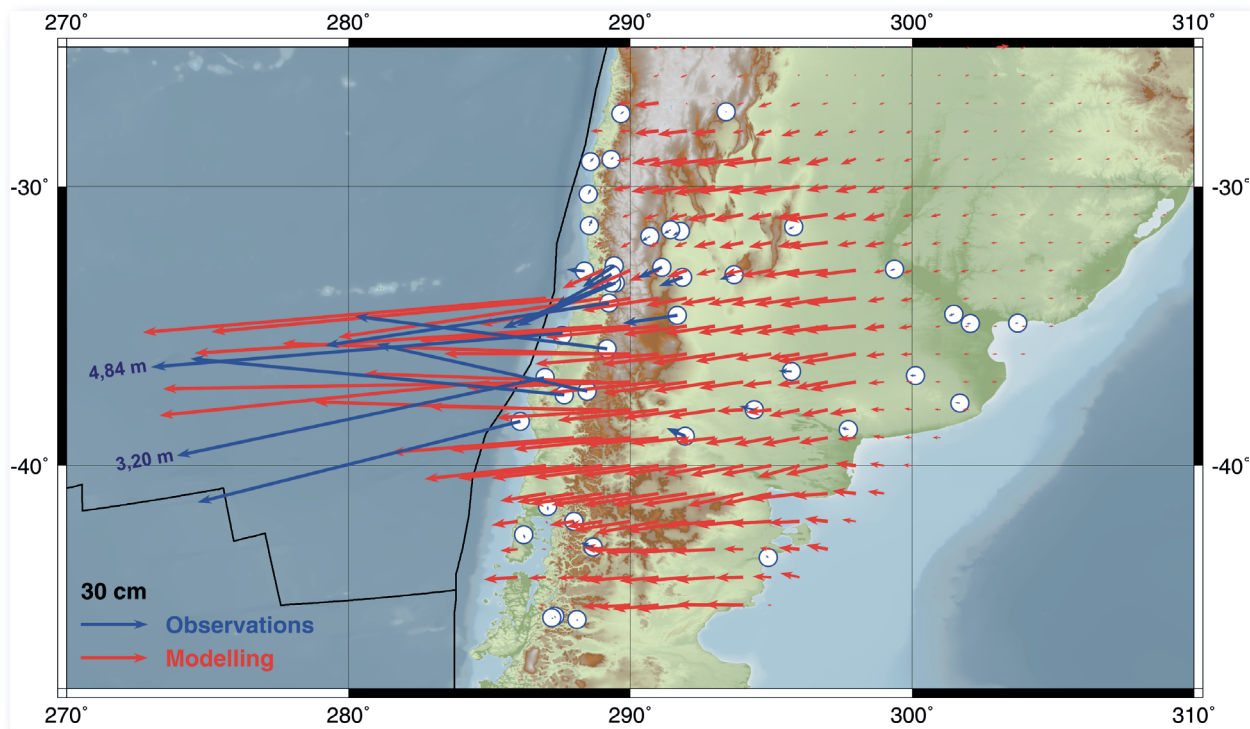


Fig. 1.4.8: Preliminary geodetic deformation model after Maule earthquake 2010.

#### Related publications:

- ANGERMANN D., DREWES H., SEITZ M.: Global terrestrial reference frame within the GGOS-D project. In: Kenyon, S. C.; Pacino, M. C.; Marti, U. J. (Eds.) *Geodesy for Planet Earth*, IAG Symposia, Vol. 136, pp 87-94, Springer, ISBN (Print) 978-3-642-20337-4, ISBN (Online) 978-3-642-20338-1, ISSN 0939-9585, DOI: 10.1007/978-3-642-20338-1\_11
- BLOSSFELD M., MÜLLER H., ANGERMANN D.: Adjustment of EOP and gravity field parameters from SLR observations. *Proceedings of ILRS Workshop*, 2011
- BLOSSFELD M., MÜLLER H., SEITZ M., ANGERMANN D.: Benefits of SLR in epoch reference frames. *Proceedings of ILRS Workshop*, 2011
- DETTMERING D., BOSCH W.: First experiences with CryoSat-2 LRM data. *Proceedings of the Cryosat Validation Workshop 2011*, Frascati, Italy, ESA Special Publication SP-693 (CD-Rom), 2011
- ROTHACHER M., ANGERMANN D., ARTZ T., BOSCH W., DREWES H., BOECKMANN S., GERSTL M., KELM R., KÖNIG D., KÖNIG R., MEISEL B., MÜLLER H., NOTHNAGEL A., PANAFIDINA N., RICHTER B., RUDENKO S., SCHWEGMANN W., SEITZ M., STEIGENBERGER P., TESMER V., THALLER D.: GGOS-D: homogeneous reprocessing and rigorous combination of space geodetic observations. *Journal of Geodesy*, DOI: 10.1007/s00190-011-0475-x, 2011
- SÁNCHEZ, L., W. SEEMÜLLER, M. SEITZ: Combination of the Weekly Solutions Delivered by the SIRGAS Processing Centres for the SIRGAS-CON Reference Frame. In: Kenyon, S. C.; Pacino, M. C.; Marti, U. J. (Eds.) *Geodesy for Planet Earth*, IAG Symposia, Vol. 136, pp 845-852, Springer, ISBN (Print) 978-3-642-20337-4, ISBN (Online) 978-3-642-20338-1, ISSN 0939-9585, DOI: 10.1007/978-3-642-20338-1\_106, 2012
- SÁNCHEZ, L., M. SEITZ: Recent activities of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR). *DGFI Report No. 87*, 2011
- SEITZ M., HEINKELMANN R., STEIGENBERGER P., ARTZ T.: Common realization of terrestrial and celestial reference frame. In: Alef W., Bernhard S. and Nothnagel A. (Eds.): *Proceedings of the 20th Meeting of the European VLBI Group for Geodesy and Astronomy*, Schriftenreihe des Instituts für Geodäsie und Geoinformation der Universität Bonn, 22, 2011
- THALLER D., DACH R., SEITZ M., BEUTLER G., MAREYEN M., RICHTER B.: Combination of GNSS and SLR observations using satellite co-locations. *Journal of Geodesy* 85/5, pp 257-272, DOI: 10.1007/s00190-010-0433-z, 2011

## 2 Gravitational Field

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

*At DGFI we focussed in 2011 on three themes related to the gravitational field. The first is the pre-processing and analysis of the GOCE gravity gradients. Another theme is the determination of regional gravity fields based on a combination of all available gravity data such as satellite gravimetry, terrestrial gravity and satellite altimeter data. A third theme is the use of the GOCE gravity gradients and regional gravity fields for geophysical applications. Highlights of these three themes are discussed in the sections below.*

### 2.1 Pre-processing and analysis of GOCE gravity gradients

The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission, part of ESA's Living Planet program, aims at the determination of the Earth's mean gravitational field. GOCE was launched in March 2009. Meanwhile the nominal mission duration has been accomplished and the extended mission phase (~2 years) is on-going. Especially the fine scale structure of Earth's gravity field is being measured by GOCE with unprecedented accuracy using a space-born gradiometer. The major scientific goal of GOCE is the determination of the geoid with an accuracy of 1-2 cm at a spatial scale of 100 km which results in an improved understanding of the global ocean circulation, unification of height systems and new insights into geodynamic processes covering global mass transport and improved understanding of the Earth's interior.

#### Calibrated gradients in the gradiometer reference frame

The GOCE gradiometer consists of six test masses flying on board the satellite in a sun synchronous orbit where the accelerations of these test masses are measured with high accuracy. The acceleration differences of the masses are combined, considering rotational effects, to the so called gravity gradients which are equal to the second derivative of Earth's gravitational potential. In the framework of the GOCE HPF (High-Level Processing Facility) Level 2 gradient products are being generated on a regular basis resulting in calibrated gradients in the gradiometer reference frame.

These calibrated gradients in the gradiometer reference frame have been used in comparison with model derived gradients. The fit of the measurements to the models reveals accuracies of the measurements and the models. Since the processing strategies of the different global gravity field solutions are different, this kind of assessment may reveal differences between the models and their processing strategies.

At this time eleven GOCE-based gravity field models are available to the scientific community. The first three (Release 1) GOCE-only gravity field models were computed using three different approaches; the time-wise approach (TIM), direct ap-

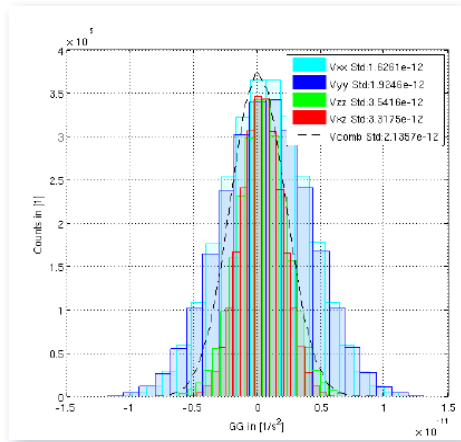


Fig. 2.1.1: Measurement distribution for the GOCE accurate components and the combined  $V_{zz}$  component for the study period November 2009 to January 2010 (reference model TIM R2).

### Comparison of gravity gradients

proach (DIR) and space-wise approach (SPW) each covering a data period of two and a half months. All three models use some kind of a priori information, either in the form of a priori gravity field models or in the form of Kaula's rule. The second release of GOCE-only gravity field models cover a time span of eight months and do no longer use a priori information coming from global gravity field solutions that include terrestrial gravity data. The Release 3 models cover a time span of 12 months.

In our analysis also combined gradients have been used where the vertical gradient error is being reduced due to averaging

$$V_{Comb} = \frac{V_{zz} - V_{xx} - V_{yy}}{2} \quad (1)$$

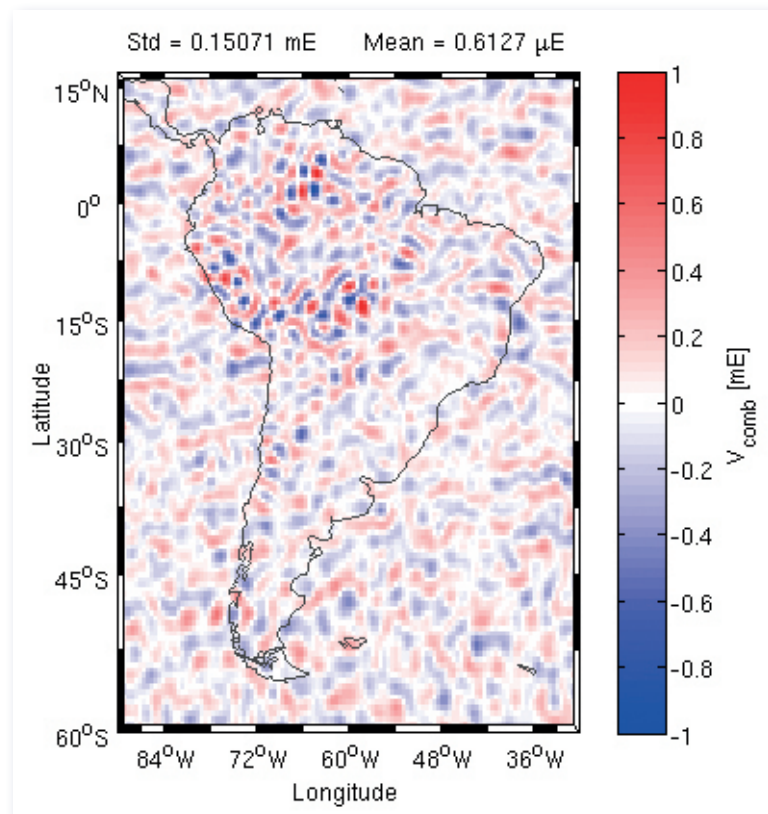
The differences in the measurement bandwidth between the TIM R2 model and the GOCE accurate gradients  $V_{xx}$ ,  $V_{yy}$ ,  $V_{zz}$  and  $V_{xz}$ , as well as for the combined gradient (1) are shown in Figure 2.1.1.

All models have been compared for the time period of November 2009 to January 2010 computing binned differences and the along-track standard deviations of these differences. The pre-processing, for this study, includes interpolation on regular time scales, tailored outlier detection and the filtering of the gradients to the measurement bandwidth (Fuchs & Bouman 2011). The binned gravity gradients show especially in regions where the contribution of a priori information is being included, deviations between the measurements and the models (see Figure 2.1.2). Local significant differences could be indicated for Release 1 of the direct model that uses EIGEN-5C, which includes terrestrial gravity data, as a priori information. In case of the direct Release 2 models the included prior information consists of the satellite-only model ITG-GRACE2010S and the significant gravity gradient differences do no longer occur. In case of the space-wise model Release 1 the  $V_{xz}$  component shows a higher standard deviation in comparison with the other models see Table 2.1.1. This is probably related to the inclusion of a GOCE quick-look model as a priori information, which performance for  $V_{xz}$  is not as good as for the diagonal gradients. All the other models show comparable results.

Tab. 2.1.1: Standard deviation of the differences between GOCE gravity gradients and model values in the measurement bandwidth from 5 mHz – 0.037 Hz. Data period is 1.11.2009 – 11.01.2010. Units are mE ( $10^{-12} \text{ s}^{-2}$ ).

Gravity gradient	DIR			SPW		TIM			GOCO	
	R1	R2	R3	R1	R2	R1	R2	R3	01S	02S
$V_{xx}$	1.65	1.65	1.65	1.65	1.66	1.63	1.64	1.65	1.65	1.65
$V_{yy}$	1.90	1.86	1.86	1.87	1.88	1.83	1.85	1.85	1.85	1.85
$V_{zz}$	3.56	3.57	3.59	3.56	3.60	3.53	3.58	3.59	3.58	3.59
$V_{xz}$	3.36	3.34	3.33	4.02	3.32	3.36	3.34	3.33	3.33	3.33

Fig. 2.1.2: Differences between GOCE  $V_{comb}$  and DIR Release 1 model over South America ( $1mE=10^{-12}s^{-2}$ ).



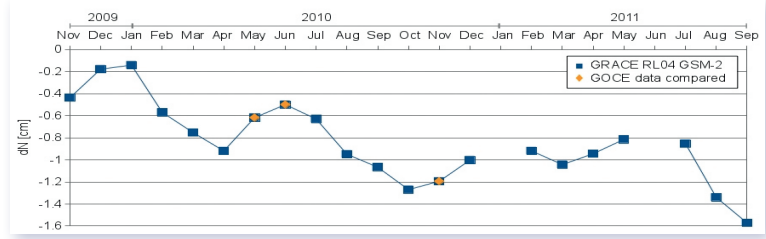
One can conclude that the latest GOCE gravity field models show high consistency in the application of the GOCE measurements and show up with comparable results while the Release 1 models have processing differences which are unique for each method respectively.

## 2.2 Regional gravity fields

### Temporal gravity variations from GOCE

A huge progress in the determination of the Earth's gravity field was made by the two satellite gravity missions GRACE and GOCE. While the measurement concept of GRACE is designed to analyze temporal variations, GOCE basically determines the static gravity field with high accuracy. Nevertheless, temporal gravity variations may also be detectable with GOCE as it has some essential advantages compared with GRACE: the lower orbit increases the sensitivity to higher parts of the frequency spectrum, whereas the regular ground track pattern enables and simplifies the detection of changes, and the measurement technique with six accelerometers on board of the satellite provides three-dimensional (3-D) information of the gravitational potential. Thus, the advantages contribute especially to improvements to the mid and short wavelengths. As GRACE is more sensitive in the low frequency parts, the idea is to combine the results of both satellite observation systems to reduce the well-known stripes within GRACE solutions and to improve the spatial resolution of time-varying gravity field models.

Fig. 2.2.1: Monthly geoid height variations: the blue-marked points show the mean values of differences between the monthly GRACE GSM-2 (Release 04) data and the EGM2008 model up to d/o 60 for the region of Greenland. The orange marked months are compared with GOCE data sets.



### Case study for Greenland

For Greenland, as an example, GRACE monthly solutions show a gravity signal with noticeable seasonal variations (Figure 2.2.1). The figure shows averaged geoid height differences  $\Delta N$  between monthly GRACE GSM-2 data (Release 04)  $N_{\text{GSM}}$  and EGM2008 as a reference model  $N_{\text{ref}} = N_{\text{EGM}}$  based on spherical harmonics up to degree and order (d/o) 60. The spatial pattern of the geoid differences  $\Delta N = N_{\text{GSM}} - N_{\text{EGM}}$  are shown in Figure 2.2.2 for May, June and September 2010. The geoid differences vary between -2 cm and +1 cm. For the three selected months, we compared these solutions with our approach of regional gravity field modeling based on scaling functions using GOCE data.

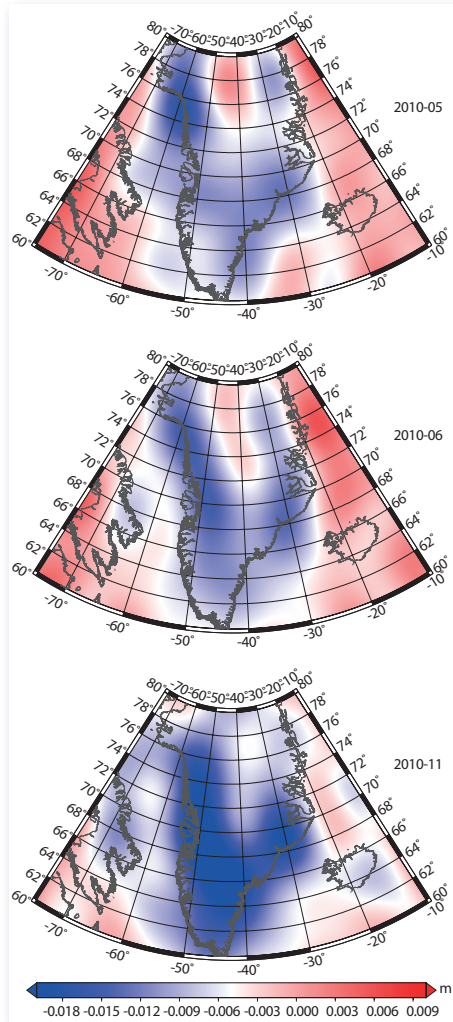


Fig. 2.2.2: Differences  $\Delta N = N_{\text{GSM}} - N_{\text{EGM}}$  of geoid heights from GRACE GSM-2 data (Release 04) for the months May, June and November 2010 over Greenland based on spherical harmonic coefficients up to d/o 60. EGM2008 (d/o 60) is used as reference model.

Concerning the evaluation of GOCE data we focused on the component  $V_{\text{ZZ}}$  of the full gradient tensor. The small rotation angles to obtain  $V_{\text{ZZ}}$  in an exact radial direction are neglected, and to increase the accuracy the modified gradients  $V_{\text{Comb}}$  according to Eq. (1) are used. To model the gravity of a specific region of the Earth we use a series expansion in terms of radial base functions  $k(\mathbf{x}, \mathbf{x}_q)$  with unknown coefficients  $d_{J,q}$ , i.e.

$$V_{\text{Comb}}(\mathbf{x}) + e_{\text{ZZ}}(\mathbf{x}) = V_{\text{ZZ,back}}(\mathbf{x}) + \sum_{q=1}^{N_J} d_{J,q} k(\mathbf{x}, \mathbf{x}_q), \quad (2)$$

where  $e_{\text{ZZ}}$  stands for the measurement error. A background model  $V_{\text{ZZ,back}}$  is introduced for subtracting the dominant parts from the observed gravity gradients, which allows modeling just the differences. The kernel functions  $k(\mathbf{x}, \mathbf{x}_q)$  are defined as

$$k(\mathbf{x}, \mathbf{x}_q) = \sum_{l=0}^l \frac{(2l+1)(l+1)(l+2)}{4\pi} \left( \frac{R}{r} \right)^{l+1} P_l(\mathbf{r}^T \mathbf{r}_q). \quad (3)$$

Herein the fraction  $(l+1)(l+2)/r^2$  results from the observation type (second derivatives of the gravitational potential  $V$  of the Earth),  $P_l$  are the Legendre polynomials of degree  $l$  and  $R$  is a mean Earth radius. Furthermore,  $\mathbf{x} = |\mathbf{x}| \cdot \mathbf{r}$  with  $|\mathbf{x}| = r$  and  $|\mathbf{r}| = 1$  is the position vector of the observation site. The positions  $P_q$  with the position vectors  $\mathbf{x}_q = |\mathbf{x}_q| \cdot \mathbf{r}_q$  with  $|\mathbf{x}_q| = R$  of the center of the kernel function  $k(\mathbf{x}, \mathbf{x}_q)$  are given on predefined grids such as the Reuter grid as shown in Figure 2.2.3 for the region of Greenland. The total number  $N_J$  of kernel functions, i.e. the number of unknown coefficients  $d_{J,q}$  depends on the size of the region of interest and on the resolution of the input data. Our procedure related to the observation  $V_{\text{Comb}}$  is based on the following steps:

- Computation of the coefficients  $d_{J,q}$  using the observation equation (2) by applying variance component estimation.
- Calculation of the gravitational potential  $V$  or functionals of  $V$  such as the gravity anomaly or geoid undulations by using appropriate base functions, e.g. the Blackman scaling functions and the estimated coefficients  $d_{J,q}$ .

### Modelling of geoid differences

To be more specific, we define the geoid difference  $\Delta N(\mathbf{x}) = N_{back}(\mathbf{x})$  at resolution level  $J+1$  as

$$\Delta N_{J+1}(\mathbf{x}) = \frac{1}{\gamma} \sum_{q=1}^{N_J} d_{J,q} \phi_{J+1}(\mathbf{x}, \mathbf{x}_q), \quad (4)$$

wherein  $\gamma$  is the normal gravity. The scaling function  $\phi_{J+1}(\mathbf{x}, \mathbf{x}_q)$  comprises signal parts until degree value  $l'_J = 2^{J+1} - 1 \leq l'$ ;  $l'_J$  should be smaller than the chosen maximum degree of the parameter estimation to avoid so called omission errors known from series expansion in spherical harmonics. In our investigations we use the Blackman scaling function.

### Specification of grid area, data area and area of interest

For the estimation of monthly solutions from the modified GOCE gravity gradients we set  $l' = 140$  in Eq. (3) and  $l'_6 = 127$  with  $J = 6$  in Eq. (4). Based on these values we setup a grid for the region of interest, i.e. Greenland with  $N_6 = 477$  grid points as shown in Figure 2.2.3.

Fig.2.2.3: Area of interest (green bordered); gray lines represent GOCE orbits for one month; red crosses are the grid points ( $N_6 = 477$ ). The interspace between the different areas depends on the chosen value of  $l'$  or highest level  $J$ , respectively.

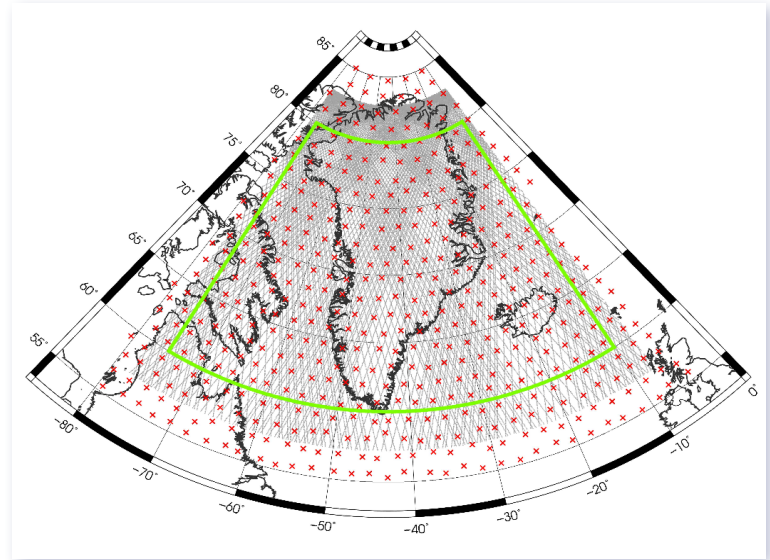


Figure 2.2.4 shows the results for the geoid heights  $\Delta N \approx \Delta N_7$  according to Eq. (4) for the three months May, June and September 2010. The subtracted background model is EGM2008, i.e.  $N_{back} = N_{EGM}$ , developed up to d/o 120. Instead of adding the background model again and subtracting afterwards a reference model, we immediately assess the geoid height differences  $\Delta N = N_{GOCE} - N_{EGM}$  with values between  $\pm 40$  cm. The variations between the two adjacent months May and June are smaller than the differences to September. This result resembles the relative half-year variations of the monthly GRACE solutions. For fur-

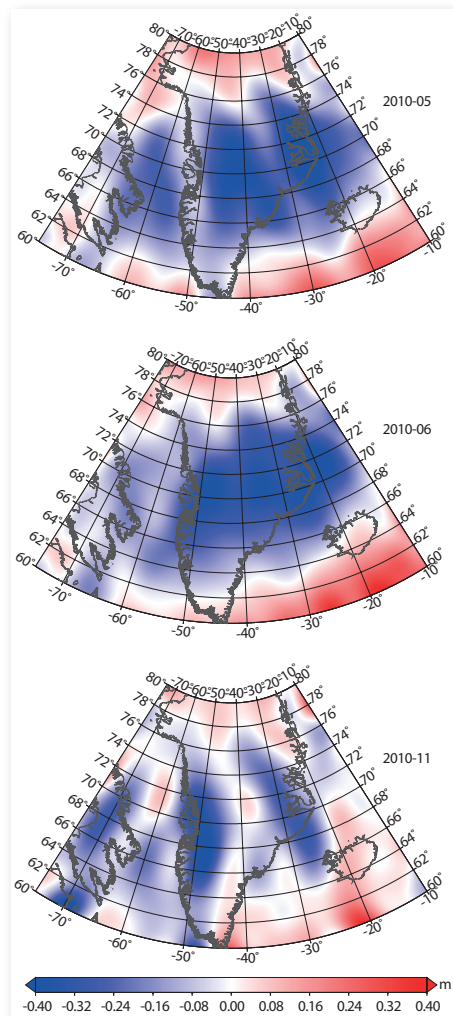


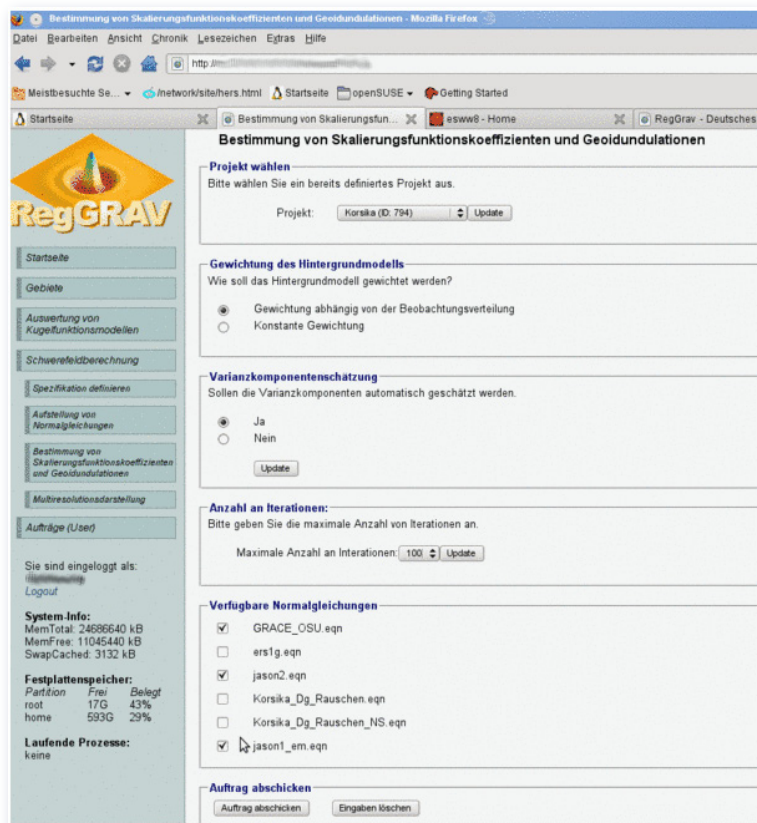
Fig. 2.2.4: Estimated geoid heights  $\Delta N$  from GOCE modified gravity gradients (1) for the three months May, June and November 2010 in Greenland with a series expansion in terms of Blackman base functions up to degree 127. As background model we used EGM2008 (d/o 120).

## RegGRAV project

Fig. 2.2.5: Web-interface of the developed RegGRAV software. The screenshot shows different options for the estimation of the unknown coefficients within a regional gravity field determination.

ther analysis the reference model and its resolution should be identical for the GRACE and the GOCE data set.

Within the RegGRAV project (Generation of a software application for producing high precise regional gravity models as a height reference surface) we developed a software package with a graphical user interface to compute regional gravity fields. Figure 2.2.5 shows the web-interface of the package that can be executed independently and simultaneously from several users. A user can define any area of interest for which the gravity field should be modeled. The expansion of this area (green bordered region in Figure 2.2.3) should be smaller than the provided observation data (gray lines) to avoid incorrect boundary effects. Next one can choose between analyzing given gravity models in terms of spherical harmonics and estimating new regional gravity fields via spherical base functions for the specific region analogously to Eq. (3). Both of these menu items are subdivided into several processing steps which contain multiple options. Examples are the choice of different background models, their spectral resolutions, several observation data sets, and the point grid of the localizing base functions, the type of base functions, the number of resolution levels within a multi-resolution representation (MRR) and the maximum resolution, as well as the desired functionals of the gravity field. The status of the computations is shown under another menu item. Furthermore, all important results are provided in figures and stored in data files.



## 2.3 Geophysical applications

### Earthquakes in Chile and Japan

Earthquakes change the gravity field of the area affected by the earthquake due to mass redistribution in the upper layers of the Earth. In addition, sub-oceanic earthquakes deformation of the ocean floor causes relative sea level changes and mass redistribution of water that has again a significant effect on gravity field.

Two such recent, large sub-oceanic earthquakes are the 27 February 2010 Chile Maule earthquake with a magnitude of Mw 8.8 and the 11 March 2011 Japan Tohoku earthquake with a magnitude of Mw 9.0. Although the mean gravity field is to be mapped with GOCE, the sheer size of both Earthquakes and associated mass redistribution make them both potential candidates for detecting the co-seismic gravity changes in the GOCE gradiometer data. To assess the detectability of gravity field changes in the GOCE gravity gradients these earthquakes have been modelled using a forward computation. This work is a feasibility study sponsored as part of ESA's Support to Science Element (STSE) in which DGFI collaborates with TU Delft in The Netherlands.

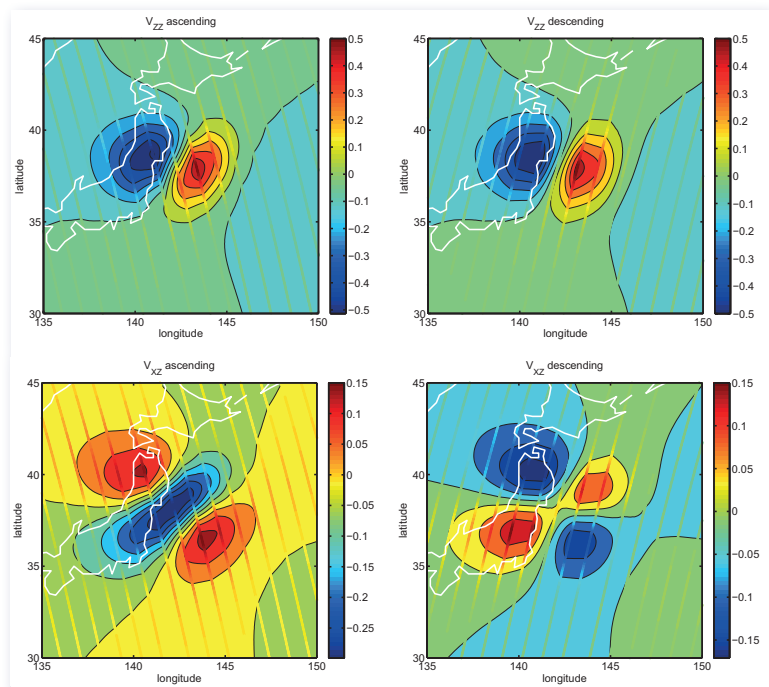


Fig. 2.3.1: Modelled co-seismic  $V_{xz}$  and  $V_{zz}$  gradients along GOCE orbits for the Japan earthquake (units in mE).

### Japan Tohoku earthquake, March 2011

For the Japan earthquake the modelled direct effect of seismic slip on vertical deformation ranges between -3.0 and 6.7 m. It has the shape of an elongated dipole, with uplift just in front of the coastline and subsidence land inwards. The changes in geoid height and gravity anomaly show a comparable dipole as for the vertical deformation. The geoid effect is between -12 and 16 mm, whereas the gravity anomaly change is between -0.24 and 0.36 mGal. The geoid height signal from the forward modelling is converted to gravity gradients as they would have been measured along the GOCE orbit. In Figure 2.3.1 these gravity gradients are displayed for  $V_{zz}$  for a period of 20 days for the Japan earthquake. Because of the orbit height the gradients are smoother than the geoid height changes, but the dipole is clearly visible. The contour lines were obtained by interpolating the values for ascending and descending tracks. Figure 2.3.1 also shows the modelled  $V_{xz}$  co-seismic sig-

nals at GOCE altitude. Clearly the spatial pattern is quite different for ascending and descending tracks and the gradients provide 3D information. The modelled gravity gradient amplitudes vary from 0.1 to 0.3 mE for the Chile earthquake, whereas the amplitude is 0.2 to 0.6 mE for the Japan earthquake. Given the GOCE measurement accuracy it is therefore challenging to detect these earthquakes in the GOCE data (see section 2.1).

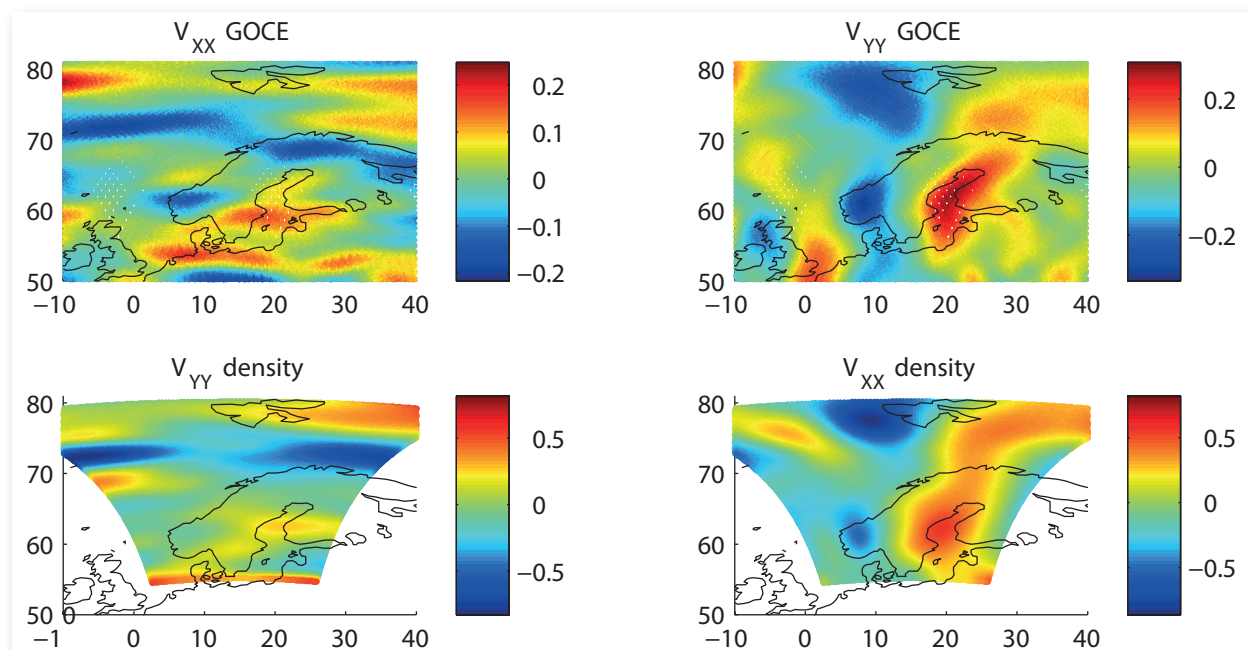
### Lithospheric modelling

GOCE data may improve the understanding and modelling of the Earth's interior and its dynamic processes, contributing to gain new insights into the geodynamics associated with the lithosphere, mantle composition and rheology, uplift and subduction processes. However, to achieve this challenging target, GOCE should be used in combination with additional data sources: e.g. magnetic, gravity and seismology in situ, airborne and satellite data sets. In the context of an ESA sponsored study, part of ESA's Support to Science Element (STSE), DGFI collaborates with NGU (Norway) and TNO (The Netherlands). The overall objective of the study is to combine GOCE gravity gradients with heterogeneous other satellite gravity information to arrive at a combined set of gravity gradients complementing (near)-surface data sets and demonstrate their utility to complement additional data to enhance geophysical modelling and exploration.

### Comparing modelled and observed gradients

In a first step, we compared the shape and amplitude of gravity gradients from a 3D lithosphere density model for the North-East Atlantic Margin with GOCE data. Gravity gradients in the north-oriented frame at GOCE altitude were used and EGM2008 to degree and order 10 was subtracted. The signal of the original GOCE gradients below the MBW was replaced by GOCO01S signal before rotation from the instrument frame to the north-oriented frame. Visual comparison showed that the invariants and vertical gravity gradient show similar anomalies, although with different amplitudes (see Figure 2.3.2).

Fig. 2.3.2: Comparison between GOCE gravity gradients and gravity gradients from lithospheric density model. Units are E ( $10^{-9} \text{ s}^{-2}$ ).



The difference in orientation of the reference frames for the density model and GOCE has to be accounted for. The modeled density gradients have the orientation East-North-Up, whereas the GOCE gradients are oriented North-West-Up. In addition, geophysical modeling software normally uses a Cartesian coordinate system, whereas the GOCE data product is defined in a geographical system. This leads among others to a difference in azimuth between the two systems. Accounting for the azimuth ensures consistency, but we assessed that the difference between the rotated gradients is not dramatic and could be neglected in the first analyses.

### **Related publications:**

- BOUMAN J.: Relation between geoidal undulation, deflection of the vertical and vertical gravity gradient revisited. *Journal of Geodesy*, DOI: 10.1007/s00190-011-0520-9, 2011
- BOUMAN J., FIOROT S., FUCHS M., GRUBER T., SCHRAMA E., TSCHERNING C.C., VEICHERTS M., VISSER P.: GOCE gravitational gradients along the orbit. *Journal of Geodesy*, DOI: 10.1007/s00190-011-0464-0, 2011
- BOUMAN J., FIOROT S., FUCHS M., GRUBER T., SCHRAMA E., TSCHERNING C.C., VEICHERTS M., VISSER P.: GOCE Level 2 Gravity Gradients. *Proceedings GOCE User Workshop 2011*, ESA SP-696, 2011
- BOUMAN J., BOSCH W., SEBERA J.: Assessment of systematic errors in the computation of gravity gradients from satellite altimeter data. *Marine Geodesy*, 34:85-107, DOI: 10.1080/01490419.2010.518498, 2011
- BOUMAN J., EBBING J., FUCHS M., SCHMIDT M., BOSCH W., SCHWATKE C., ABDUL FATTAH, MEEKES S., ABBINK O., SCHAVEMAKER Y.: Heterogeneous gravity data combination for earth interior and geophysical exploration research. *Proceedings GOCE User Workshop 2011*, ESA SP-696, 2011
- BOUMAN J., FUCHS M., SCHMIDT M.: Feasibility Study Report, The Earth's time-variable gravity field observed by GOCE, Report GOCE/TH4/FSR, Draft, 2011
- BROERSE T., VISSER P., BOUMAN J., FUCHS M., VERMEERSEN B., SCHMIDT M.: Modelling and observing the 8.8 Chile and 9.0 Japan earthquakes using GOCE. *Proceedings GOCE User Workshop 2011*, ESA SP-696, 2011
- EBBING J., ABDUL FATTAH R., BOUMAN J.: Requirements Baseline, Heterogeneous gravity data combination for Earth interior and geophysical exploration research, Report DD-GOCE+-DNT-01, Issue 2.0, 2011
- FUCHS M., BOUMAN J.: Rotation of GOCE gravity gradients to local frames. *Geophysical Journal International*, DOI: 10.1111/j.1365-246X.2011.05162.x, 2011
- MURBÖCK M., PAIL R., FUCHS M., BOUMAN J.: GOCE gravity gradients: a new satellite observable. *Proceedings GOCE User Workshop 2011*, ESA SP-696, 2011
- RISPENS, S.M., BOUMAN, J. : External calibration of GOCE accelerations to improve derived gravitational gradients. *Journal of Geodetic Science*, vol. 1, no. 2, pp. 114-126, DOI: 10.2478/v10156-010-0014-3, 2011
- SCHRAMA E., BROERSE T., VISSER P., FUCHS M., SCHMIDT M., BOUMAN J.: Preliminary Analysis Report, The Earth's time-variable gravity field observed by GOCE, Report GOCE/TH4/PAR, Issue 2.1, 2011
- VEICHERTS M., TSCHERNING C.C., BOUMAN J.: Improved Cal/Val of GOCE gravity gradients using terrestrial data. *Proceedings GOCE User Workshop 2011*, ESA SP-696, 2011

### 3 Geodetic Earth system modelling

*The main components of the Earth system are the atmosphere, the hydrosphere, consisting of the oceans and the continental hydrology, the geosphere, i.e. the solid Earth, the cryosphere and the biosphere. This research field aims on the improvement of understanding the dynamic processes and their interactions within the 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 information on the dynamic processes, which are of great importance for monitoring and assessment of climate change. The results will be delivered to other scientific disciplines and especially to the public in order to provide competent knowledge for discussions on global change.*

*For the present research area following themes have been identified: (i) Earth system models, (ii) atmosphere, (iii) hydrosphere and (iv) the solid Earth. Results of various projects are presented in the corresponding subsections.*

#### Using space-geodetic observations

Geodetic Earth system modelling is a primary research topic at DGFI. The precise and high-resolution space geodetic observations provide in general integral information. Thus, one of the most basic issues of this research field is the separation of the integral signal into its individual components. This can be achieved by combining different observation techniques with the chance to compensate the weakness of some sensor systems (e.g. low sensitivity and sampling rate) by other techniques. Stochastic models, appropriate adjustment procedures and/or assimilation techniques

are to be applied to derive improved geophysical models. The most important questions to be investigated are:

- how to separate the measured integral signals into the individual contributions,
- how to access the accuracy of single process parameters,
- how to close the balance between Earth system components, and
- how to improve geophysical models?

#### 3.1 Earth system models

Mass displacements and motions in the subsystems of the Earth cause Earth rotation changes. Up to now the individual Earth rotation excitation mechanisms are mainly estimated with geophysical models of the atmosphere, oceans and continental hydrosphere. The combination of geometric, gravimetric and altimetric space-geodetic observations allows the separation of the integral excitation mechanism of polar motion into the atmospheric, oceanic and hydrological mass effects as well as the integral motion effect.

##### Analysis and validation of geodetic Earth system models from Earth rotation variations

Polar motion can be monitored by the precise geometric observation techniques: SLR, VLBI, GNSS and DORIS. The pole coordinates allow to draw conclusions on the integral excitation mechanism. We determine the equatorial angular momentum functions

$$\chi(t) = \chi^{mass}(t) + \chi^{motion}(t)$$

### Modelling of mass variations

for the integral effect from the polar motion time series IERS EOP 08 C04, ITRF2008 and DTRF2008 as described in Götzl<sup>1</sup> (2008). The integral mass effect  $\chi^{mass}(t) = \chi_l^{mass}(t) + i \cdot \chi_2^{mass}(t)$  with  $i = \sqrt{-1}$  can be estimated from time variable gravity field changes, which are observed by the gravity satellite mission GRACE. Long wavelength gravity field variations can be also determined from SLR satellites. For our investigations we use the gravity field solutions GFZ RL04, CSR RL04, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010 and CSR SLR RL04. We first add the 2<sup>nd</sup> degree gravity field coefficients of the level 2 products GSM and GAC, then determine the moments of inertia and, finally, derive the equatorial angular momentum functions for the integral mass effect  $\chi^{mass}(t)$ ; for more details see Götzl<sup>1</sup> (2008). By applying (1) a spatial filter which reduces the systematic errors and (2) an ocean mask, the oceanic mass effect can be also determined from the level 2 products GSM and GAD or GAC of the gravity field solutions GFZ RL04, CSR RL04, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010. Furthermore, the oceanic mass effect can be estimated from sea level anomalies which are observed by satellite altimeter missions. Due to the fact that sea level anomalies are caused by volume changes of the sea water, the volume (steric) effect has to be removed. We use the multi-mission altimetry solutions: AVISO and DGFI. The steric effect is determined from three dimensional temperature and salinity fields of the World Ocean Atlas 2009 and Ishii and Kimoto<sup>2</sup> (2009). In Götzl et al. (submitted) the gravimetric and altimetric computation strategies for the oceanic mass effect  $\chi^O(t) = \chi_l^O(t) + i \cdot \chi_2^O(t)$  are described. The hydrological mass effect  $\chi^H(t) = \chi_l^H(t) + i \cdot \chi_2^H(t)$  can be determined analog to the oceanic mass effect by applying a filter and a land mask from the level 2 products GSM of the gravity field solutions GFZ RL04, CSR RL04, JPL RL04, EIGEN-GRGS.RL02, ITG-Grace2010.

### Combining angular momentum functions

SLR, VLBI, GNSS, Doris	$\chi(t)$	$= \chi^A(t) + \chi^O(t) + \chi^H(t) + \chi^m(t)$
SLR, GRACE	$\chi^{mass}(t)$	$= \chi^A(t) + \chi^O(t) + \chi^H(t)$
GRACE, Altimetrie	$\chi^O(t)$	$= \chi^O(t)$
GRACE	$\chi^H(t)$	$= \chi^H(t)$
Modell	$\chi^A(t)$	$= \chi^A(t)$

Fig. 3.1.1: Observation equations of the adjustment model to combine geometric, gravimetric and altimetric observations (light gray) in order to estimate the atmospheric, oceanic and hydrological mass effects  $\chi^A(t)$ ,  $\chi^O(t)$  and  $\chi^H(t)$  as well as the integral motion effect  $\chi^m(t) = \chi^{motion}(t)$  (dark gray).

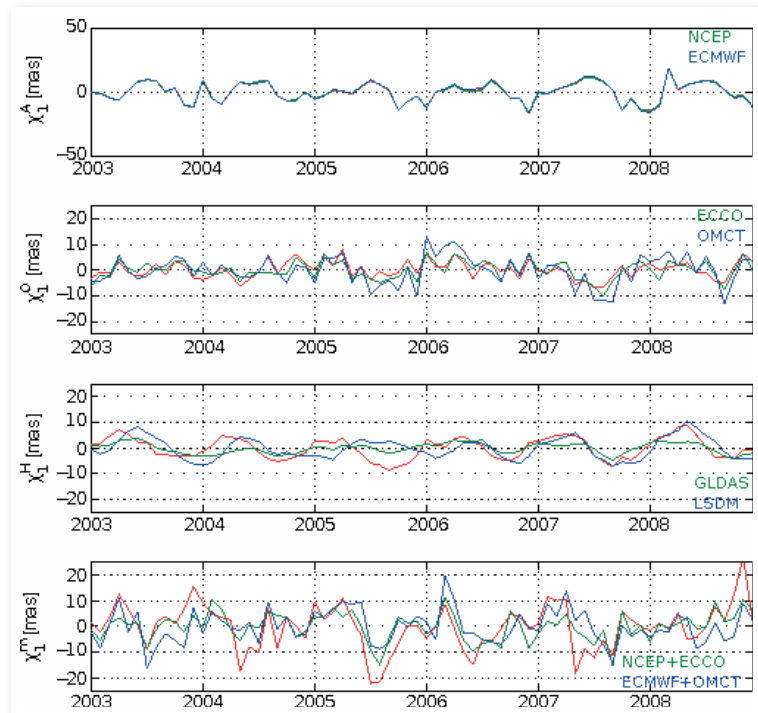
The combination of geometric, gravimetric and altimetric angular momentum functions aims at the separation of individual polar motion excitation mechanisms by compensating the weaknesses of each parameter estimation procedure and by benefiting of the strengths of each space-geodetic technique. In Figure 3.1.1 the observation equations of the linear Gauss-Markoff model are shown. As input for the combination we use the above mentioned geodetic angular momentum functions as well as two atmospheric model (NCEP, ECMWF) solutions for the atmospheric mass effect  $\chi^A(t)$ . These observations are treated as uncorrelated in a least squares adjustment. The weighting of the observations is based on empirical estimated variances and autocorrelations. In Figure 3.1.2 the results for the real-valued parts of the angular momentum functions of the combination are compared with geophysical model estimations; the corresponding results for the im-

1 GÖTTL F.: Earth rotation variations from geometric, gravimetric and altimetric observations and geophysical models, DGFI Report 84, 2008

2 ISCHI M. and M. KIMOTO: Reevaluation of historical ocean heat content variations with time varying XBT and MBT depth bias corrections, J. of Oceanography, 65: 287-299, 2009

aginary parts are not shown here. While the geophysical and geodetic results for the oceanic mass effect agree very well, the results for the hydrological mass effect show a higher disagreement. The uncertainty of hydrology models is larger than of atmosphere and ocean models because the observations of the hydrological state variables are more imprecise. Geophysical model results show higher agreement with the adjusted geodetic results than with the single geodetic solutions (not shown here). Thus, we conclude that a weighted adjustment of geometric, gravimetric and altimetric angular momentum functions improves the quality of the geodetic estimations.

Fig. 3.1.2: Monthly angular momentum functions for the atmospheric, oceanic and hydrological mass effects  $\chi_1^A(t)$ ,  $\chi_1^O(t)$  and  $\chi_1^H(t)$  and for the integral motion effect  $\chi_1^m(t)$  estimated from geophysical models (blue, green) and combined geodetic observations (red); similar results are obtained for the angular momentum functions  $\chi_2^A(t)$ ,  $\chi_2^O(t)$ ,  $\chi_2^H(t)$  and  $\chi_2^m(t)$ .



## 3.2 Atmosphere

### Determination and analysis of troposphere parameters

The observations of space geodetic techniques based on microwave signals are all affected by the atmosphere in the same way. The impact of tropospheric refraction is considered within the data analysis by an a priori (hydrostatic) part and an estimated wet part of the zenith delay. In addition two horizontal gradients are determined, in order to account for the dependency of the delay on the azimuth.

The CONT08 campaign of IVS provides 15 days of continuous VLBI observation data from a global network of eleven VLBI stations co-located with GNSS (GNSS data of site Zelenchukskaya are missing). The data quality sufficient to compare and to study the combination of the tropospheric parameters derived from VLBI and GPS. For this purpose, the effect of the height difference between the instruments must be considered. This can be done by (1) modelling, considering the meteorological data at one instrument or by (2) ray tracing data based on a weather model.

**Modelling the hydrostatic zenith delay**

(1) If the temperature  $T_0$  and the air pressure  $p_0$  at one instrument and the height difference  $(h - h_0)$  between the instruments are known, the difference  $\Delta ZHD$  in the hydrostatic zenith delay can be computed by F. Brunner<sup>3</sup>

$$\Delta ZHD = -0.002277 \cdot 0.02416 \cdot \frac{p_0}{T_0} \cdot (h - h_0).$$

The difference  $\Delta ZWD$  in the wet zenith delay can be derived from the temperature and the vapor pressure  $e_0$  by

$$\Delta ZHD = -2.789 \cdot \frac{e_0}{T_0} \cdot \frac{5383 - 0.7803 \cdot T_0}{T_0 (h - h_0)}$$

Figure 3.2.1 shows the differences in total zenith delay derived from a comparison of GPS and VLBI and from the Brunner model introduced before. The meteorological input data are the meteorological measurements at the VLBI stations aligned to the ECMWF model in order to remove existing offsets, which might be caused by calibration errors of the meteorological sensors.

The absolute model values are often larger than the absolute differences derived from the space geodetic techniques, except for NYA1, HRAO and in particular WEST. In case of WTZR, KOKE and TIGO the sign is inverted. A very good agreement of better than 1 mm can only be found for SVTL.

**Ray tracking with ECMWF data**

(2) Ray tracing data derived from the global atmospheric model ECMWF are provided by J. Böhm<sup>4</sup> from TU Vienna. Figure 3.2.2 compares the results of Figure 3.2.1 with the differences obtained from a comparison of the zenith delay differences ( $\Delta ZD$ ) derived from GNSS-VLBI and from ray tracing. The differences obtained for ray tracing are in general a bit smaller than the Brunner model. For some stations even a large improvement can be found:

- for station HARB the height difference to VLBI is very large (143 mm). The ray tracing data fit the  $\Delta ZD$  obtained from the space geodetic techniques much better than the model values,
- for stations ONSA and TSKB also a large improvement can be seen. The reasons are not clear.

There are also stations with only small improvements, e.g. the offsets for MEDI, WEST and CONZ are still larger than 4 mm.

A combination of VLBI tropospheric parameters of the CONT08 campaign, which have been derived from different IVS Analysis Centres is performed by Heinkelmann et al. (2011).

<sup>3</sup> BRUNNER F., *personal communications*

<sup>4</sup> BÖHM J., *personal communications*

Fig. 3.2.1:  $\Delta ZD = \Delta ZHD + \Delta ZWD$  derived from GPS-VLBI and from Brunner model. The height difference between VLBI and GPS is also given (scaled).

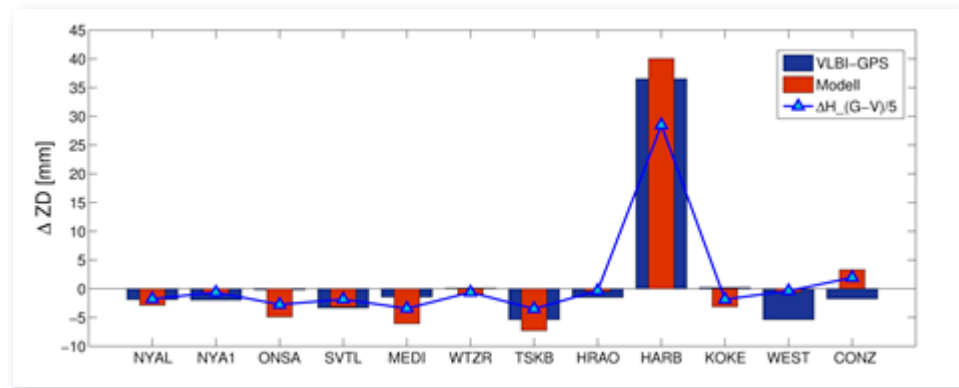
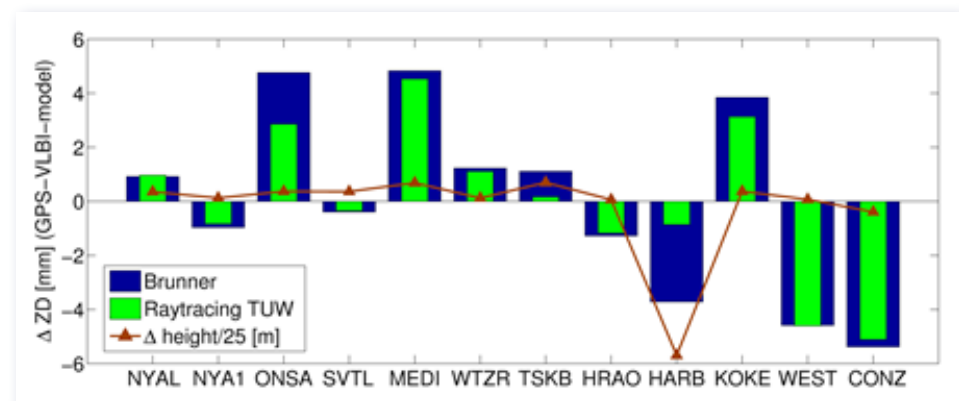


Fig. 3.2.2:  $\Delta ZD$  derived from GPS-VLBI compared to Brunner model (blue) and compared to ray tracing derived offsets (green). The height difference between VLBI and GPS is also given (scaled). The co-locations are named by the GPS station name.



### Progress in B-spline modelling of the ionosphere

During the last years, DGFI made great achievements on pure mathematical ionosphere modelling based on compactly supported B-spline series expansions; latest studies on these topics as well as on the development of appropriate combination strategies have been published by Dettmering et al. (2011a, b). The influence of data gaps on global maps of the vertical total electron content (VTEC) represented by series expansions in spherical harmonics and B-splines is discussed by Schmidt et al. (2011). Whereas spherical harmonic models are distorted everywhere on the globe, B-splines show significant influences just in the near surrounding of the gaps. Koch and Schmidt (2011) developed the lofting method as an efficient algorithm on four-dimensional B-spline models and apply the approach to electron density value of the International Reference Ionosphere (IRI).

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

One future issue of ionosphere modelling at DGFI is the development of a data driven physical ionosphere model. As an important step in this direction a physics-motivated modeling approach was developed within the DFG project MuSIK, which merges the expertise of DGFI, the Institute of Astronomical and Physical Geodesy (IAPG) of the Technical University Munich (TUM) and the German Aerospace Center (DLR) in Neustrelitz.

Generally, the ionosphere can be divided into the *D* and *E* layer as well as into the two *F* layers *F1* and *F2*. In particular, the *F2* layer is the most important, where the electron density  $N_e$  reaches

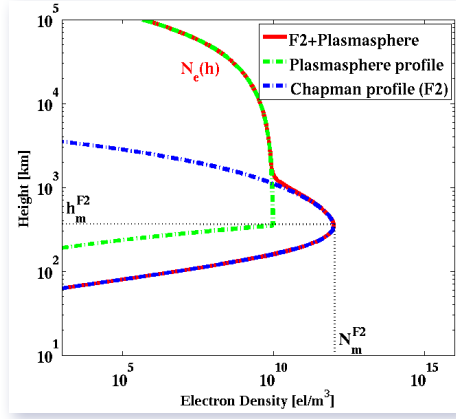


Fig. 3.2.3: Vertical electron density profile of the ionosphere and the plasmasphere according to Eq. (1).

### Modelling the basic parameters for electron density profiles

its maximum. Above the ionosphere the plasmasphere is located. The physics-motivated profile function

$$N_e(h) = N_e^{F2}(h) + N_e^P(h) \quad (1)$$

$$= N_e^{F2} e^{0.5(1-e^{-z})} + N_0^P e^{-|h-h_{max}^{F2}|/H^P}$$

with  $z = (h - h_{max}^{F2})/H^{F2}$  and  $H^P = 10$  km for  $h < h_{max}^{F2}$  describes the vertical behavior of the electron density and means a combination of an F2-Chapman layer  $N_e^{F2}(h)$  and the plasmasphere profile  $N_e^P(h)$ ; see Figure 3.2.3.

This profile is defined by altogether five parameters, namely the F2 peak electron density  $N_0^{F2}$ , the peak height  $h_{max}^{F2}$ , the F2 scale height  $H^{F2}$ , the plasmasphere basis density  $N_0^P$  and the plasmasphere scale height  $H^P$ . In our approach, each of these parameters will be decomposed into a background model part, derived from given ionosphere and plasmasphere models, and an unknown correction term. In case of the F2 scale height  $H^{F2}$ , for instance, we use the decomposition

$$H^{F2} = H_{IRI}^{F2} + \Delta H^{F2}(\mathbf{d}), \quad (2)$$

wherein the values  $H_{IRI}^{F2}$  are calculated from IRI which serves as the background model. To be more specific, we calculate the function  $H_{IRI}^{F2}(\lambda, \varphi, t) = VTEC(\lambda, \varphi, t)/(4.13 \cdot N_0^{F2})$ , wherein the values for  $VTEC$  and  $N_0^{F2}$  were taken from IRI 2007. The correction term  $\Delta H^{F2}(\mathbf{d})$  is modelled as a series expansion in terms of tensor products of three one-dimensional B-spline functions  $\phi_k$  depending on latitude  $\varphi$ , longitude  $\lambda$  and time  $t$  with initial unknown series coefficients  $d_{k_1, k_2, k_3}$  collected in the vector  $\mathbf{d}$ , i.e.

$$\Delta H^{F2}(\mathbf{d}) = \sum_{k_1=0}^{K_1-1} \sum_{k_2=0}^{K_2-1} \sum_{k_3=0}^{K_3-1} d_{k_1, k_2, k_3} \phi_{k_1}(\lambda) \phi_{k_2}(\varphi) \phi_{k_3}(t);$$

more information about the B-spline approach can, e.g. be found in Schmidt et al. (2011). Since the quantity  $H^{F2}$  is part of the exponential term in Eq. (1), linearization is required. For that purpose we decompose the scaling coefficient vector  $\mathbf{d} = \mathbf{d}_0 + \Delta \mathbf{d}$  into an initial vector  $\mathbf{d}_0$  and a correction part  $\Delta \mathbf{d} = \mathbf{d} - \mathbf{d}_0$ . Considering this decomposition Eq. (2) yields

$$H^{F2} = H_{IRI}^{F2} + \Delta H^{F2}(\mathbf{d}_0) + \left. \frac{\partial H^{F2}}{\partial \mathbf{d}} \right|_{\mathbf{d}=\mathbf{d}_0} \Delta \mathbf{d}.$$

Thus, for the linearization of Eq. (1) we obtain the general formulation

$$N_e(H^{F2}) = N_e(H_0^{F2}) + \left( \left. \frac{\partial N_e}{\partial H^{F2}} \right|_{H^{F2}=H_0^{F2}} \right) \left( \left. \frac{\partial H^{F2}}{\partial \mathbf{d}} \right|_{\mathbf{d}=\mathbf{d}_0} \right) \Delta \mathbf{d}$$

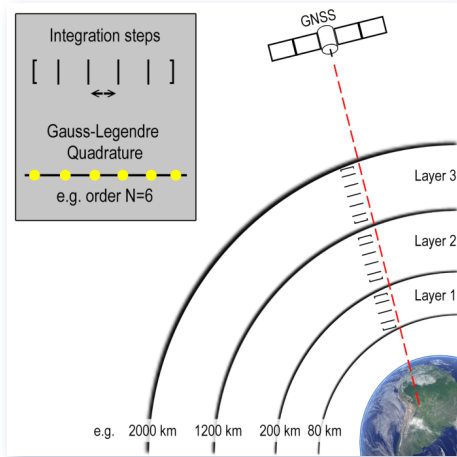


Fig. 3.2.4: Decomposition of the ionosphere into three layers. Along the ray-path between the satellite and the terrestrial observation site the numerical integration is performed with layer-dependent step sizes. Applying the Gauss-Legendre quadrature within each integration step  $N$  knots (yellow dots) are introduced. In the example we selected  $N=6$ .

### Case study for stations in South America

with initial values  $H_0^{F2} = H_{IRI}^{F2} + \Delta H^{F2}(d_0)$ . The slant total electron content  $STEC$  is defined as the integral

$$STEC = \int_R^S N_e ds \quad (3)$$

of the electron density along the ray-path between the satellite  $S$  and the receiver  $R$ . Introducing the linearized equation for the electron density into the integrand of Eq. (3) yields the observation equation for estimating  $\Delta d$  from geometry-free GPS observations. Since a huge number of integrations has to be performed, effective algorithms have to be developed. For that purpose we introduce three layers as shown in Figure 3.2.4.

For selecting appropriate values for the step sizes related to the three layers we simulated GPS observations based on five SIRGAS stations in South America as shown in Figure 3.2.5. Based on altogether 2404 generated STEC observations we computed a reference solution by fixing the step sizes of the three layers to 1 km each and choosing the Gauss-Legendre quadrature technique of order  $N = 9$ , i.e. we chose 9 weighted nodal points per integration step. To reduce the computation time for the evaluation of the generated grid but keeping the integration as accurate as possible we chose a large number of scenarios with various values for the step sizes  $\Delta s_1/\Delta s_2/\Delta s_3$  related to the layers 1, 2 and 3. Figure 3.2.6 shows bar diagrams which are kindly provided by M. Limberger, coworker of the project MuSIK at IAPG.

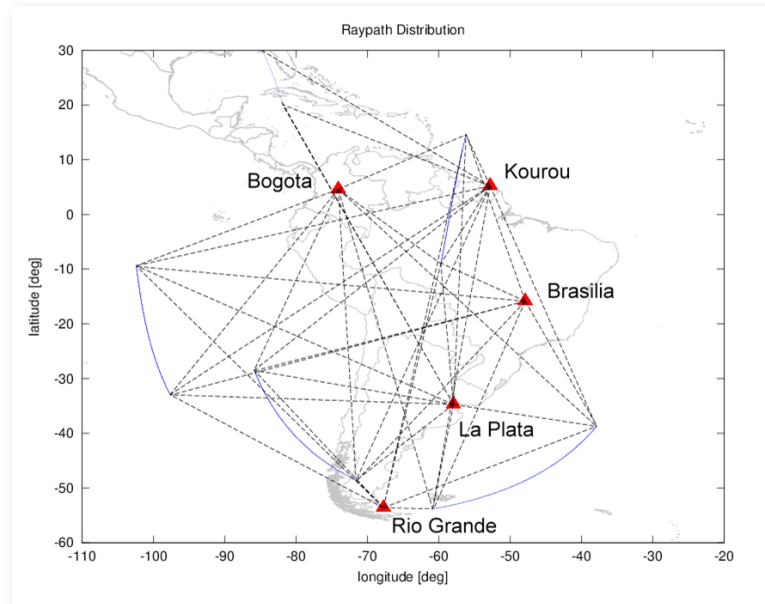


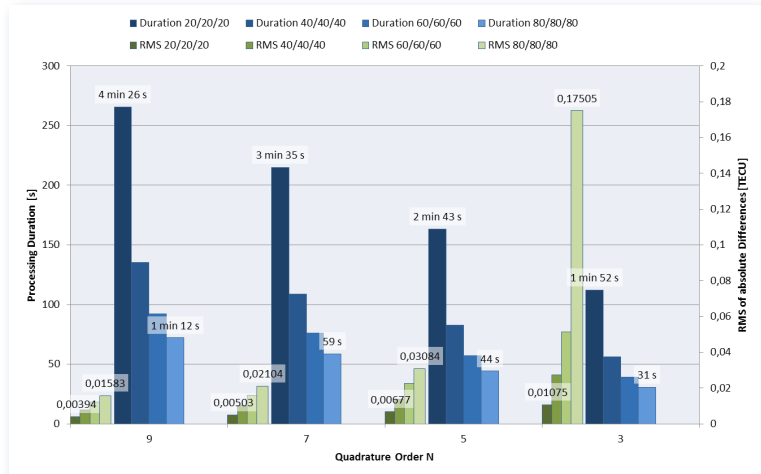
Fig. 3.2.5: 5 GPS stations of the SIRGAS network in South America. Along the GPS satellite arcs (blue lines) we create STEC data with a sampling interval of 30 seconds within the time interval 06 – 07 UT, 2002/07/01. With these assumptions we generated a network with 2404 ray-paths, i.e. STEC observations.

In Figure 3.2.6 we present results of solutions with equal step sizes related to all three layers. Besides these computations we also chose a variety of different step sizes. Studying the RMS

### Investigating options for quadrature

values of all these solutions with respect to the reference solution mentioned before we finally conclude that the best integration results (computation time vs. RMS value) are obtained for step sizes  $\Delta s_1 = 80 \text{ km}/\Delta s_2 = 70 \text{ km}/\Delta s_3 = 100 \text{ km}$  and quadrature order  $N = 6$ . The smallest step size value, i.e. 70 km is chosen for that part of the profile where the electron density has its maximum; cf. Figure 3.2.3. Based on this setting various grids of simulated STEC observations were evaluated. Since the electron density profile, Eq. (1), is highly non-linear regarding the F2 scale height, the convergence of the iterative parameter estimation is a further severe problem, which has to be studied in detail.

Fig. 3.2.6: Comparison of Gauss-Legendre quadrature of order  $N$  with a reference solution step sizes 1 km/1 km/1 km,  $N=9$ . Blue bars indicate computation time with scale on the left, green bars give RMS differences wrt the reference solution. Dark to light colours indicate increasing step size from 20 - 80 km.



## 3.3 Hydrosphere

### Empirical Ocean Tide Model EOT11a

A new version of the empirical ocean tide models, EOT11a, has been issued by DGF1 and is available on the anonymous ftp-server <ftp.dgfi.badw.de> at directory `pub/EOT11a`. The model includes the constituents Mm, Mf, O1, K1, P1, Q1, S1, M2, S2, N2, K2, 2N2, and M4. EOT11a is based on the altimeter data listed in Table 3.3.1. To rebut the suspicion that any tidal signal is mapped to the radial error estimates, the cross calibration was not applied. Instead, mission specific offsets were estimated for every grid node.

Table 3.3.1: Altimeter data used for the development of EOT11a.

Mission	Cycles	Time period	Source
TOPEX/Poseidon	001 - 481	1992/09/23 - 2005/10/08	MGDR-B (NASA)
Jason-1	001 - 291	2002/01/15 - 2009/12/04	GDR-C (NASA,CNES)
Jason-2	000 - 064	2008/07/04 - 2010/04/07	GDR (CNES)
ERS-2	000 - 085	1995/04/29 - 2003/07/02	OPR-V6 CERSAT
ENVISAT	009 - 064	2002/09/24 - 2008/01/07	GDR-A,GDR-B ESA/CNES

In order to judge its quality, any new tide model is compared with other recently published models e.g. by direct comparison with the independent tidal constants from coastal and bottom pressure tide gauges. The results of this comparison can be

found in Tables 3.3.2 and 3.3.3 showing RMS differences to the pelagic ST102p data set and to Ray's data compilation of coastal pressure gauges respectively. In general, all new tide models are rather close to each other. According to Table 3.3.2 EOT10a and EOT11a exhibit the best performance over the deep ocean. In shallow water (c.g. Table 3.3.3) EOT11a is also good but is slightly outperformed by DTU10, which shows a remarkable good fit to M2 and S2. Due to the inhomogeneous distribution of sites with known tidal constants these results are not necessarily representative for the global ocean. Savcenko and Bosch (2011) give some other quality estimates, based on variance reduction of crossover differences.

Table 3.3.2: RMS differences between various tide models and the tidal constants of the ST102p data set.

Tide model	M2	S2	N2	K2	K1	O1	P1	Q1	RSS
FES2004	1.45	0.86	0.67	0.49	1.01	0.75	0.41	0.3	2.32
EOT08a	1.43	0.97	0.65	0.45	0.98	0.74	0.42	0.3	2.32
EOT10a	1.41	0.84	<b>0.64</b>	0.43	0.97	<b>0.73</b>	<b>0.37</b>	<b>0.27</b>	<b>2.23</b>
EOT11a	1.42	0.84	<b>0.64</b>	0.46	<b>0.96</b>	<b>0.73</b>	<b>0.37</b>	0.28	2.24
GOT4.7	1.43	0.93	0.65	0.4	1.01	0.76	<b>0.37</b>	<b>0.27</b>	2.3
TPX07.2	1.43	<b>0.82</b>	<b>0.64</b>	<b>0.37</b>	1.07	0.86	<b>0.37</b>	<b>0.27</b>	2.31
HAMTIDE11a	1.48	0.88	0.65	0.49	1.06	0.8	0.42	0.3	2.38
DTU10	<b>1.38</b>	0.87	<b>0.64</b>	0.45	1.01	0.74	0.42	0.31	2.26
num	<b>101</b>	<b>101</b>	<b>98</b>	<b>97</b>	<b>101</b>	<b>97</b>	<b>97</b>	<b>95</b>	

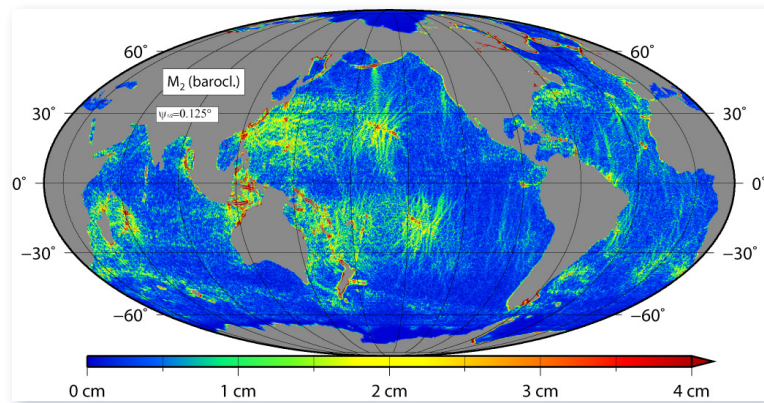
Table 3.3.3: RMS differences between the tidal constants of tide models and independent tidal constants of coastal bottom pressure data set of R. Ray.

Tide model	M2	S2	N2	K2	K1	O1	P1	Q1	M4	RSS
FES2004	7.56	4.85	2.68	2.21	1.87	1.31	1.07	0.94	4.23	10.86
EOT08a	6.82	4.13	2.19	1.55	<b>1.63</b>	1.24	0.8	0.87	2.29	9.03
EOT10a	6.8	4.02	2.33	1.56	1.65	1.24	0.9	0.84	2.67	9.12
EOT11a	6.33	3.96	2.09	<b>1.38</b>	1.67	1.44	<b>0.78</b>	<b>0.82</b>	2.61	8.66
GOT4.7	6.09	3.38	<b>2.06</b>	1.65	1.67	1.31	0.94	0.85	2.33	8.19
TPX07.2	6.94	3.81	2.09	1.68	1.77	<b>1.14</b>	0.97	1.08	<b>1.88</b>	8.94
HAMTIDE11a	6.84	4.77	2.25	2.19	2.04	1.21	2.43	0.86	(3.72)	10.27
DTU10	<b>5.18</b>	<b>2.99</b>	2.1	1.65	1.73	1.4	1.07	0.87	2.3	7.42
num	<b>176</b>	<b>176</b>	<b>173</b>	<b>96</b>	<b>176</b>	<b>176</b>	<b>97</b>	<b>139</b>	<b>129</b>	

### Baroclinic tides detected

Density variations within the oceans cause internal waves when tides interact e.g. with topographic features like a sea-mount. Internal waves may reach amplitudes of several tens of meters, the associated sea surface height fluctuations remain, however, in the order of a few centimeters only. Also, the wavelength of such baroclinic tides is much shorter than for barotropic tides. Knowledge on baroclinic tides is important for energy dissipation studies. Therefore the empirical modelling of baroclinic tides is challenging. Although these signals were already identified ana-

Fig. 3.3.1: Global map with amplitudes (cm) of  $M_2$  baroclinic tide.



lyzing along-track data of Topex/Poseidon the diamond shaped gaps in between the ground tracks inhibit a complete mapping of baroclinic tides. The multi-mission altimeter processing at DGFI solves this problem. Using data from all altimeter missions operating between 1992 and 2010 the gaps are filled and allow applying a corresponding band pass filter to look for short wavelength. This way it was possible to analyze baroclinic tides on global scale for the most energetic tidal constituents.

Figure 3.3.1 shows the amplitudes of  $M_2$  baroclinic tide with patterns present in nearly all parts of the ocean. In general, the baroclinic surface signal remains small ( $< 2$  cm amplitude), but may reach and exceed the 5 cm level at generating places like Hawaii Ridge. From such generating locations the baroclinic tides propagate several thousand kilometers across the ocean before they degenerate and become undetectable.

### Shallow water tides

The tidal spectrum in shallow water is much more complex than in the deep ocean. This is not only because the astronomic tides exhibit enhanced amplitudes. Due to resonances there are also a large number of non-linear ocean tides. The alias effect is multiplied due to compound tides and the de-correlation can only be achieved by analyzing carefully calibrated multi-mission altimetry data.

To investigate the estimation of shallow water tides the North-West European shelf was chosen as a test area because it exhibits a strong non-linear tidal regime and allows validation by a considerable number of shallow water bottom pressure data (R. Ray<sup>5</sup>). The residual tide analysis w.r.t. FES2004 was applied for  $M_4$ ,  $MS_4$ ,  $MN_4$ ,  $M_6$ ,  $2MS_6$ ,  $2MN_6$ , and  $2SM_2$ . In addition, the eight major astronomic tidal constituents, annual and semi-annual signal as well as mean value were estimated simultaneously. No mission specific parameters were considered in this analysis as the cross-calibrated data described above were used.

Figure 3.3.2 shows for some of the shallow water tides the distribution of amplitudes together with the amplitudes known from

<sup>5</sup> RAY R., personal communication

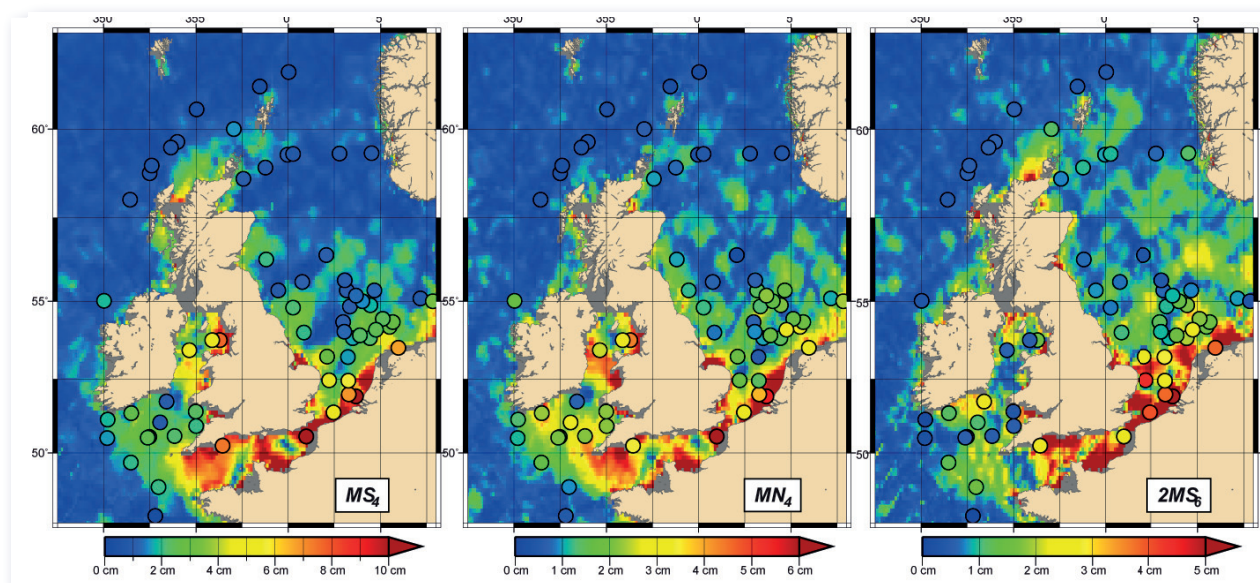


Fig. 3.3.2: Colour coded amplitudes (cm) of selected shallow water tides in the North-West European shelf. The coloured circles on top of the background colour show the amplitudes of the bottom pressure gauges and indicate the high coincidence between estimated and observed data.

Table 3.3.4: RMS values (cm) of tidal constants before (RMS) and after ( $\delta$ RMS) analysis.

	RMS	$\delta$ RMS
$M_6$	1.36	0.77
$MS_4$	2.57	0.96
$MN_4$	1.53	0.83
$2MN_6$	0.76	0.58
$2MS_6$	1.19	0.80
$2SM_2$	1.13	0.76
RSS	3.75	1.93

bottom pressure gauges.  $MS_4$  and  $MN_4$  hit amplitudes of up to 10 and 6 cm, respectively. The other shallow water tides have up to 5 cm amplitudes. The significant reduction of RMS values at the 67 bottom pressure gauges confirms the validity of the results. Table 3.3.4 faces the original signal (RMS) with the remaining misfit after analysis ( $\delta$ RMS). The most significant reduction with a factor above 2.5 is seen for  $MS_4$ . To judge the separability of shallow water tides the correlations among the estimated signals were investigated. Correlation factors up to about 0.4, found between  $M_2$  and  $MS_4$ , and  $2MS_6$  and  $M_4$  indicate a rather satisfactory separation.

Overall this case study demonstrates that harmonic analysis of multi-mission altimetry is capable to provide significant estimates of shallow water tides.

### Dynamic ocean topography (DOT)

One of the mission objectives of ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) is – as the acronym indicates – the determination of the global ocean circulation. Indeed, the latest GOCE gravity field solutions realize another significant improvement in the knowledge of the Earth gravity field allowing for the first time to estimate meso-scale pattern of the dynamic ocean topography (DOT) by subtracting the geoid undulations  $N$  from sea surface heights  $h$ .

In order to avoid any initial gridding of  $h$  with undesirable smoothing a particular method (called „profile approach“) has been developed at DGFI to estimate the DOT directly along the altimeter profiles. The most important aspect of this task is to perform a consistent treatment of the geoid heights  $N$  and the sea surface heights  $h$ , which have completely different spectral properties ( $N$  is rather smooth compared to  $h$ ). A Gauss-type low pass filter is consistently applied to both,  $h$  and  $N$ . While the filtering

of  $N$  can be performed in the spectral domain, the filtering of  $h$  is performed in the spatial domain and in one dimension only – along the profiles. A filter correction accounts for the systematic differences between one and two-dimensional filtering. Compared to GRACE, the latest GOCE gravity field (GOCO02S) allows to shorten the low pass filter down to a half-width of 70 km, thus approaching meso-scale resolution. This is visible, for example, by the meandering and Eddy formation in the Agulhas stream, a strong western boundary current at the Cape of Good Hope, South Africa (see Figure 3.3.3).

#### DOT estimates on individual altimeter profiles

The advantage of the profile method is that it provides DOT estimates on individual altimeter profiles, allowing to generate, for example, a time series of 10-day DOT snapshots with high spatial resolution for a period of nearly two decades, 1993 up to now. The instantaneous dynamic ocean topography (iDOT) profiles of nearly all altimeter mission (provided on the DGFI anonymous ftp-server at [ftp.dgfi.badw.de](ftp://ftp.dgfi.badw.de) at directory `pub/iDOT`) can be combined and exhibit not only the well-known large scale gyres of the ocean topography (see the map on the title page) but also meso-scale eddies along with their temporal evolution. The iDOT time series can be gridded and subsequently translated to surface velocities by using the geostrophic equations

#### Gridding and translation to geostrophic velocities

$$u = -\frac{g}{f} \cdot \frac{\partial DOT}{\partial y}$$

$$v = \frac{g}{f} \cdot \frac{\partial DOT}{\partial x}$$

where  $u$  and  $v$  are velocity components in East-West ( $x$ ) and South-North direction ( $y$ ) respectively,  $g$  is gravity acceleration and  $f = 2\Omega \sin\varphi$  is the Coriolis factor, a function of latitude  $\varphi$  and the Earth angular velocity  $\Omega$ .

A snapshot of the velocity field of the Gulf Stream is shown in Figure 3.3.4. Most impressive are animated time series of both, the DOT and its associated velocity field which are available on the DGFI web site at <http://dgfi.badw.de/?333>.

#### Animations on DGFI web site

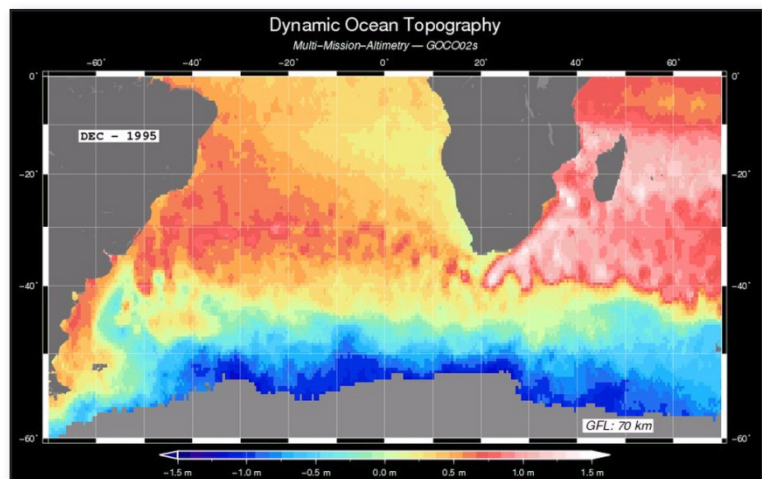
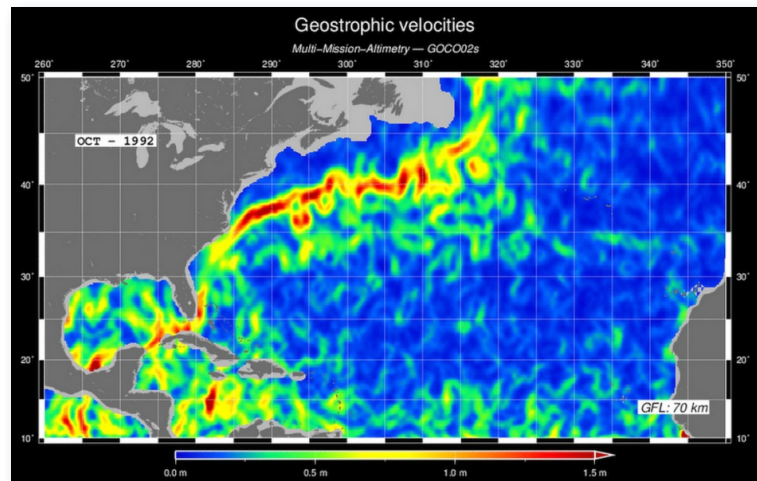


Fig. 3.3.3: Snapshot of the dynamic ocean topography at the Agulhas Stream.

Fig. 3.3.4: Snapshot of the surface velocities at the Gulf Stream.

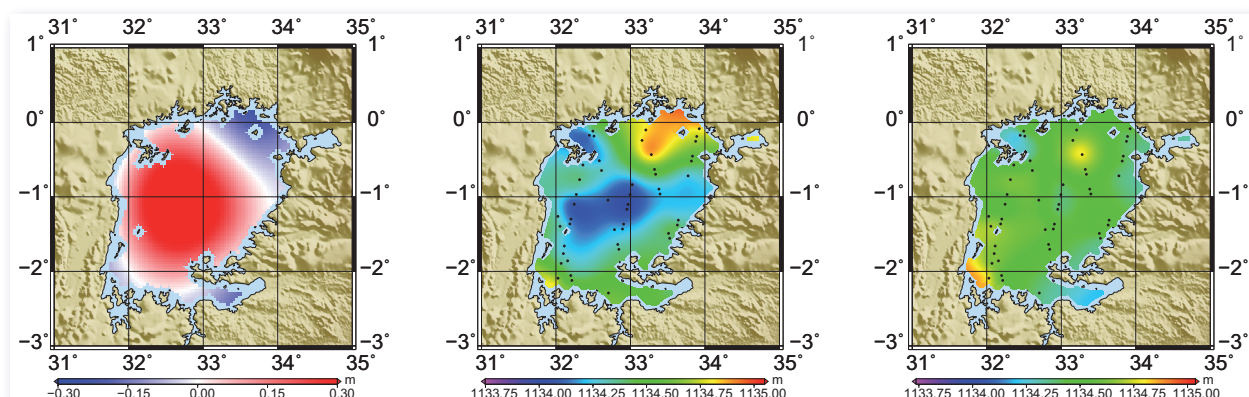


### Determination of lake level by using satellite altimetry

Nowadays satellite altimetry is not only used over open oceans, but also over continental water surfaces. Some applications such as investigations on inundation zones require the consideration of physical heights, since they define the direction water is flowing. This procedure implies to reduce geometric (ellipsoidal) lake heights by an utmost precise geoid. Physical heights of a lake surface should exhibit a flat surface, as in general the water is in balance with gravity and the hydrodynamics of lakes can be neglected. Consequently, satellite altimetry over inland water means a new tool to detect geoid errors.

We investigate physical heights over large lakes by using different geoid models. The high resolution of EGM 2008 seems to be most convenient for this purpose. However, physical lake heights, derived with EGM 2008 are not flat. The latest gravity field models from GOCE indicate significant errors of EGM 2008 in particular over land areas. Therefore, we generated a hybrid model by extending the GOCO02S model by the high frequency parts of EGM 2008. This hybrid model improves the determination of the physical heights, but deviations from a flat surface remain. These deviations are too large to be explained as geostrophic currents. Thus the remaining variations of physical heights must be interpreted as residual geoid errors. The geoid differences were investigated over Lake Victoria (Figure 3.3.5) and Lake Tanganyika (Figure 3.3.6) in Africa.

Fig. 3.3.5: Example on Lake Victoria. Left panel: difference between both geoid models, mid panel: orthometric heights obtained by reducing altimetry derived ellipsoidal lake heights from Envisat (Cycle 34) by EGM 2008 geoid heights; right panel: geoid heights from the hybrid model.



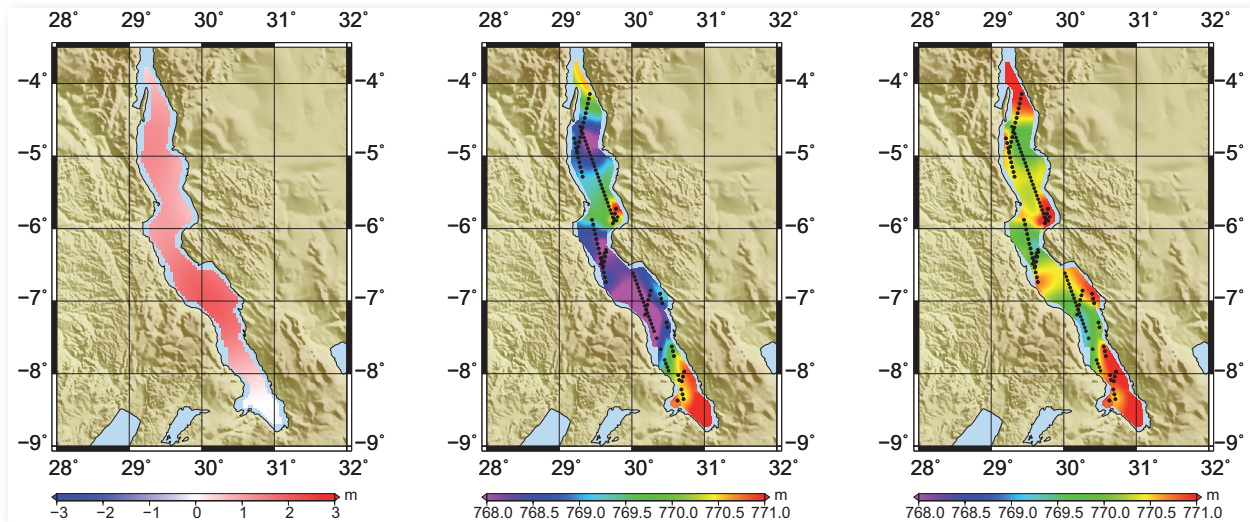


Fig. 3.3.6: Example on Lake Tanganyika. Left panel: difference between both geoid models; mid panel: orthometric heights obtained by reducing altimetry derived ellipsoidal lake heights from Envisat (Cycle 34) and Jason-1 (Cycle 124) by EGM 2008 geoid heights; right panel: geoid heights from the hybrid model.

### 3.4 Solid Earth

#### Free Oscillation of the Earth due to the earthquake in Japan



Fig. 3.4.1: Pendulum mass and inductive tap of DGFI's 30m vertical pendulum in the saltmine of Berchtesgaden.

DGFI is operating a vertical pendulum in the saltmine of Berchtesgaden. Figure 3.4.1 shows the pendulum arrangement in the measurement chamber within the saltmine. The pendulum mass is hanging on a 30 m long wire. Its displacements within only a few tenths of millimeters are measured frequently by an inductive tap with a high temporal resolution.

If the seismic waves of an earthquake arrive at the measurement chamber, the pendulum mass starts swinging and their displacements are measured by the inductive tap. If the magnitude of the earthquake is bigger than 6.5 on the Richter scale, elastic natural oscillations (also called free oscillations) of the Earth are excited and can also be measured by the pendulum. The measured signal is then analyzed in the spectral domain by using the Fourier-Transformation and the wavelet transform. The input for the analysis is a complex signal which valued

$$\Delta \tilde{x}(t) = \Delta x_{NS}(t) + i \cdot \Delta x_{EW}(t) \quad (4)$$

consisting of the North-South displacement  $\Delta x_{NS}(t)$  and the East-West displacement  $\Delta x_{EW}(t)$ .

On March 11th in 2011 the big earthquake near Japan had a magnitude of 9.0 on the Richter scale. This earthquake excites free oscillations of the Earth which were measured with the vertical pendulum. Figure 3.4.2 shows the measured displacements of the pendulum mass caused in the North-South direction. The main displacement reaches a magnitude of about 0.2 mm. After the main shock, several small aftershocks have been measured.

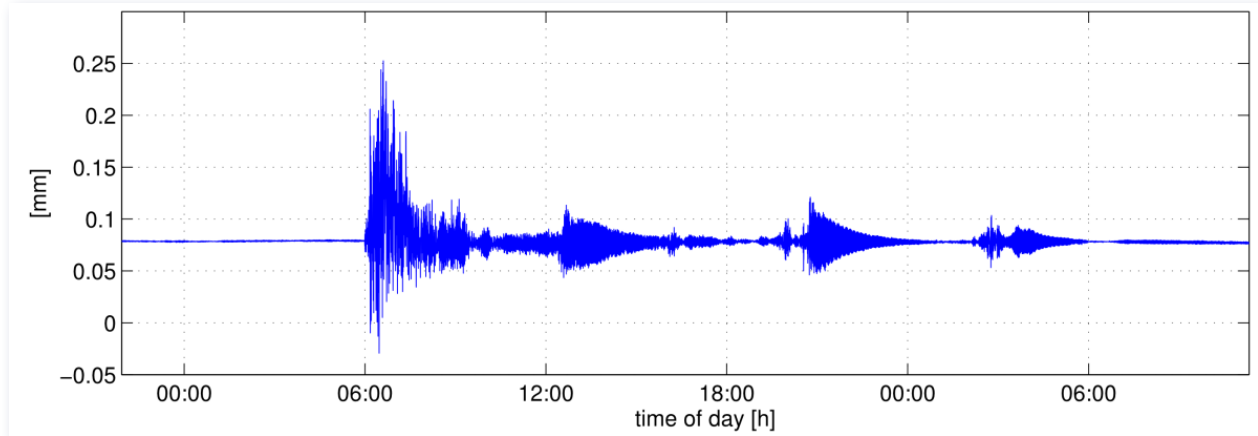


Fig. 3.4.2: Measured displacements of the pendulum mass in North-South direction  $\Delta x_{NS}(t)$  due to the earthquake in the eastern offshore area of Japan on March, 11<sup>th</sup> in 2011.

Fig. 3.4.3: Wavelet scalogram of the complex signal  $\Delta \tilde{x}(t)$ . The upper panel shows the scalogram of the prograde signal part whereas the lower panel shows the scalogram of the retrograde signal part.

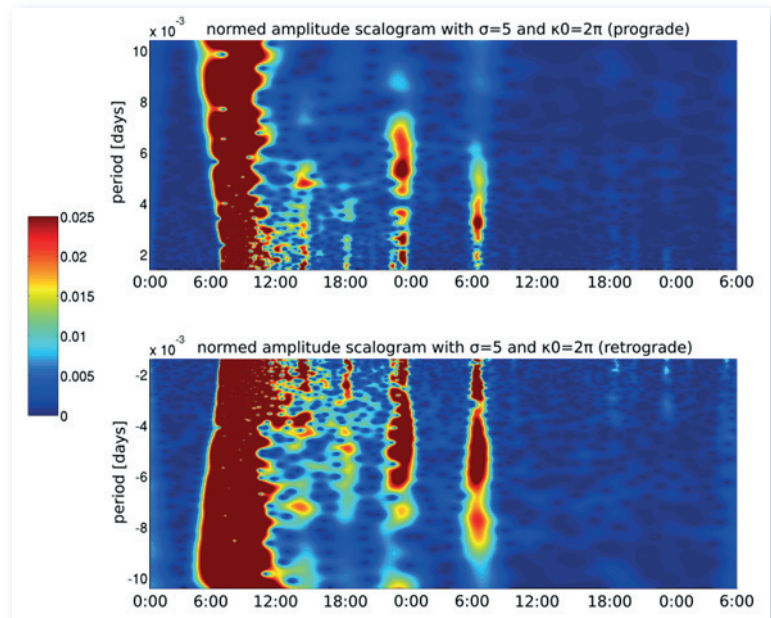


Figure 3.4.3 shows the wavelet scalogram of the complex-valued signal defined in Eq. (4). The upper plot shows the scalogram of the prograde signal part whereas the lower plot shows the scalogram of the retrograde signal part. The various aftershocks cause high amplitudes during the days after the mainshock. Excited by the mainshock, the noise is damped totally in the analyzed frequency interval after one day. Some of these noise signals are associated with the free oscillation frequencies.

**Related publications:**

- DETTMERING D., HEINKELMANN R., SCHMIDT M.: Systematic differences between VTEC obtained by different space-geodetic techniques during CONT08. *Journal of Geodesy* 85(7), 443-451, doi 10.1007/s00190-011-0473-z, 2011
- DETTMERING D., SCHMIDT M., HEINKELMANN R., SEITZ M.: Combination of different space-geodetic observations for regional ionosphere modeling. *Journal of Geodesy* 85(12), 989-998, DOI: 10.1007/s00190-010-0423-1, 2011
- GÖTTL F., SCHMIDT M., HEINKELMANN R., SAVCENKO R.: Combination of gravimetric and altimetric space observations for estimating oceanic polar motion excitations, *JGR Ocean*, (submitted)
- HEINKELMANN R., BÖHM J., BOLOTIN S., ENGELHARDT G., HAAS R., LANOTTE R., MACMILLAN D.S., NEGUSINI M., SKURIKHINA E., TITOV O., SCHUH H.: VLBI-derived troposphere parameters during CONT08. *Journal of Geodesy* Volume 85, Number 7, 377-393, DOI: 10.1007/s00190-011-0459-x, 2011
- KOCH K.R., SCHMIDT M.: N-dimensional B-spline surface estimated by lofting for locally improving IRI. *Journal of Geodetic Science*, 1, 41-51, DOI: 10.2478/v10156-010-0006-3, 2011
- SAVCENKO R. and W. BOSCH: EOT11a – empirical ocean tide model from multi-mission satellite altimetry. Report No. 89, Deutsches Geodätisches Forschungsinstitut, München, 2011
- SCHMIDT M., DETTMERING D., MÖSSMER M., WANG Y., ZHANG J.: Comparison of spherical harmonic and B spline models for the vertical total electron content. *Radio Science*, 46, RS0D11, DOI: 0.1029/2010RS004609, 2011

## 4 Methodology

*Working on methodology has been identified as an important cross-cutting research field which has so far not been treated as a self-contained topic. The general objective is to develop and provide standards, tools and research infrastructure supporting the other research fields and enable faster and well-founded scientific results and assessment in all projects. The need for, e.g. a new algorithm may be derived from particular requirements identified within a specific project. To develop, test, document, provide and maintain it as generic algorithm will allow using it also in other projects. Others requirements are of general interest as, for example the development and application of standards and conventions. It is essential to apply identical or consistent correction models between alternative solutions to avoid the risk to interpret differences of the correction models as geophysical signal.*

*General themes for the research area methodology are (i) new sensor systems, (ii) numerical methods and parameter estimation, (iii) informatics, (iv) standards and conventions, (v) treatment of special functions, and (vi) combination procedures. Not all of these themes were covered in 2011. The following sections give a report on those topics that were subject of investigations.*

### 4.1 Numerical methods and parameter estimation

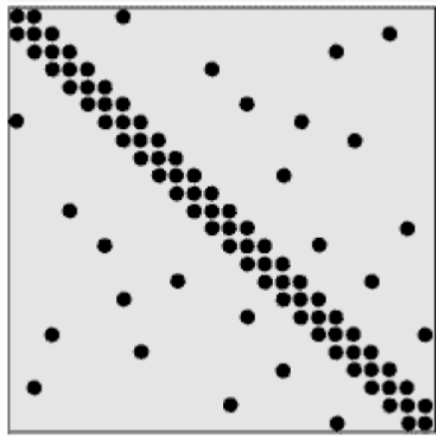


Fig. 4.1.1 Normal equations for the multi-mission cross-calibration (MMXO) composed of a tri-diagonal and a sparse structure.

#### Conjugate gradient algorithm

The cross-calibration of multi-mission satellite altimetry (MMXO), described in section 1.2 leads – even after segmentation to 10-day periods – to huge systems of equations with up to 300000 unknowns. Treating systems of that size in a rigorous way would not be able if the coefficient matrix would be dense. Fortunately, the least squares solution can be set up such that the normal equation system is composed of a sparse and a tri-diagonal part (as indicated by Figure 4.1.1).

A direct solver of such systems is not easy to implement, as fill-in during reduction is difficult to avoid and blows up the storage requirements. Thus, the normal equations for the MMXO, known to be symmetric and positive definite, are solved iteratively using the Conjugate Gradient (CG) algorithm as described e.g. by Golub & van Loan<sup>1</sup> (1993). The CG-algorithm requires one matrix-vector multiplication per iteration. In order to keep storage requirements minimal the sparse and the tri-diagonal part of the normals were treated separately and the matrix-vector product was coded individually for the sparse and the tri-diagonal parts. The multiplication is performed exclusively with non-zero elements which speeds up the computation and quickly terminates even after some thousand iterations.

### 4.2 Standards and Conventions

#### GGOS Bureau for Standards and Conventions

The Bureau for Standards and Conventions (BSC) has been established as a GGOS component in 2009 (see Fig. 4.2.1). The BSC is jointly operated by the Deutsches Geodätisches Forschungsinstitut (DGFI), and the Institut für Astronomische und Physikalische Geodäsie (IAPG) of Technische Universität München, both in Munich, Germany, under the umbrella of the Forschungsgruppe Satellitengeodäsie (FGS).

<sup>1</sup> GOLUB G. H. and C. F. VAN LOAN: *Matrix Computations*, John Hopkins University Press, 1993

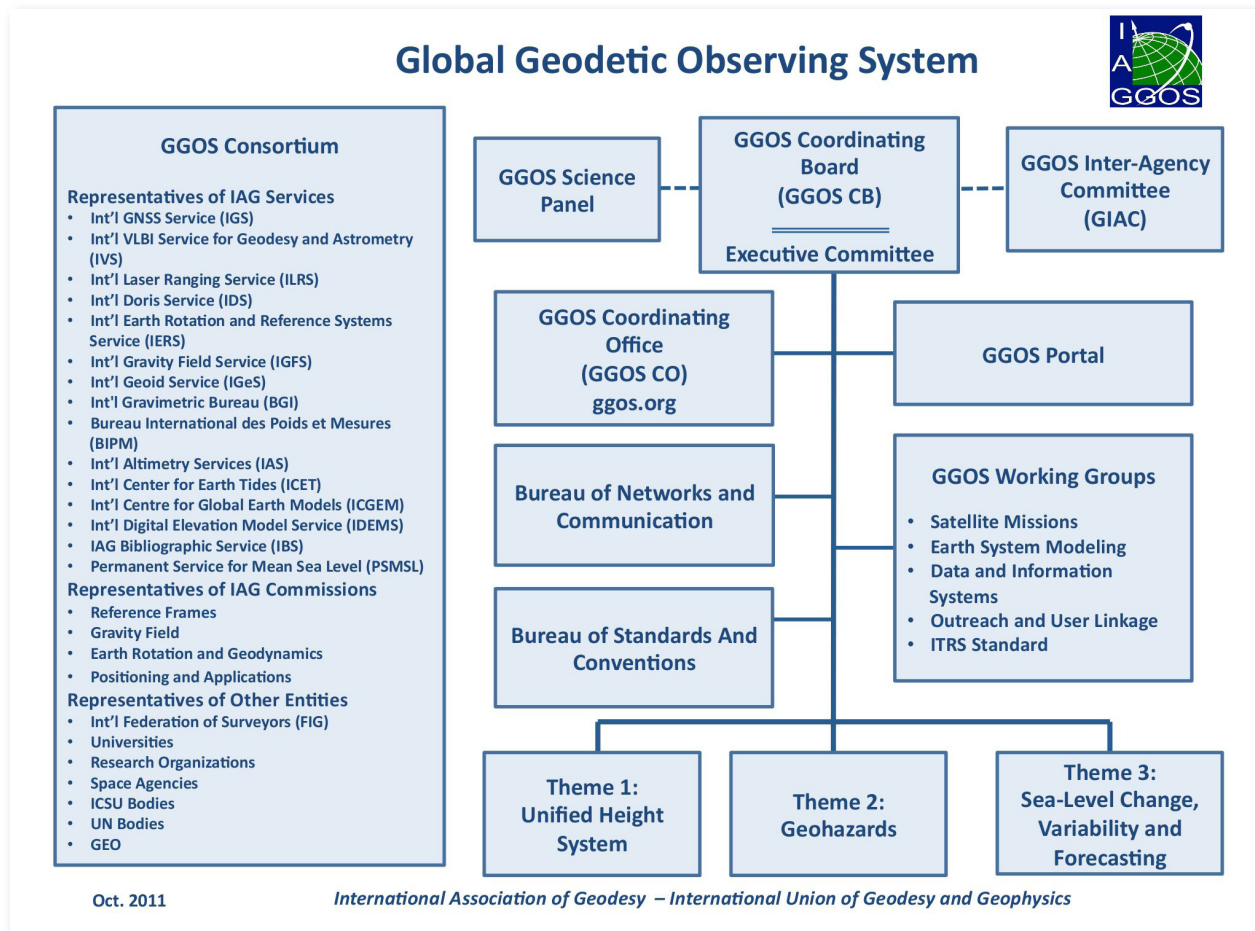


Fig. 4.2.1: GGOS organisation chart 2011.

### Mission and goals

The implementation of common standards and conventions for the generation of geometric and gravimetric products is of crucial importance for GGOS. The BSC supports GGOS in its goal to obtain products of highest accuracy, consistency, temporal and spatial resolutions, and referring to a unique reference frame stable over decades.

The major tasks of the BSC are to keep track of the strict observance of adopted geodetic standards, standardized units, fundamental physical constants, resolutions and conventions in all official products provided by the geodetic community, to identify gaps and deficiencies in standards and conventions, to initiate steps to close them, and to propagate geodetic standards and conventions in the geodetic and general scientific community and promote their use.

To fulfil its mission the BSC works closely together with experts in the field and maintains regular contact and establishes a strong interface with all the IAG Services and Commissions and international bodies involved in the adoption of standards, physical constants, resolutions and conventions.

**On-going activities**

The BSC evaluates the geodetic standards and conventions currently in use by all the IAG Services for the generation of geodetic/geophysical products. A major focus in 2011 was on the compilation of numerical and processing standards currently used by the GGOS components based on review of existing resolutions, standards and conventions, satellite gravity mission standards, literature and polling of geometric and gravimetric IAG services. Various inconsistencies were identified, such as a different handling of permanent tides by the geometric and gravimetric services, or a different use concerning the time system, geocentric coordinate time TCG vs. terrestrial time TT. Another deficiency is, that different values for the potential value  $W_0$  at the geoid and  $U_0$  at the reference ellipsoid are included as standards in the IERS conventions. The  $W_0$  utilized by the IAU (and also included in the IERS conventions) considerably differs of recent  $W_0$  estimations based on the newest mean sea surface and global gravity models. An on-going task and major goal is to identify and eliminate all existing inconsistencies in standards and conventions aiming at clearly described, reproducible and consistent common numerical standards for all geometric and gravimetric products. If necessary, the BSC will propose the adoption of new standards and conventions, changes and revisions.

### 4.3 Special functions and series expansion

#### Ellipsoidal versus spherical harmonics

Gravity data observed at or close to the Earth's surface is usually reduced to the ellipsoid. Traditionally, however, the Earth gravity field is expressed by spherical harmonics series. In order to relate data on the ellipsoid to the spherical harmonics ellipsoidal corrections are applied. Ellipsoidal corrections are also required, if the impact of mass variations on the Earth surface (or the ellipsoid) is to be computed for low Earth orbiting (LEO) satellites. In these cases the use of ellipsoidal harmonics would provide a better representation with faster convergence. The problem is that ellipsoidal harmonics

$$V(u, \vartheta, \lambda) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^n \frac{Q_{n,m}(i \frac{u}{E})}{Q_{n,m}(i \frac{b}{E})} (\bar{C}_{n,m}^e \cos m\lambda + \bar{S}_{n,m}^e \sin m\lambda) \bar{P}_{n,m}(\cos \vartheta),$$

are not as easy to use because the computation of associated Legendre functions of the second kind and their first and second derivatives is not as straightforward as for the Legendre functions of the first kind.

There are numerous investigations on theoretical and practical applications with ellipsoidal harmonics. Heiskanen and Moritz<sup>2</sup> points out, that data  $V(u, \vartheta, \lambda)$  on the ellipsoid can be expressed by ellipsoidal harmonics (see box on the left) with  $Q_{nm}$  the associated Legendre functions of the second kind by expanding the data into a spherical harmonic series with  $u = b$ ,  $\theta$  the reduced

<sup>2</sup> HEISKANEN W. A. and H. MORITZ: *Physical Geodesy*, Freemann & Company, 1967

co-latitude, and  $\lambda$  the longitude. A transformation is then needed to convert ellipsoidal harmonics to spherical harmonics and vice versa. Jekeli introduced for this transformation degree and order dependent factors to the normalized Legendre functions of the second kind and provided recurrence relations for the renormalized functions. These recurrence relations were extended by Sebera et al. (2012) to the second derivative allowing now to compute also gravitational gradients from ellipsoidal harmonics (which is of specific interest for processing GOCE data). In addition, the recurrence relations were further optimized by a suitable transformation of the hypergeometric function.

It could be shown that the optimized recurrence relations converge faster and reduce the effect of rounding errors which was verified by comparing functionals of the gravitational potential up to the second derivative computed with both ellipsoidal and spherical harmonic synthesis. As input the global gravity field EGM2008, expanded up to degree/order 2190 was used. The relative agreement between the ellipsoidal and spherical synthesis was found to be  $10^{-14}$ ,  $10^{-12}$  and  $10^{-8}$  for the potential, its first and second derivatives respectively. The investigations of Sebera et al. (2012) are a step forward to the practical application and numerical stability of high degree ellipsoidal harmonics.

**Related publication:**

ANGERMANN D.: Standards and conventions. Geodesist Handbook (in press), 2011

HUGENTOBLE U., GRUBER T., STEIGENBERGER P., ANGERMANN D., BOUMAN J., GERSTL M., RICHTER B.: GGOS Bureau for Standards and Conventions: Integrated standards and conventions for geodesy. In: Kenyon, S. C., Pacino M. C., Marti U. J. (Eds.): Geodesy for Planet Earth, IAG Symposia, Vol. 136, pp 995-998, Springer, ISBN (Print) 978-3-642-20337-4, ISBN (Online) 978-3-642-20338-1, ISSN 0939-9585, DOI: 10.1007/978-3-642-20338-1\_124, 2012

SEBERA J., BOUMAN J., BOSCH W.: On computing ellipsoidal harmonics using Jekeli's renormalization. Journal of Geodesy, DOI 10.1007/s00190-012-0549-4, 2012

## 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 of scientific results is a basic requirement for any research, 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 below provides a list of those papers, printed or published online in 2011. It is followed by a list of posters and oral presentations, given by DGFI staff at numerous workshops, symposia and conferences.*

*Beside that the Internet is intensively used as a platform for information exchange. DGFI maintains a homepage on which all research activities, projects and cooperation of the institute are described in detail. By “hot stories” we call attention to most recent interested results. Quite a number of additional web sites are maintained by DGFI, above all for the Office of the International Association of Geodesy (IAG) and for the German Geodetic Commission (Deutsche Geodätische Kommission, DGK) including an online catalogue with up to 1000 volumes (predominantly dissertations) published by the DGK. Further internet sites are set up and maintained for large projects, services and national research programs.*

### 5.1 Internet representation

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

#### Typo3 Content Management System

The multiple Internet sites are realized and maintained by means of the Typo3 Content Management System (CMS). The content of pages is administered by a database system. Typo3 ensures a common layout by predefined templates and provides simple interfaces to the editors. With Typo3, the Internet sites can be remotely administered by means of a browser interface without any need of specific knowledge of “mark up” languages such as HTML or CSS. Typo3 is an ‘Open Source’ project and therefore available free of charge. It is one of the most actively developed content management systems, applied by many commercial sites. Typo3 provides comfortable functions to handle graphics, a necessary feature for the presentation of scientific results.

#### Internet sites set up and maintained by DGFI

The Internet sites of DGFI inform about

- the institute and its research programme (DGFI home page),
- its responsibility for the Office of the International Association of Geodesy (IAG),
- the “Deutsche Geodätische Kommission (DGK)”,
- a Geodesy Information System (GeodIS), and
- the EUROLAS Data Centre (EDC).

DGFI uses the same system also for Internet sites, dedicated to

- the DFG priority program “Mass transport and mass distribution in the Earth system” (SPP1257),
- Geocentric Reference System for the Americas (SIRGAS),
- the Open Altimeter Database (OpenADB),
- and the International Altimeter Service (IAS)
- an ESA study on lithospheric modelling with GOCE (GOCE + Geoexplore).

Moreover, the Internet is used to maintain

- several file transfer servers for extensive data exchange, which are necessary for the DGFI to act as data and analysis centre,
- collaborative Internet sites for specific projects and
- an intranet site to support compilation and distribution of internal information (blackboard, calendar, library).

**DGFI** The DGFI home page, available under

<http://www.dgfi.badw.de>,

informs about the structure and results of the actual research program, ongoing research topics, the national and international projects DGFI is involved in and the multiple contributions of DGFI to international services. The home page (see Figure 5.1.1, left) also provides a complete list of papers and reports published since 1994 by the employees as well as a compilation of all posters and presentations. Most recent publications and posters are as far as possible available in electronic form (mostly with the portable document format, pdf).

**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 Director of DGFI, and the IAG Office was established at DGFI. The website

<http://iag.dgfi.badw.de>

was installed to support the work of the Office (see Figure 5.1.1, right).

### Geodesy Information System GeodIS

The geodesy information system GeodIS, located at

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

is further maintained by DGFI with the objective to compile informations about the most important areas of geodesy. The intention of GeodIS is to give support the most areas of geodesy. GeodIS provides also links to the home pages of international scientific organizations (see Figure 5.1.2, left).



Fig. 5.1.1: Screenshots of the DGFI home page (left) and the Internet site for the IAG Office (right).

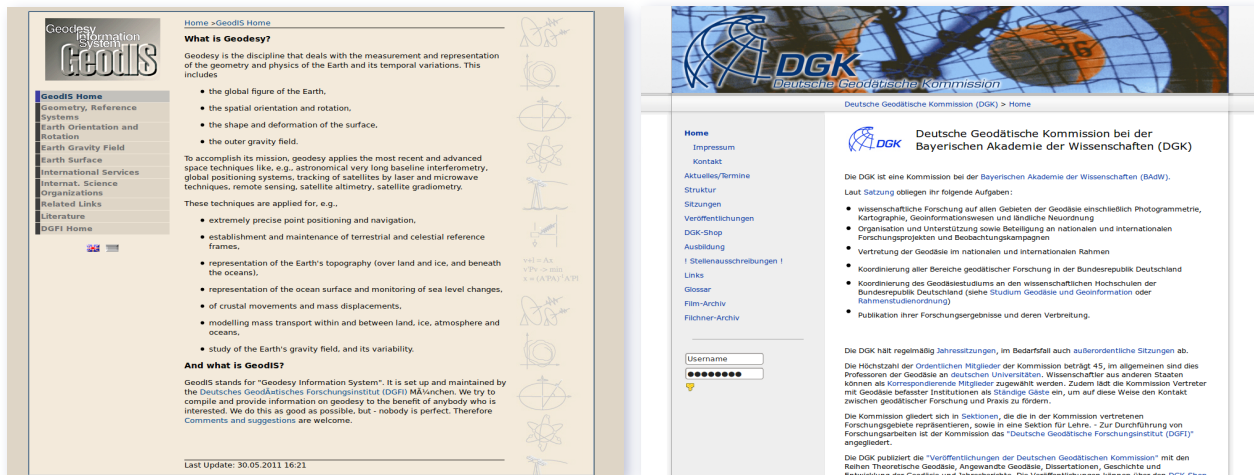


Fig. 5.1.2: Screenshots of the web site of GeodIS (left) and of the home page of the Deutsche Geodätische Kommission, DGK (right).

## Deutsche Geodätische Kommission (DGK)

Another Internet site is maintained for the “Deutsche Geodätische Kommission” (DGK). It is available at

<http://dggk.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 Figure 5.1.2, right).

## DGFI priority program „Mass transport and mass distribution in the Earth system“

A further Internet site for the DFG priority program “Mass transport and mass distribution in the Earth system”, SPP1257, was realized with the Typo3 content management system. It resides on a DGFI server, but has its own domain name

<http://www.massentransporte.de>.

The site (see Figure 5.1.3, left) makes the SPP program known to the public and other scientists (outreach), supports the organization of international symposia, but provides also a basis for internal information exchange with links to data and products that are relevant for the priority program.

## 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://www.sirgas.org>.

The SIRGAS website comprises (see Figure 5.1.3, right)

- a scientific description presenting definition, realization, and kinematics of the SIRGAS reference frame,

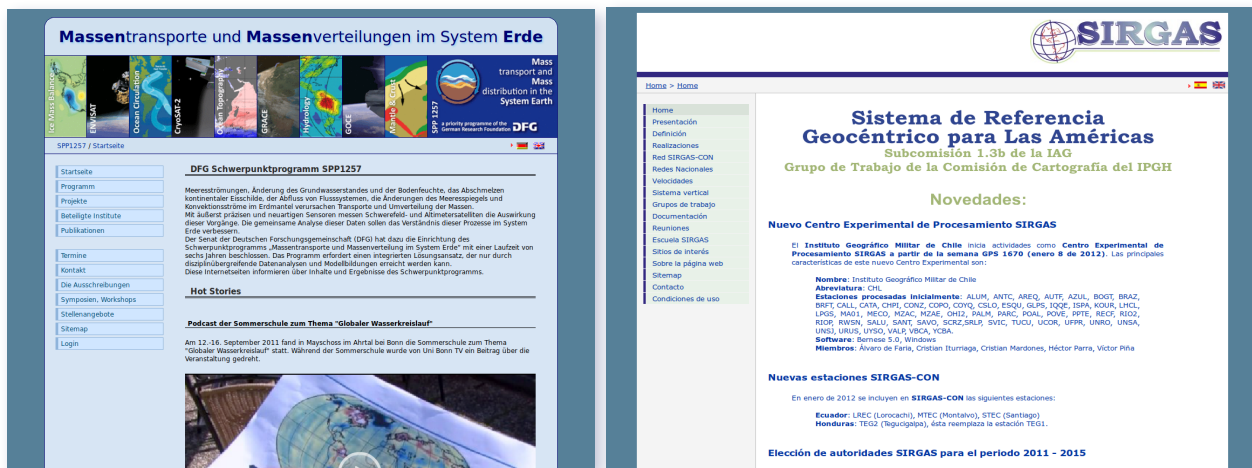


Fig. 5.1.3: Screenshots of the web site of the DFG priority program “Mass transport and mass distribution in the Earth system” (left) and of the web site of SIRGAS (right).

- 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.

The SIRGAS Continuously Operating Network (SIRGAS-CON) is presented in detail through interactive tools, which allow to call coordinates, velocities, log files, and the main chronological events of each station. The SIRGAS web page has been hosted by DGFI since August 2007 in both English and Spanish.

### Open Altimeter Database home page (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 data base extracts with user defined formats and parameters. The usage of OpenADB is open after registration to anyone (see Figure 5.1.4, left). This site is available under

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

### Internet site for the International Altimeter Service (IAS)

The home page of the International Altimeter 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 analyse 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 analyse data, and to respond to altimeter user requirements.

This site is available under

<http://ias.dgfi.badw.de>,

but is still under development.

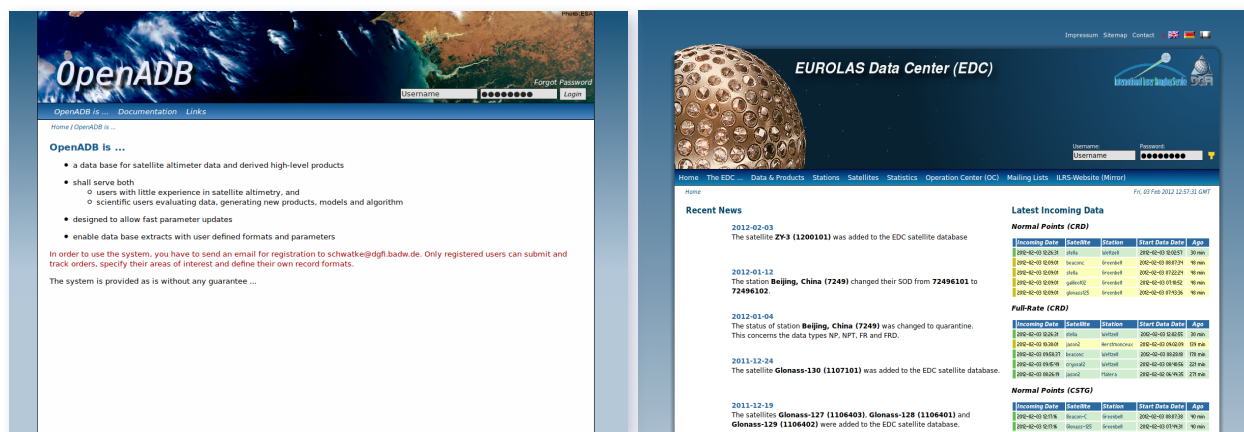


Fig. 5.1.4: Screenshots of the web site for the Open Altimeter Data Base (left) and an access statistics for selected web sites (right).

### EUROLAS Data center EDC

The EUROLAS Data Center (EDC) provides access to the data base of SLR observations and derived products. This website informs about the data flow within the Operation Center (OC) and the data holding of the Data Center (DC). This site is available under

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

### Mailing Lists

Mailing lists are maintained by DGFI to fulfill the requirements for information exchange within the ILRS Global Data Center and the Reference System SIRGAS. 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, again, on the basis of the Typo3 content management system. The internal information exchange is supported by a black board, a meeting calendar, the access to the library data base, 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.

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### 5.3 Posters and oral presentations

- ABDUL FATTAH, MEEKES S., GUASTI E., BOUMAN J., SCHMIDT M., EBBING J.: Heterogeneous gravity data combination for geophysical exploration research. The applications of the GOCE satellite data for regional basin and petroleum system analysis (Example from the Arabian Peninsula), MAPG-AAPG 2nd International Convention, Conference and Exhibition, Marrakesh, 2011-10-05
- ABDUL FATTAH, MEEKES S., SCHAVEMAKER Y., GUASTI E., BOUMAN J., SCHMIDT M., EBBING J.: Heterogeneous gravity data combination for geophysical exploration research: Applications for basin and petroleum system analysis in the Arabian Peninsula, EAGE Arabian Plate Workshop, Kuwait, 2011-11-30 (Poster)
- ANGERMANN D.: DGFI reference frame solution as contribution to ITRF2008, COST Action ES0701 Meeting: GIA model optimisation and ice mass balance, Brussels, Belgium, 2011-02-04
- ANGERMANN D.: Linking Space, Satellites and Earth, DFG-Begutachtung der Forschergruppe Referenzsysteme, Bonn, Germany, 2011-05-18
- ANGERMANN D., RICHTER B.: PN5 Consistent celestial and terrestrial reference frames by improved modelling and combination, DFG-Begutachtung der Forschergruppe Referenzsysteme, Bonn, Germany, 2011-05-18 (Poster)
- ANGERMANN D.: Terrestrial Reference System Realizations: Status, Challenges and new Developments, Geomatik-Seminar, ETH Zurich, Switzerland, 2011-05-26
- ANGERMANN D.: GGOS Bureau for Standards and Conventions, GGOS Unified Analysis Workshop, Zurich, Switzerland, 2011-09-16
- ANGERMANN D.: Entwicklungen zur Realisierung hochgenauer terrestrischer Referenzsysteme, Geodetic Week 2011, Nürnberg, Germany, 2011-09-27
- ANGERMANN D.: Verknüpfung der geodätischen Raumbeobachtungsverfahren durch Ko-lokation auf Satelliten, DFG Rundgespräch, Infrastrukturschwerpunkt: Wissenschaftliche Nutzung des Geodätischen Observatoriums Wettzell, Höllenstein, Germany, 2011-10-05
- ANGERMANN D.: Satellites and radiosources VLBI (proposed by R. Heinkelmann), DFG Rundgespräch, Infrastrukturschwerpunkt: Wissenschaftliche Nutzung des Geodätischen Observatoriums Wettzell, Höllenstein, Germany, 2011-10-05
- ANGERMANN, D., GRUBER, T., BOUMAN J., GERSTL, M., HEINKELMANN R., HUGENTOBLE, U., SÁNCHEZ, L., STEIGENBERGER, P.: Report on GGOS Bureau for Standards and Conventions, GGOS Coordinating Board Meeting No. 1, San Francisco, USA, 2011-12-03
- ANGERMANN, D., GRUBER, T., BOUMAN, J., GERSTL, M., HEINKELMANN, R., HUGENTOBLE, U., SÁNCHEZ, L., STEIGENBERGER, P.: The importance of common standards and conventions for consistent GGOS products, AGU Fall Meeting, San Francisco, USA, 2011-12-09
- BIANCALE R., GAMBIS D., SEITZ M., RICHARD J.-Y., LOYER S., SOUDARIN L., THALLER D., SPRINGER T., KOENIG R., SCIARRETTA C.: IERS Working group on Combination of Space Geodetic Techniques at the Observation Level (COL), European Geosciences Union General Assembly 2011, 2011-04-07 (Poster)
- BIANCALE R., GAMBIS D., SEITZ M., RICHARD J.-Y., LOYER S., ET AL.: IERS Working group on Combination of Space Geodetic Techniques at the Observation Level (COL), IUGG 2011, Melbourne, Australia, 2011-07-05 (Poster)
- BIANCALE R., GAMBIS D., RICHARD J.-Y., SEITZ M.: Activity of the Combination at Observation Level Working Group, Journées 2011, Vienna, Austria, 2011-09-21
- BLOSSFELD M., SEITZ M., ANGERMANN D.: Zeitlich hoch aufgelöste Schätzung von TRF, EOP und SFK, Statusseminar der Forschergruppe Erdrotation, Vienna, Austria, 2011-02-24/25
- BLOSSFELD M., SEITZ M., HEINKELMANN R., ANGERMANN D.: Estimation of EOP series by a combination of different space geodetic techniques, EGU Vienna, 2011-04-06
- BLOSSFELD M., MÜLLER H., ANGERMANN D.: Adjustment of EOP and gravity field parameter from SLR observations, EGU Vienna, 2011-04-06 (Poster)

- BLOSSFELD M., MÜLLER H., SEITZ M., ANGERMANN D.: Benefits of SLR in epoch reference frames, 17th Workshop on Laser Ranging, Bad Kötzting, Germany, 2011-05-16
- BLOSSFELD M., MÜLLER H., ANGERMANN D.: Adjustment of EOP and gravity field parameter from SLR observations, 17th Workshop on Laser Ranging, Bad Kötzting, Germany, 2011-05-18 (Poster)
- BLOSSFELD M., SEITZ M., ANGERMANN D.: Stationskoordinaten und EOPs in Epochenreferenzrahmen, Geodetic Week 2011, Nürnberg, Germany, 2011-09-27
- BLOSSFELD M., SEITZ M., ANGERMANN D.: A comparison of Epoch Reference Frames and Multi-Year Reference Frames, AGU Fall Meeting 2011, San Francisco, USA, 2011-12-09
- BOSCH W., DETTMERING D.: Global cross-calibration of satellite altimeters and possible synergies with absolute local calibrations, Workshop on Satellite Altimetry Calibration & Deformation Monitoring with GNSS, Chania, Crete/Greece, 2011-01-20
- BOSCH W., SAVCENKO R.: Long-term evolution of the dynamic ocean topography as observed by satellite altimetry and GOCE, EGU General Assembly, Vienna, Austria, 2011-04-08
- BOSCH W., DETTMERING D.: ICESat and CryoSat-2 cross-calibration with classical radar altimeters, IUGG XXV General Assembly, Melbourne, Australia, 2011-06-28/07-07
- BOSCH W., SAVCENKO R.: The challenge of GOCE and multi-mission altimetry: instantaneous dynamic ocean topography profiles with meso-scale resolution, OSTST Meeting, San Diego, USA, 2011-10-20
- BOSCH W., SAVCENKO R.: Dynamic ocean topography time series with meso-scale resolution from GOCE and multi-mission altimetry, AGU2011, San Francisco, 2011-12-08
- BOUMAN J., FUCHS M., SCHMIDT M., BROERSE T., VISSER P., SCHRAMA E., VERMEERSEN B.: The Earth's time-variable gravity field observed by GOCE, GOCE+ ITT Theme 4 Negotiation Meeting, Noordwijk, The Netherlands, 2011-01-28
- BOUMAN J., SCHMIDT M., BOSCH W., EBBING J., ABDUL FATTAH R., ABBINK O., SCHAVEMAKER Y.: Heterogeneous gravity data combination for Earth interior and geophysical exploration research, GOCE+ ITT Theme 2 Negotiation Meeting, Noordwijk, The Netherlands, 2011-03-10
- BOUMAN J., EBBING J., FUCHS M., SCHMIDT M., BOSCH W., SCHWATKE C., ABDUL FATTAH R., MEEKES S., ABBINK O., SCHAVEMAKER Y.: Heterogeneous gravity data combination for Earth interior and geophysical exploration research, GOCE User Workshop, Munich, Germany, 2011-03-31/04-01 (Poster)
- BOUMAN J., FIOROT S., FUCHS M., GRUBER T., SCHRAMA E., TSCHERNING C.C., VEICHERTS M., VISSER P.: GOCE Level 2 Gravity Gradients, GOCE User Workshop, Munich, Germany, 2011-03-31/04-01 (Poster)
- BOUMAN J., FUCHS M., BROERSE T., VERMEERSEN B., VISSER P., SCHRAMA E., SCHMIDT M.: Modeling and Observing the 8.8 Chile 2010 and 9.0 Japan 2011 Earthquakes using GOCE, IUGG XXV General Assembly, Melbourne, Australia, 2011-07-05
- BOUMAN J., EBBING J., FUCHS M., GRADMANN S., SCHMIDT M., BOSCH W., SCHWATKE C., ABDUL FATTAH R., MEEKES S.: GOCE gravity gradient invariants for Earth interior and geophysical exploration research, AGU Fall Meeting, San Francisco, 2011-12-08 (Poster)
- BROERSE T., VISSER P., BOUMAN J., FUCHS M., VERMEERSEN B., SCHMIDT M.: Modelling and observing the 8.8 Chile and 9.0 Japan earthquakes using GOCE, GOCE User Workshop, Munich, Germany, 2011-03-31/04-01
- BRUNINI C., SÁNCHEZ L., MACKERN V., MARTÍNEZ W., LUZ R.: SIRGAS: Basis for Geosciences, Geodata, and Navigation in Latin America, Latin American Geospatial Forum, Rio de Janeiro, Brazil, 2011-08-19
- DETTMERING D., BOSCH W.: First experiences with CryoSat-2 LRM data, Cryosat Validation Workshop, Frascati, Italy, 2011-02-01 (Poster)
- DETTMERING D., BOSCH W.: Multi-mission satellite altimetry: Comparing global relative and absolute in-situ calibrations, IUGG XXV General Assembly, Melbourne, Australia, 2011-06-28/07-07 (Poster)
- DETTMERING D., BOSCH W.: Multi-Mission cross-calibration: Latest results with new missions and products, OSTST Meeting, San Diego, USA, 2011-10-20

- DETTMERING D., BOSCH W.: Influence of latest orbit reprocessing on multi-mission altimetry, OSTST Meeting, San Diego, USA, 2011-10-21
- DREWES H.: Geodätische Überwachung seismisch bedingter Deformationen in Lateinamerika, Geowissenschaftliches Kolloquium, Karlsruhe, Germany, 2011-02-01
- DREWES H.: Geodätische Überwachung seismisch aktiver Zonen mit Beispiel des Erdbebens in Chile 2010, DVW Bayern, München, Germany, 2011-02-11
- DREWES H.: Geodätische Überwachung seismisch aktiver Zonen mit Beispiel des Erdbebens in Chile 2010, Fachhochschule Ansbach, Germany, 2011-02-18
- DREWES H.: 150 Jahre Schweizerische Geodätische Kommission aus Sicht der IAG, Festveranstaltung, Zürich, Switzerland, 2011-06-10
- DREWES H.: Report 2007 – 2011 of the IAG Secretary General, IUGG General Assembly, Melbourne, Australia, 2011-06-29
- DREWES H., SEITZ M., ANGERMANN D.: Thoughts to future realizations of the International Terrestrial Reference Frame, IUGG General Assembly, Melbourne, Australia, 2011-06-29
- DREWES H., SÁNCHEZ L.: Recent aseismic, co-seismic and post-seismic deformations in the pacific orogenic zone of Latin America, IUGG General Assembly, Melbourne, Australia, JG06, 2011-07-02
- DREWES H., BARRIENTOS S., SÁNCHEZ L., MATURANA R.: The Maule earthquake in Chile, February 27, 2010, IUGG General Assembly, Melbourne, Australia, 2011-07-04 (Poster)
- DREWES H.: Beobachtung des Wasserkreislaufs mit geodätischen Methoden, Institut für Physik der Atmosphäre im Deutschen Zentrum für Luft- und Raumfahrt (DLR) Seminar, 2011-07-27
- DREWES H., SÁNCHEZ L., BRUNINI C., MACKERN V.: Cómo mitigar el impacto de eventos sísmicos en los marcos de referencia?, Reunión SIRGAS, Heredia, Costa Rica, 2011-08-08/10
- DREWES H.: Los servicios científicos de la IAG y el marco de referencia ITRF2008, Reunión SIRGAS, Heredia, Costa Rica, 2011-08-09
- DREWES H.: Sistemas y marcos de referencia, Curso en sistemas de referencia. Santiago de Chile, 2011-09-26/30
- EBBING J., BOUMAN J., GRADMAN S., FUCHS M., ABDUL FATTAH R.: Use of GOCE gravity gradient data for lithospheric modeling – A case study for the NE Atlantic margin, AGU Fall Meeting, San Francisco, 2011-12-08
- FUCHS M., BOUMAN J.: Modelling and reducing systematic errors in LNOF rotated GOCE gravity gradients, REAL-GOCE 4. Projekttreffen, Munich, Germany, 2011-03-30
- FUCHS M., MURBÖCK M., BOUMAN J., PAIL R.: GOCE Gravity Gradients: A new satellite observable, GOCE User Workshop, Munich, Germany, 2011-03-31/04-01 (Poster)
- FUCHS M., BOUMAN J.: Modelling and reducing systematic errors in the GOCE gravity gradients, EGU, Vienna, Austria, 2011-04-04/08 (Poster)
- FUCHS M., BOUMAN J.: EGG\_NOM\_2 data quality and processing status, HPF-Progress Meeting, Milan, Italy, 2011-06-20/21
- FUCHS M., BOUMAN J.: Regional estimation of GOCE GGs with a 2D-Fourier series approach, 5. Real-GOCE Projekttreffen, Stuttgart, Germany, 2011-10-10
- FUCHS M., BOUMAN J., BOSCH W.: GOCE gravity gradients: Tensor rotation and quality assessments, GEOTechnologien Statusseminar Real-GOCE, Stuttgart, Germany, 2011-10-11 (Poster)
- FUCHS M., BOUMAN J.: Pre-Analysis of the 8.8 Chile (Maule) and 9.1 Japan (Tōhoku) Earthquake using GOCE gravity gradients, GOCE+ Theme4 TM#1, Delft, The Netherlands, 2011-10-17
- FUCHS M., BOUMAN J.: Gravity gradient analysis, Mid-term review GOCE+ Theme4, Noordwijk, The Netherlands, 2011-10-18
- GÖTTL F., SCHMIDT M., HELLER M., HEINKELMANN R.: Geophysikalische Anregungsfunktionen aus geodätischen Raumbeobachtungsverfahren, Statusseminar Forschergruppe Erdrotation, Wien, Österreich, 2011-02-24

- GÖTTL F., HUGENTOBLE U., SCHMIDT M.: Kombination geophysikalischer Anregungsfunktionen: Berechnung der Kofaktormatrix mit der "N-cornered-hat" Methode, Geodätische Woche, Nürnberg, Deutschland, 2011-09-28
- HEUBLEIN M., SCHMIDT M., DETTMERING D.: 3-dimensionale B-Spline-Modelle des VTEC aus der Kombination verschiedener geodätischer Beobachtungsverfahren, Geodetic Week 2011, Nürnberg, Germany, 2011-09-28
- HUGENTOBLE U., SEITZ M., ANGERMANN D.: PN6 Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters, DFG-Begutachtung der Forschergruppe Referenzsysteme, 2011-05-18 (Poster)
- LIANG W., SCHMIDT M., DETTMERING D., HUGENTOBLE U., LIMBERGER M.: Modeling the electron density of the ionosphere as a combination of physical and mathematical approaches, Geodetic Week 2011, Nürnberg, Germany, 2011-09-27
- LIMBERGER M., HUGENTOBLE U., SCHMIDT M., DETTMERING D., LIANG W.: Effiziente Umsetzung der Integration der Elektronendichte innerhalb der Ionosphäre entlang des Signalweges, Geodetic Week 2011, Nürnberg, Germany, 2011-09-27
- MEEKES S., ABDUL FATTAH, BOUMAN J., SCHMIDT M., EBBING J.: Heterogeneous gravity data combination for geophysical exploration research: Linking satellite gravity to basin maturity, Geological Remote Sensing Group Workshop: Advances in Geological Remote Sensing (Including the Oil and Gas Earth Observation Group Workshop), ESA/ESRIN, Frascati, Italy, 2011-12-07 (Poster)
- MORA-DIAZ J., HEINKELMANN R.: Source structure correction in Geodetic VLBI, Journees 2011, Vienna, Austria, 2011-09-19 (Poster)
- MORA-DIAZ J., HEINKELMANN R.: Source structure correction in Geodetic VLBI, Geodätische Woche 2011, Nürnberg, Deutschland, 2011-09-21
- MÜLLER H.: Statistical Analysis of SLR tracking in 20xx, 17th International Workshop on Laser Ranging, Bad Kötzing, Germany, 2011-05-16/20
- RICHARD J.-Y., GAMBIS D., BIANCALE R., SEITZ M.: Combination of Space Geodetic Techniques at the Normal Equation Level, ESA 3rd Int. Colloquium - Galileo Science, Copenhagen, Denmark, 2011-09-02 (Poster)
- SÁNCHEZ L.: Physical height systems in South America, STSE-GOCE+Height System Unification Progress Meeting 2, Frankfurt am Main, Germany, 2011-12-14/15
- SAVCENKO R., GEBLER M., BOSCH W.: Validation of recent tide models by means of crossover differences and time series of bottom pressure and tide gauges, EGU General Assembly, Vienna, Austria, 2011-04-06 (Poster)
- SAVCENKO R., BOSCH W.: Tides in shallow water from multi-mission-altimetry, 5th Coastal Altimetry Workshop, San Diego, USA, 2011-10-16/18 (Poster)
- SAVCENKO R., BOSCH W.: EOT11a - a new tide model from Multi-Mission Altimetry, OSTST Meeting, San Diego, USA, 2011-10-19/21 (Poster)
- SAVCENKO R., BOSCH W.: Potential of multi-mission altimetry for detecting small scale tidal structure, AGU2011, San Francisco, 2011-12-07 (Poster)
- SÁNCHEZ L., BRUNINI C., MACKERN V., MARTINEZ W., LUZ R.: Status and new perspectives of the SIRGAS Reference Frame, IUGG XXV General Assembly, Melbourne, Australia, 2011-06-30
- SÁNCHEZ, L.: Numerical approach for a unified World Height System, IUGG XXV General Assembly, Melbourne, Australia, 2011-07-04
- SÁNCHEZ L.: Sistemas verticales de referencia (Lecture), Third IAG-PAIGH-SIRGAS school on reference systems, San José, Costa Rica, 2011-08-05
- SÁNCHEZ L., LUZ R.: Requerimientos para la unificación de los sistemas de alturas existentes en la Región SIRGAS, SIRGAS 2011 General Meeting, San José Costa Rica, 2011-08-08
- SÁNCHEZ L., SEITZ M.: Actividades recientes del Centro Regional de Análisis Asociado del IGS para SIRGAS (IGS RNAAC SIR), SIRGAS 2011 General Meeting, San José, Costa Rica, 2011-08-09

- SÁNCHEZ L., SEITZ M., DREWES H.: Cinemática del marco de referencia SIRGAS, SIRGAS 2011 General Meeting, San José, Costa Rica, 2011-08-09
- SÁNCHEZ L.: Training course on GNSS analysis for the installation of a SIRGAS Processing Centre in Chile, Instituto Geográfico Militar, Santiago de Chile, Chile, 2011-09-26/10-07
- SÁNCHEZ L.: Procesamiento preciso de mediciones GNSS (Lecture), Curso en sistemas de referencia, Instituto Geográfico Militar, Santiago de Chile, Chile, 2011-09-26/28
- SÁNCHEZ L.: Tipos de alturas, superficies de referencia y unificación de datums verticales (Lecture), Curso en sistemas de referencia, Instituto Geográfico Militar, Santiago de Chile, Chile, 2011-09-29
- SÁNCHEZ L.: SIRGAS: marco de referencia para las Américas (Lecture), Curso en sistemas de referencia, Instituto Geográfico Militar, Santiago de Chile, Chile, 2011-09-30
- SÁNCHEZ L., BRUNINI C.: Geoinformation and Navigation supported by the Geocentric Reference System for the Americas, International Symposium on Global Navigation Satellite Systems, Space-Based and Ground-Based Augmentation Systems and Applications Berlin, Germany, 2011-10-10
- SÁNCHEZ L., CIOCE V.: Sistema de Referencia para las Américas - SIRGAS (Lecture), Curso avanzado en posicionamiento GNSS, Universidad Politécnica de Madrid, Spain, 2011-10-12
- SÁNCHEZ L.: The role of TIGA in the vertical datum standardization, Twelfth Session of the GLOSS Group of Experts, Paris, France, 2011-11-08
- SCHEINERT M., EWERT H., SCHWABE J., LIEB V., Dietrich R.: Mean Sea-Surface Topography in the Weddell Sea Region, Antarctica, from ICESat Laser Altimetry and a Regional Geoid Solution, 25th IUGG General Assembly, Melbourne, Australia, 2011-07-01
- SCHEINERT M., LIEB V., SCHWABE J., EWERT H., DIETRICH R.: The Combination of ICESat Laser Altimetry, GOCE Satellite Gravimetry and Ground-Based Gravimetry for the Determination of the Mean Sea-Surface Topography in the Weddell Sea Region, Antarctica, AGU Fall Meeting, San Francisco, California, USA, 2011-12-07 (Poster)
- SCHMIDT M., FUCHS M., BOUMAN J., BOSCH W.: Heterogeneous gravity data combination, GOCE+ ITT Theme 2 Negotiation Meeting, Noordwijk, The Netherlands, 2011-03-10
- SCHMIDT M., HUGENTOBLE U., JAKOWSKI N., DETTMERING D., LIANG W., LIMBERGER M., HOQUE M., WILKEN V.: Multi-scale model of the ionosphere from the combination of modern space-geodetic satellite techniques, EGU General Assembly 2011, Vienna, Austria, 2011-04-04/08, 2011-04-05 (Poster)
- SCHMIDT M., DETTMERING D., LIANG W., HEINKELMANN, R. : Concepts for modeling VTEC as a multi-scale representation, EGU General Assembly 2011, Vienna, Austria, 2011-04-04/08, 2011-04-05 (Poster)
- SCHMIDT M., HEINKELMANN R., GÖTTL F.: Combination of time series of excitation functions by introducing operator software impact (OSI) parameters, EGU General Assembly 2011, Vienna, Austria, 2011-04-04/08, 2011-04-06 (Poster)
- SCHMIDT M.: Towards the combination of data sets from various observation techniques, QuGOMS'11, Garching/Munich, Germany, 2011-04-13/15
- SCHMIDT M.: Multi-dimensionale Signalanpassung durch Spline-Funktionen (Keynote-Vortrag), Geodetic week, Nürnberg, Germany, 2011-09-27
- SCHMIDT M., LIEB V.: Regional Gravity Field Recovery, GOCE+ Theme4 Mid-term review, Noordwijk, The Netherlands, 2011-10-18
- SCHMIDT M., HABERKORN C.: GRACE L1b processing, GOCE+ Theme4 Mid-term review, Noordwijk, The Netherlands, 2011-10-18
- SCHMIDT M., BOUMAN J., FUCHS M., DETTMERING D., LIEB V., SCHRAMA E., VISSER P., VERMEERSEN B., BROERSE T.: Greenland Ice Mass Variations Observed with GOCE, AGU Fall Meeting, San Francisco, 2011-12-08 (Poster)
- SCHWATKE C., BOUMAN J., BOSCH W.: Promotion, GOCE+ ITT Theme 2 Negotiation Meeting, Noordwijk, The Netherlands, 2011-03-10

- SCHWATKE C., FORBERG B.: The EUROLAS Data Center (EDC) - Status Report 2011, 17th Workshop on Laser Ranging, Bad Kötzing, Germany, 2011-05-18 (Poster)
- SCHWATKE C.: Automated Data Management of SLR Data and Products at the EUROLAS Data Center (EDC), 17<sup>th</sup> Workshop on Laser Ranging, Bad Kötzing, Germany, 2011-05-20
- SCHWATKE C., BOSCH W., KOCH T.: Satellite Altimetry over Inland Water: A New Tool to Detect Geoid Errors!, 5<sup>th</sup> Coastal Altimetry Workshop, San Diego, USA, 2011-10-16/18 (Poster)
- SCHWATKE C., BOSCH W., KOCH T.: Satellite Altimetry over Inland Water: A New Tool to Detect Geoid Errors!, Ocean Surface Topography Science Team Meeting, San Diego, USA, 2011-10-19/21 (Poster)
- SEITZ M., HEINKELMANN R., STEIGENBERGER P., ARTZ TH.: Common Realization of Terrestrial and Celestial Reference Systems, European VLBI General Assembly, Bonn, Germany, 2011-03-29/31
- SEITZ M., HEINKELMANN R., STEIGENBERGER P.: Consistent Estimation of CRF and TRF, EGU, Vienna, Austria, 2011-04-03/08 (Poster)
- SEITZ M.: Combination of different space geodetic data types in order to compute terrestrial reference frames and time series of geodetic parameters, QuGOMS, Garching, Germany, 2011-04-13/15
- SEITZ M., STEIGENBERGER P., ARTZ T., HEINKELMANN R.: Consistent adjustment of combined terrestrial and celestial reference frames, IUGG XXV General Assembly, Melbourne, Australia, 2011-06-29
- SEITZ M.: Simultaneous Adjustment of TRF and CRF, GGOS Unified Analysis Workshop, Zurich, Switzerland, 2011-09-17
- SINGH A., SEITZ F., SCHWATKE C., SCHMIDT M., GÜNTNER A.: Changing hydrology of the Aral Sea: Results from satellite altimetry, GRACE satellite gravimetry and hydrological modeling, EGU, Vienna, Austria, 2011-04-05 (Poster)
- SINGH A., SEITZ F., SCHWATKE C.: Inter-annual Water Storage Changes in the Aral Sea from Multi-mission Satellite Altimetry, Remote Sensing, and GRACE Satellite Gravimetry, Geodetic Week 2011, Nuremberg, Germany, 2011-09-28
- STEIGENBERGER P., HUGENTOBLE U., SCHMID R., HESSELS U., KLÜGEL T., SEITZ M.: GNSS-specific local effects at the Geodetic Observatory Wettzell, European Geosciences Union General Assembly 2011, Wien, 2011-04-07
- VEICHERTS M., TSCHERNING C.C., BOUMAN J.: Gravity gradient calibration with terrestrial data, GOCE User Workshop, Munich, Germany, 2011-03-31/04-01 (Poster)

## 5.4 Membership in scientific bodies

### International Union of Geodesy and Geophysics (IUGG)

- Representative to the Panamerican Institute for Geodesy and History (PAIGH), H. Drewes

### International Association of Geodesy (IAG)

- Secretary General: H. Drewes
- Assistant Secretary General: H. Hornik
- Sub-commission 1.1, Working Group 2 “Interactions and consistency between Terrestrial Reference Frame, Earth rotation, and gravity field”, Chair: D. Angermann
- Sub-commission 1.3, Working Group “Regional Dense Velocity Fields”: SIRGAS Representative: L. Sánchez
- Sub-commission 1.3a “Reference Frame for Europe (EUREF)”, Secretary until June 2011: H. Hornik
- Sub-commission 1.3b “Geocentric Reference Frame for the Americas (SIRGAS)”, Vice-President: L. Sánchez
- Sub-commission 1.3b “Geocentric Reference Frame for the Americas (SIRGAS)”, Scientific Committee member: H. Drewes
- Sub-commission 1.4 “Interaction between Celestial and Terrestrial Reference Frames”: R. Heinkelmann
- Sub-commission 1.4 , Working Group 1.4.1 “Geophysical and Astronomical effects and the consistent determination of CRF and TRF”: R. Heinkelmann
- Sub-commission 1.4 , Working Group 1.4.2 “Co-location on Earth and in space for the determination of the CRF”: R. Heinkelmann, M. Seitz
- Commission 1 Inter-commission Working Group 1.3 “Concepts and Terminology Related to Geodetic Reference Systems”: H. Drewes
- Commission 1 Joint Working Group 1.4 “Strategies for epoch reference frames”: M. Seitz (Chair), M. Bloßfeld
- Commission I Working Group 1.4.2 Co-location on Earth and in Space for the Determination of Celestial Reference Frame: M. Seitz
- Commission 4 Study Group SC 4.3.1 “Ionosphere Modelling and Analysis”, Chair: M. Schmidt, D. Dettmering, R. Heinkelmann
- Intercommission Committee on Theory (ICCT), Study Group 3 “Configuration Analysis of Earth Oriented Space Techniques”, Member: M. Schmidt, M. Seitz
- Inter-commission Working Group 1.3 “Concepts and Terminology Related to Geodetic Reference Systems”: H. Drewes
- Inter-commission Study Group 1: “Theory, Implementation and Quality Assessment of Geodetic Reference Frames”: H. Drewes
- Inter-commission Study Group 5: “Satellite Gravity Theory”: W. Bosch, M. Schmidt
- Inter-commission Study Group 9: “Application of Time-Series Analysis in Geodesy”: M. Schmidt
- GGOS Bureau for Standards and Conventions, Director: D. Angermann, Members: J. Bouman, M. Gerstl, R. Heinkelmann, L. Sánchez
- GGOS Coordinating Board, Member: D. Angermann
- GGOS Working Group 0.1.1 “Vertical Datum Standardization”, Chair: L. Sánchez
- GGOS Bureau for Networks and Communication: R. Heinkelmann

### International Altimetry Service

- Steering Committee, Chair: W. Bosch

### International Earth Rotation and Reference Systems Service (IERS)

- ITRS Combination Centre, Chair: M. Seitz
- Working Group “Site Survey and Co-location”: D. Angermann, M. Seitz
- Working Group on Combination on Observation Level: D. Angermann, M. Seitz (Co-Chair), H. Müller, R. Heinkelmann

**International GNSS Service (IGS)**

- Regional Network Associate Analysis Centre for SIRGAS, Chair: L. Sánchez
- TIGA Analysis Centre, Chair: L. Sánchez

**International Laser Ranging Service (ILRS)**

- Governing Board member: H. Müller
- Data Centre (EDC): Chair: C. Schwatke, H. Müller
- Analysis Centre: Chair: H. Müller
- Operations Centre at DGFI. Chair: C. Schwatke
- Working Group “Data Format and Procedures”, Chair: H. Müller, C. Schwatke

**International VLBI Service for Geodesy and Astrometry (IVS)**

- Member: R. Heinkelmann, M. Seitz
- Analysis Centre, Chair: R. Heinkelmann, J. A. Mora-Diaz
- Combination Centre: R. Heinkelmann, M. Gerstl, M. Seitz (jointly with BKG)
- IERS Working Group on the second realization of the International Celestial Reference Frame ICRF2: R. Heinkelmann

**European VLBI Group for Geodesy and Astrometry (EVGA),**

- Member: R. Heinkelmann

**Sistema de Referencia Geocéntrico para las Américas (SIRGAS)**

- Vice-President: L. Sánchez
- IAG Representative: H. Drewes

**Group on Earth Observation (GEO)**

- IAG Substitute Delegate in the Committee on Capacity Building and Outreach: H. Drewes

**American Geophysical Union (AGU)**

- JGR - Solid Earth, Associate Editor: J. Bouman

**European Geosciences Union (EGU)**

- Geodesy Division, Vice-Presidents: J. Bouman, M. Schmidt

**European Space Agency (ESA)**

- CryoSat2 Calibration and Validation Team: W. Bosch

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

- Ocean Surface Topography Science Team for Jason2: W. Bosch, D. Dettmering
- SARAL/Altika Calibration/Validation Team: W. Bosch

**COST Action ESO701: Improved Constraints on Models of Glacial Isostatic Adjustment**

- Working Group 2 “Velocity determination/reference frame realization”: D. Angermann

**Deutsche Geodätische Kommission (DGK)**

- Member: H. Drewes
- Section Geodesy: H. Drewes
- Executive Secretary: H. Hornik

**Deutscher Verein für Vermessungswesen (DVW), Gesellschaft für Geodäsie, Geoinformation und Landmanagement**

- Working Group 7 “Experimentelle, angewandte und theoretische Geodäsie”: M. Schmidt (Gast-Status)

## 5.5 Participation in meetings, symposia, conferences

2011-01-10/11	GOCE HPF Progress Meeting 21, Bonn, Germany (Bouman J.)
2011-01-13	GEOTOP Projectmeetig (telephone conference), DGFI, München (Bosch W., Savcenko R.)
2011-01-20/21	Workshop on Satellite Altimetry Calibration & Deformation Monitoring with GNSS, Chania, Crete/Greece (Bosch W.)
2011-01-27	Session Wissenschaftlicher Ausschuss der Deutschen Geodätischen Kommission, Karlsruhe/Germany (Hornik H.)
2011-01-28	GOCE+ ITT Theme 4 Negotiation Meeting, Noordwijk, The Netherlands (Bouman J.)
2011-02-01/03	Cryosat Validation Workshop, ESA, Frascati, Italy (Dettmering D.)
2011-02-03/04	COST Action ES0701 Meeting: GIA model optimisation and ice mass balance, Brussels, Belgium (Angermann D.)
2011-02-08	CGE Management Board, IAPG, München, Germany (Angermann D., Bosch W., Bouman J., Schmidt M.)
2011-02-10/11	DFG priority program “Mass Transport”, Coordination Meeting, Bonn, Germany (Bosch W.)
2011-02-14/15	MuSIK Kick-Off Meeting, Neustrelitz, Germany (Dettmering D., Liang W., Schmidt M.)
2011-02-21	CGE Management Board, IAPG, München, Germany (Angermann D., Bosch W., Bouman J., Schmidt M.)
2011-02-24/25	Statusseminar der Forschergruppe Erdrotation, Vienna, Austria (Bloßfeld M., Göttl F., Seitz M., Angermann D.)
2011-03-01	ESPACE Lecturer Meeting, IAPG, München, Germany (Bosch W., Bouman J., Schmidt M.)
2011-03-03/04	55 <sup>th</sup> Meeting of the EUREF Technical Working Group, Padua/Italy (Hornik H.)
2011-03-09	DGK Working Group “Rezente Krustenbewegung”, Braunschweig, Germany (Bosch W.)
2011-03-09/10	DGK, Sektion “Erdmessung”, Spring Meeting, Braunschweig (Bosch W.)
2011-03-10	GOCE+ ITT Theme 2 Negotiation Meeting, Noordwijk, The Netherlands (Bouman J., Schmidt M.)
2011-03-16/17	RegGRAV 5th Progress Meeting, AGeoBW, Euskirchen, Germany (Bosch W., Goebel G., Schmidt M.)
2011-03-29/31	20 <sup>th</sup> EVGA Meeting & 12th Analysis Workshop, Bonn, Germany (Bloßfeld M., Seitz M.)
2011-03-30	REAL-GOCE 4. Projekttreffen, Munich, Germany (Bosch W., Bouman J., Fuchs M.)
2011-03-31/04-01	GOCE User Workshop, Munich, Germany (Bosch W., Bouman J., Dettmering D., Fuchs M., Savcenko R.)
2011-04-03/08	European General Assembly, Vienna, Austria (Bloßfeld M., Bosch W., Fuchs M., Schmidt M.)
2011-04-12	Verabschiedung des bisherigen und Amtseinführung des neuen Präsidenten des Bundesamtes für Kartographie und Geodäsie (BKG), Frankfurt a.M./Germany (Hornik H.)
2011-04-13/15	QuGOMS, Garching, Germany (Schmidt M., Seitz M.)
2011-05-16/20	17 <sup>th</sup> Workshop on Laser Ranging, Bad Kötzing, Germany (Bloßfeld M., Müller H., Stefka V., Schwatke Ch.)
2011-05-18	Begutachtung DFG Forschergruppe “Referenzsysteme”, Bonn, Germany (Angermann D., Seitz M.)
2011-05-24	56 <sup>th</sup> Meeting of the EUREF Technical Working Group, Chisinau/Moldova (Hornik H.)

2011-05-25/28	21 <sup>st</sup> Symposium of the IAG-Sub-commission EUREF, Chisinau/Moldova (Hornik H.)
2011-06-27/07-07	2011 XXV General Assembly of the International Union of Geodesy and Geophysics (IUGG) / Meetings of the Executive Committee of the International Association of Geodesy (IAG) / Meetings of the Council of the IAG, Melbourne, Australia (Hornik H.)
2011-06-28/07-07	IUGG XXV General Assembly, Melbourne, Australia (Bosch W., Bouman J., Drewes H., Hornik H., Sánchez L., Seitz M.)
2011-07-02/05	21 <sup>st</sup> GGOS Steering Committee Meeting, Melbourne, Australia (Bouman J.)
2011-08-01/02	COTAGA Projectmeetig, Munich, Germany (Bosch W., Savcenko R.)
2011-08-03/05	Third IAG-PAIGH-SIRGAS school on reference systems, San José, Costa Rica (Drewes H., Sánchez L.)
2011-08-08/10	SIRGAS 2011 General Meeting, San José, Costa Rica (Drewes H., Sánchez L.)
2011-09-12/16	SPP1257 Sommerschule, Mayschoss, Germany (Bosch W., Fuchs M., Göttl F., Liang W., Savcenko R., Schwatke Ch.)
2011-09-16/17	GGOS Unified Analysis Workshop, Zurich, Switzerland (Angermann D., Müller H., Seitz M.)
2011-09-26/30	Curso en sistemas de referencia, Instituto Geográfico Militar, Santiago de Chile, Chile (Drewes H., Sánchez L.)
2011-09-27/29	Geodetic Week, Nürnberg, Germany (Angermann D., Schmidt M., Bloßfeld M., Stefka V., Mora-Diaz J., Liang W., Göttl F., Bosch W.)
2011-10-05/06	DFG Rundgespräch “Infrastrukturschwerpunkt Wettzell”, Höllenstein, Deutschland (Angermann D., Bosch W., Schmidt M., Seitz M.)
2011-10-14	Session Wissenschaftlicher Ausschuss der Deutschen Geodätischen Kommission, Dresden/Germany (Hornik H.)
2011-10-16/18	5 <sup>th</sup> Coastal Altimetry Workshop, San Diego, USA (Dettmering D., Savcenko R., Schwatke Ch.)
2011-10-18	Joint Argo and Altimetry Workshop, San Diego, USA (Savcenko R.)
2011-10-18	GOCE+ ITT Theme 4 Mid-term Review, Noordwijk, The Netherlands (Bouman J., Schmidt M., Fuchs M.)
2011-10-19/21	Ocean Surface Topography Science Team Meeting (OSTST), San Diego, USA (Dettmering D., Savcenko R., Schwatke Ch.)
2011-11-07/08	GEOTOP project meeting, Fulda, Germany (Bosch W., Savcenko R.)
2011-11-07/11	Twelfth Session of the GLOSS Group of Experts, Paris, France (Sánchez L.)
2011-11-21/22	COL Working Group Meeting, Paris, Frankreich (Angermann D., Seitz M.)
2011-12-03	GGOS Coordinating Board Meeting No. 1, San Francisco, USA (Angermann D., Bosch W., Drewes H.)
2011-12-04/09	AGU Fall Meeting, San Francisco, USA (Angermann D., Blossleld M., Bosch W., Bouman J.)
2011-12-14/15	Meeting of the ESA Project “Height system unification with GOCE”, Frankfurt am Main, Germany (Sánchez L.)

## 5.6 Guests

2011-01-12/21	Majid Naeimi, IFE Hannover, Germany
2011-03-11	20 Students, Technical University Prague, Czech Republic
2011-04-05/29	Beatriz Vaquero, CDT Yebes, Madrid, Spain
2011-04-25/05-06	Verena Lieb, TU Dresden, Germany
2011-04-26/05-10	Klaus Bataille, Universidad de Concepción, Concepción, Chile
2011-04-26/05-31	Juan Carlos Báez, Universidad de Concepción, Concepción, Chile
2011-06-06/07-15	Marion Heublein, KIT Karlsruhe, Germany / INSA Strasbourg, France
2011-08-01/09-09	Benedikt Soja, TU Wien, Austria
2011-10-17/20	Claudio Brunini, Universidad Nacional de La Plata, La Plata, Argentina
2011-11-11	Prof. K.-R. Koch, IGG, Bonn, Germany

## 6 Personnel

### 6.1 Number of personnel

Total staff of DGFI during the 2011 period (incl. DGK Office):

#### Regular budget

- 10 scientists
- 7 technical and administrative employees
- 1 worker
- 6 student helpers with an average of 230 hours/year
- 1 minor time employee

#### Project funds

- 8 junior scientists

#### Funding of the following projects is gratefully acknowledged:

COTAGA	Combined ocean tide analysis by GRACE and altimetry data (DFG)
GEOTOP	Sea surface topography and mass transport of the Antarctic Circumpolar Current (DFG)
PROMAN	Program management and scientific networking (DFG)
CEMIG	Consistent estimation of water mass variations in different continental storage components by the combined inversion of a global hydrological model with time-variable gravity and complementary observation data (DFG)
MUSIK	Multi-scale ionosphere model from the combination of modern 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, CAVERMO, (DFG)
REAL-GOCE	Real data analysis GOCE, GEOTECHNOLOGIEN programme (BMBF)
GOCE HPF	Validation and frame transformation of GOCE gravity gradients (ESA/TUM)
GOCE+Geo Explore	Heterogeneous gravity data combination for Earth interior and geophysical exploration research
GOCE+Time Variations	Feasibility study to the potential of GOCE data to detect temporal gravity field variations
REGGRAV	Software application for high-resolution regional geoid models (AGeoBw)
CHL 10/018	Geodätisches Beobachtungs- und Analysesystem in seismisch aktiven Gebieten Chiles (IB BMBF)

### 6.2 Lectures at universities

Bosch W.: University lectures “Oceanography and Satellite Altimetry”, TU München, WS 2011/2012

Bouman J.: University lectures “Gravity and Magnetic Field from Space”, TU München, WS 2011/2012

Schmidt M.: University lectures “Numerical Modelling”, TU München, WS 2010/2011

Schmidt M.: University lectures “Wavelets”, TU München, SS 2011

Schmidt M.: University lectures “Numerical Modelling”, TU München, WS 2011/2012

### **6.3 Lectures at seminars and schools**

Drewes H. Sistemas y marcos de referencia, IAG-PAIGH-SIRGAS School on Reference Systems, Heredia, Costa Rica, 2011-08-03

Drewes H.: Objetivos científicos de SIRGAS, IAG-PAIGH-SIRGAS School on Reference Systems, Heredia, Costa Rica, 2011-08-05

Drewes H.: Sistemas y marcos de referencia, Curso en sistemas de referencia. Santiago de Chile, 2011-09-26/30

Sánchez L.: Sistemas verticales de referencia, IAG-PAIGH-SIRGAS School on Reference Systems, Heredia, Costa Rica, 2011-08-05

Sánchez L.: Procesamiento de datos de GNSS, Curso en sistemas de referencia. Santiago de Chile, 2011-09-26/30

Sánchez L.: Sistemas verticales de referencia, Curso en sistemas de referencia. Santiago de Chile, 2011-09-26/30

## **7 Miscellaneous**

With its collection of geodetic instruments DGFI participated in the “Lange Nacht der Museen (Long Night of Museums)”, Munich, Germany, 2011-10-15.

DGFI supervised 13 grammar school pupils of the Bertold Brecht Gymnasium, Pasing for a one and a half year high school seminar on “Global Change and sea level rise”.