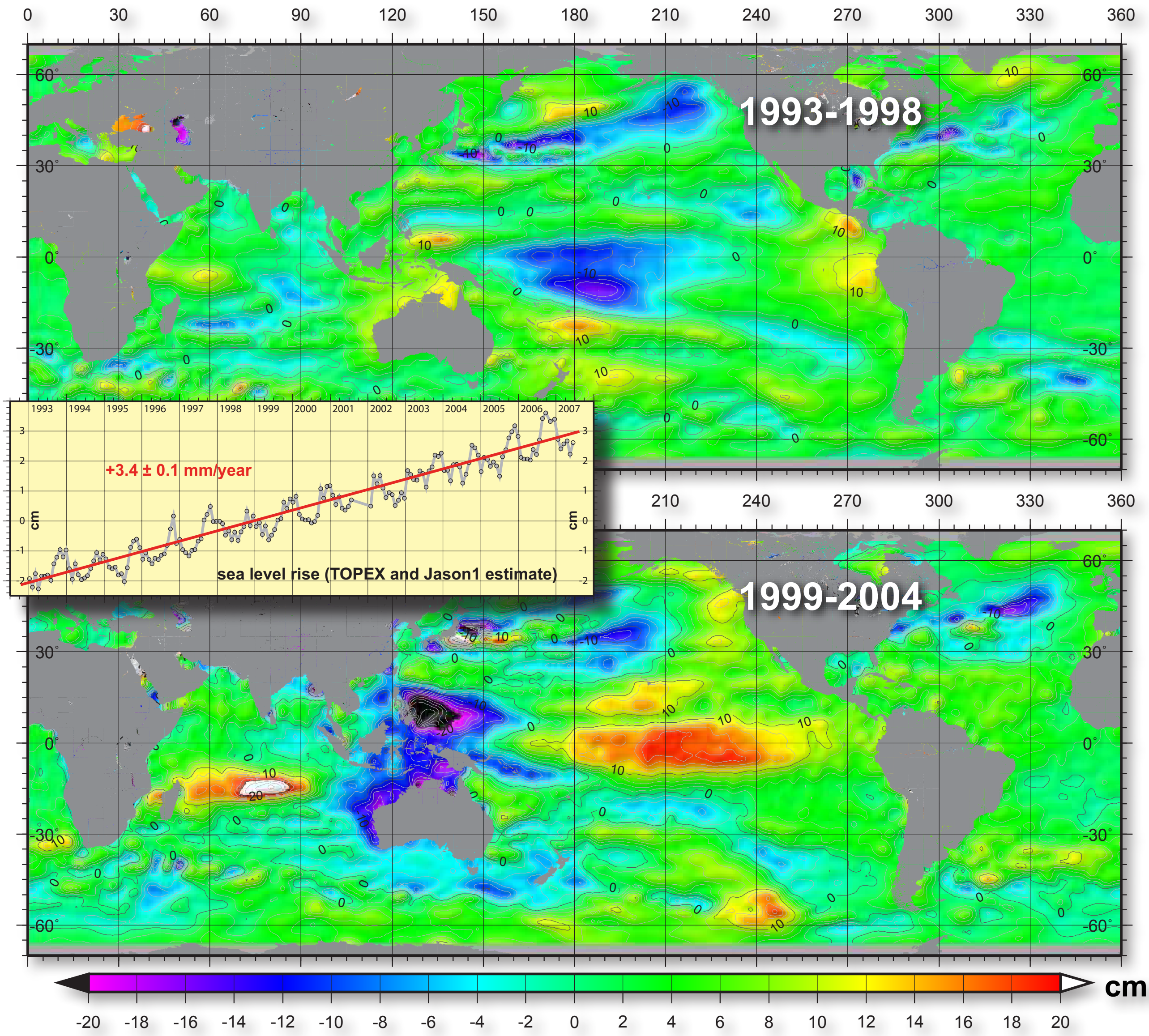
Deutsches Geodätisches Forschungsinstitut (DGFI)

ANNUAL REPORT 2006/2007



A global sea level rise of +3.4mm/year is estimated from TOPEX and Jason1 altimetry. On regional scale the long-period changes of the mean sea surface have amplitudes up to 20cm with opposing sign and pronounced geographical pattern. For most areas the changes within the two six-year periods 1993–1998 and 1999–2004 compensate each other – except for the central axis of the Gulf Stream where the mean sea level dropped down in both periods, an indication for the weakening of the Gulf Stream.

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1st Edition

The Institute

The German Geodetic Research Institute (Deutsches Geodätisches Forschungsinstitut, DGFI) is an autonomous and independent research institution located in Munich. It is supervised by the German Geodetic Commission (Deutsche Geodätische Kommission, DGK) at the Bavarian Academy of Humanities and Sciences (Bayerische Akademie der Wissenschaften, BAdW). The research covers all fields of geodesy and includes the participation in national and international research projects as well as various functions in international bodies.

Research Programme

The overall research programme of DGFI is established for a long period (several years) in order to meet the continuous requirements of international activities and the demands of modern society. The current general theme is "Geodetic research for observing and analysing the System Earth". This theme reflects the scientific orientation of Geodesy as the discipline of measuring and representing the changing Earth and responds to the challenges for a better understanding of the phenomena and processes of geodynamics and global change. It includes the study of geometric and gravimetric observation techniques, fundamentals of geodetic reference systems, methods for estimating geodetic parameters, and analyses of physical models of the Earth.

Motivation

The demands of the society to Geodesy are based on the increasing consciousness of helplessness against natural hazards. Extreme disasters can only be prevented if the characteristics and processes of earthquakes, tsunamis, flooding, etc. are well understood in order to envisage a prognosis of future events. Geodesy is capable of quantifying the effects of such processes by measuring the variations of the surface geometry of the solid Earth and oceans, the Earth's rotation, and the Earth's gravity field. As these variations are very small, all efforts have to be made to exhaust the full information included in the geodetic measurements. This can only be done by a thorough study of the techniques, models and results and by the development of sophisticated methods for observing and analysing the parameters describing the dynamics of the System Earth.

Practical Applications

Basic requirement for geodetic measurements and parameters (time-dependent positions, orientation angles, gravity values, etc.) are unique reference systems. Fundamental research of DGFI is therefore dedicated to this field. The frames realizing the reference systems are also used in many practical applications. The celestial reference frame enables to describe the orientation of Earth in space. It is necessary for space travel, global navigation, astrometry etc. The terrestrial reference frame is the basis for all precise positioning in surveying, engineering, navigation, and geo-information systems. It allows the unification of all national and continental reference systems, which is a prerequisite for globalization of society and economics. The Earth's gravity is represented with respect to physical reference surfaces, e.g., the geoid as an equipotential surface or the mean sea level in a state of equilibrium. It is also the reference for physical heights used in practical applications (levelling, barometric heights). The DGFI research activities support these applications.

University Connections

There is a very close cooperation of DGFI with all German universities involved in geodetic education. This is mainly done under the umbrella of the DGK, but also in bilateral arrangements. Members of DGFI give lectures and courses at various universities. Doctoral and Diploma theses are supervised by DGFI scientists. Interdisciplinary cooperation was established with university institutes for Geophysics, Meteorology and Oceanography.

Research Group Satellite Geodesy (FGS)

Most intensive cooperation exists with the Technical University of Munich (TUM), in particular within the Research Group on Satellite Geodesy (Forschungsgruppe Satellitengeodäsie, FGS). It is a consortium formed by TUM's Institute of Astronomical and Physical Geodesy (IAPG) and Research Establishment (Forschungseinrichtung) Satellite Geodesy (FESG), the Institute for Geodesy and Geoinformation, University of Bonn (IGG), the Federal Agency (Bundesamt) for Cartography and Geodesy (BKG), and the German Geodetic Research Institute (DGFI).

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 scientific services of IAG for practice and research, and cooperates in these services as data, analysis and research centres. Scientists of DGFI have taken leading positions and supporting functions in IAG and its commissions, services, projects, working and study groups and in 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.

Structure of the Programme

The present research programme for the years 2007–2008 is an update of the previous programme. It was evaluated and revised by the Scientific Council (Beirat) of DGK and approved by the DGK General Assembly on November 23, 2006. It is divided into the four long-term research fields

1. Earth System observations,
2. Earth System analysis,
3. International scientific services and projects,
4. Information systems and scientific transfer.

Observations of the Earth System include modelling of measurement techniques, methods and approaches of data processing and data combination, definition and realization of reference systems, up to the provision of consistent parameters. Analysis of the Earth System deals with the study of the properties and interactions of system elements which are reflected by the corresponding geodetic parameters and their correlation among each other. The participation in international services and projects as well as the maintenance of information systems and science transfer are indispensable requirements for a research institute. The research fields are subdivided into specific topics, sixteen in total. DGFI scientists are working simultaneously in several scientific topics in order to ensure the connection between the different fields and the consistency of methods, models and results.

1 Earth System Observations

The research field "Earth System Observation" is concerned with the modelling, data processing and parameter estimation for the primary geodetic observing techniques for monitoring the System Earth. These are in particular the Very Long Baseline Interferometry (VLBI), the Satellite and Lunar Laser Ranging (SLR/LLR), the Global Navigation Satellite Systems (GNSS) including the microwave techniques GPS, GLONASS and in future GALILEO, the French Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS), and the satellite altimetry and gravity field sensors (Radar, SST, gradiometry). These observation techniques form the basis for monitoring the surface structure, the rotation and the gravity field of the Earth along with its variations in time, and allow the representation of the interactions between these parameters. The results of this research field provide an important input for the Global Geodetic Observing System (GGOS) installed as a fundamental programme of the International Association of Geodesy (IAG).

The investigations are divided into four topics. The modelling for the above-mentioned observation techniques is dealt with in topic 1.1. The objective is to get optimal models for the individual techniques and a unification of the modelling for better consistency of the results by advanced combination methods. Topic 1.2 concentrates on the basic research for geometric reference systems which enter directly into the realization of the terrestrial and the celestial reference systems. In topic 1.3 we deal with the fundamentals of physical parameter estimations. They are an important prerequisite for the procedures of combining geometric and gravimetric observations, which are treated in topic 1.4. A consistent estimation of geodetic parameters (e.g. station coordinates, positions of radio sources, Earth orientation parameters, harmonic coefficients of the gravity field) shall be achieved by the rigorous combination of the data of the different observation techniques.

1.1 Modelling for space geodetic observations

The primary geodetic space observation techniques are intensely utilized at DGFI: GPS by means of the Bernese software, SLR by the DOGS-OC software, VLBI by the OCCAM software and satellite altimetrie by several packages. For other space techniques (DORIS, LLR, SST), normal equations or solutions are provided by co-operation partners. The major goal is to develop uniform standards, models, and parameterizations and to implement them in the different software packages to ensure that the measurements of the different observation techniques can be uniformly processed and combined into consistent solutions. The modelling has to be adapted to the state-of-the-art standards. During the period 2006/2007 the work focussed mainly on contributions to the project "Integration of Space Geodetic Techniques as a Basis for a Global Geodetic-Geophysical Observing System (GGOS-D)".

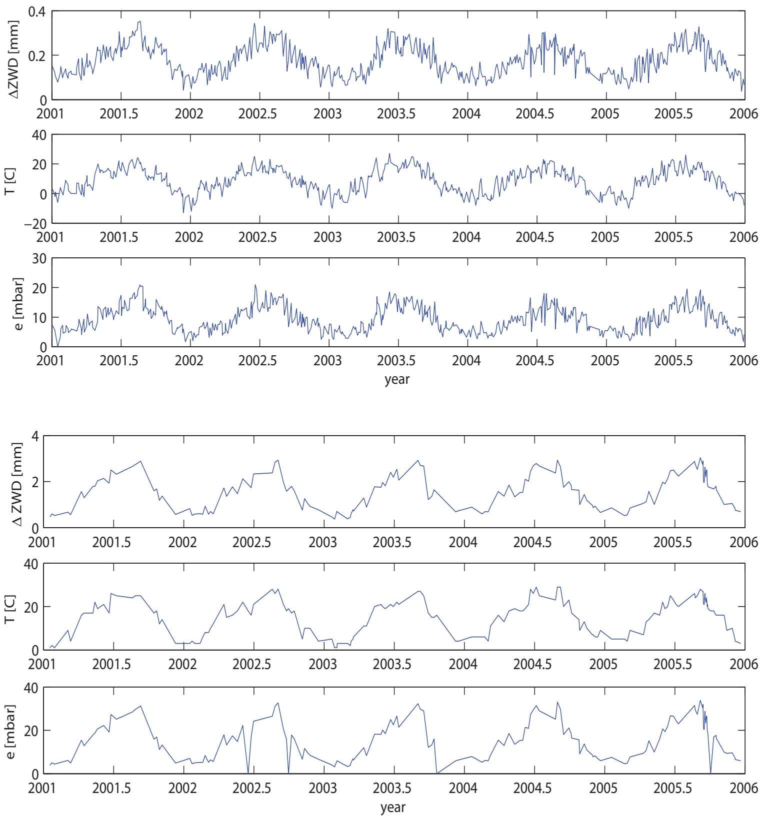
GGOS-D Project

GGOS-D is a joint project of the "GeoForschungsZentrum (GFZ) Potsdam", the "Bundesamt für Kartographie und Geodäsie (BKG)", the "Institut für Geodäsie und Geoinformation, Universität Bonn (IGGB)", and DGFI funded by the German Ministry for Education and Research (BMBF) in the frame of the programme GEOTECHNOLOGIEN. Within GGOS-D unified standards, models, and parameterizations for the processing were defined and implemented in the different software packages in use by the contributing institutions. The work at DGFI has been focussed on updates of the software packages DOGS-OC and OCCAM and on the generation of fully consistent observation time series of SLR and VLBI observations (see 3.4 and 3.5).

Comparison of tropospheric parameters

The wet part of tropospheric parameters (ZWD) estimated from GPS and VLBI data can be combined if the the effect of the height difference between the stations is considered. Fig. 1.1.1 shows the ZWD difference for two stations. The ZWD differences are computed from the Saastamoinen model introducing meteorological data observed at the VLBI telescope, which are also displayed. The meteorological data for the GPS station are computed from he VLBI values using formulae to describe the dependency of water vapour pressure and temperature from the station height. The ZWD difference show a clear annual signal. For the station Wettzell, with a height difference between GPS and VLBI of about 3 m, the annual ZWD variation is very small but for the station Tsukuba, there the height difference between GPS and VLBI is 17 m, the ZWD variation is 2.5 mm from peak to peak. Consequently, the annual variation of the ZWD differences has to be considered to reach a consistent combination of tropospheric parameters.

Fig. 1.1.1: Differences of ZWD between GPS and VLBI, temperature (T) and water vapour pressure at VLBI stations in Wettzell (top) and Tsukuba (bottom).



DOGS-OC: Equilibration and unit

Parameter estimation within the DGFI software DOGS-OC (satellite orbit perturbation method) always results in the solution of a normal equation system for the parameter corrections. A two-sided scaling of the normal equation matrix such that the diagonal elements receive the same order of magnitude, is a nearly optimal strategy to improve the condition of the matrix. Two-sided scaling corresponds to a change of unit of the parameters solved for. Over the past years, a good equilibration of the normal equation matrix was achieved by the selection of the most suitable physical units for the parameters, and the optimal units were fixed within the program

It turned out that the optimal units depend on both the measurement technique and the satellite hight. Hence the "choice of unit" had to be allowed to the user of the software. An optional input was established to prescribe for certain parameters an arbitrary scale factor which is used to scale the corresponding rows and columns of the normal equation matrix. The default of that factor transforms the parameter to the former "optimal unit". For example, Keplerian orbit angles are by default converted to seconds of arc, and unnormalized spherical harmonic coefficients are scaled to fully normalized ones.

Solution number

At the instigation of the International Laser Ranging Service (ILRS), the Domes-number was supplemented within the DOGS-OC software by a point and solution indicator. Since that solution number may be changed from one TRF solution to the next, the use of the solution number as a decisive station identifier may be a problem in the future.

Comparisons of GGOS-D and IVS-standard normal equations in SINEX format

In the GGOS-D context (in close cooperation with the VLBI group of the University of Bonn), the results from two VLBI analysis software packages, OCCAM and Calc/Solve were compared to detect systematic differences. The comparisons were carried out with station position time series and Earth orientation parameter series calculated from standard normal equations (SINEX-Files), as used for the official IVS combination (contributions are from DGFI and the NASA Goddard Space Flight Centre). In addition, the same comparisons were done with consistent time series generated after a number of effects adapted to the same models in both software packages, as used in GGOS-D (contributions from DGFI and the VLBI group of the University of Bonn, GIB).

The importance of using identical models is very well illustrated by the following results: Fig. 1.1.2 and 1.1.3 represent the differences of the computed height time series derived from the normal equations (the north components show similar effects up to 3 mm for Fortaleza). Besides the station position time series, also EOP

Fig. 1.1.2: Height time series for the station Fortaleza ,GGOS-D GIB – DGFI differences (lower panel), GSFC(IVS)–DGFI(IVS) differences (upper panel).

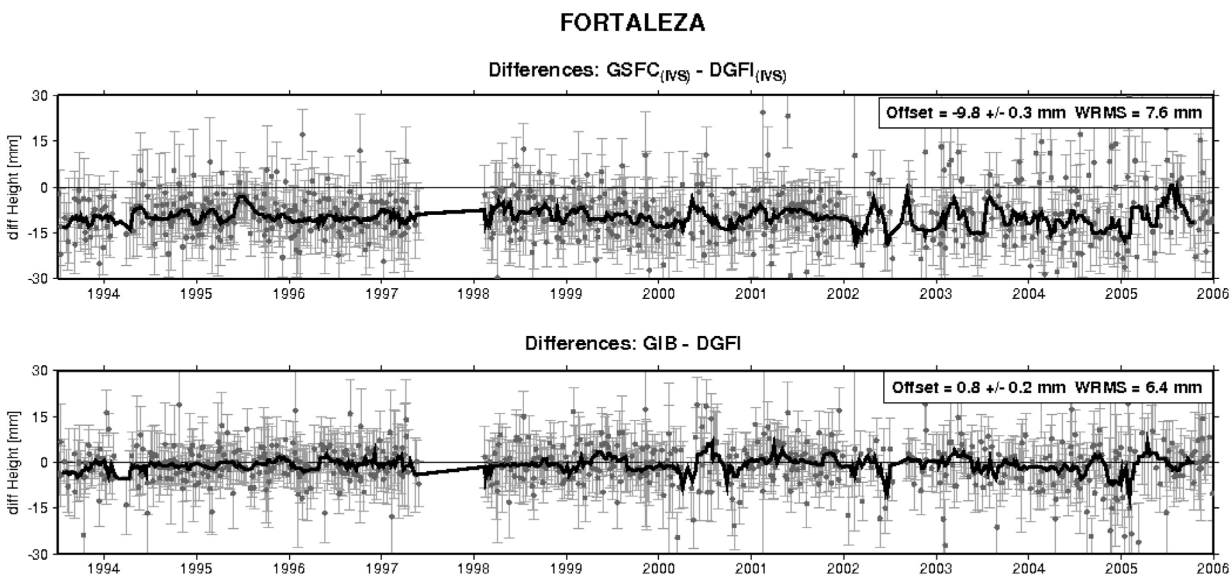
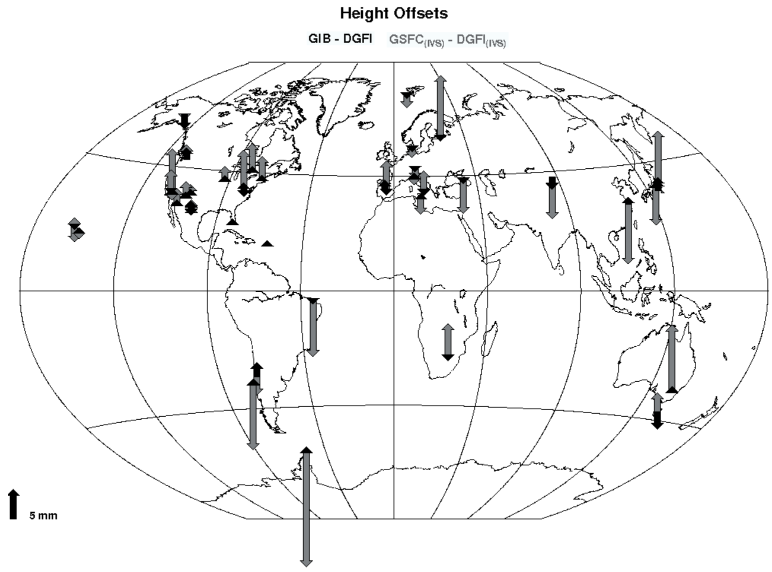


Fig. 1.1.3: Height offsets of all VLBI stations (computed as weighted mean of the position time series), GGOS-D GIB − DGFI differences in black, GSFC(IVS) − DGFI(IVS) differences in grey.



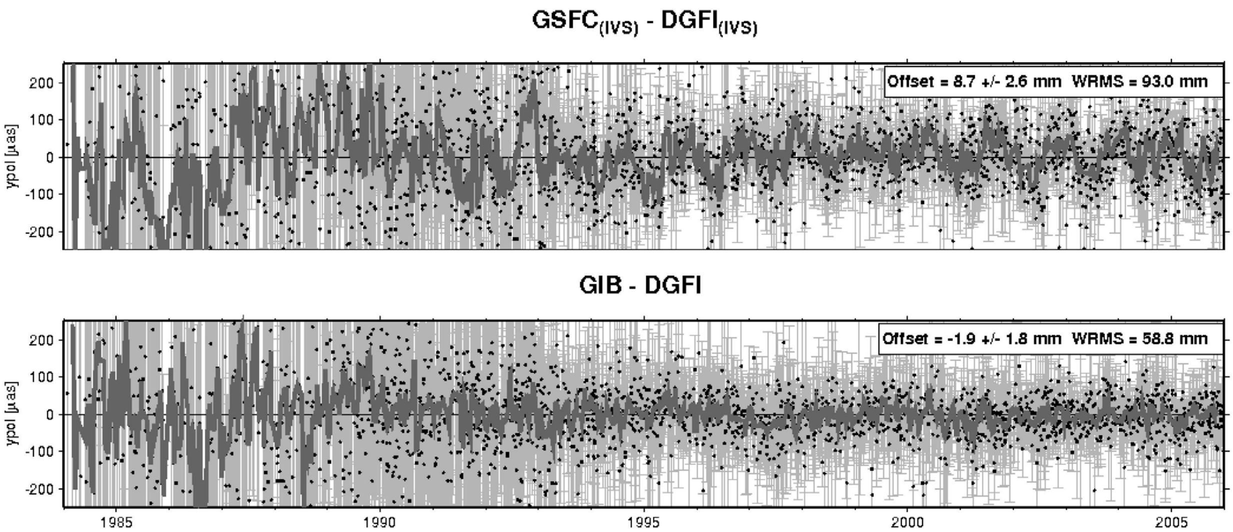
series were computed and compared (Fig. 1.1.4). The systematic differences are mainly attributed to differences in the pole tide model and the models for the effects of the troposphere.

Comparison of different models to estimate nutation and polar motion rates

VLBI is the only space geodetic technique by which nutation angles can be determined. But, as the terrestrial networks usually only consist of 5–8 stations (which is few compared to global GPS networks), its ability to determine polar motion rates is not very good. Nevertheless, in order to have a common set of Earth Orientation Parameters (EOP), it is common practice to determine the full set of EOP (dUT1 and LOD, polar motion and their rates as well as nutation offsets) for each 24-h VLBI session, like in the IVS-context. But, estimating the full set of EOP as quasi-daily parameters comes along with a mathematical correlation of the nutation offsets and the terrestrial pole rates, as illustrated in Fig. 1.1.5 (because nutation offsets are equivalent to a retrograde daily oscillation in the terrestrial frame).

Fig. 1.1.4: Y-pole GSFC(IVS) − DGFI(IVS) differences (upper panel), GGOS-D GIB − DGFI differences (lower panel).

Therefore, efforts were made to estimate nutation parameters not for each session, but for several sessions or even weeks, which



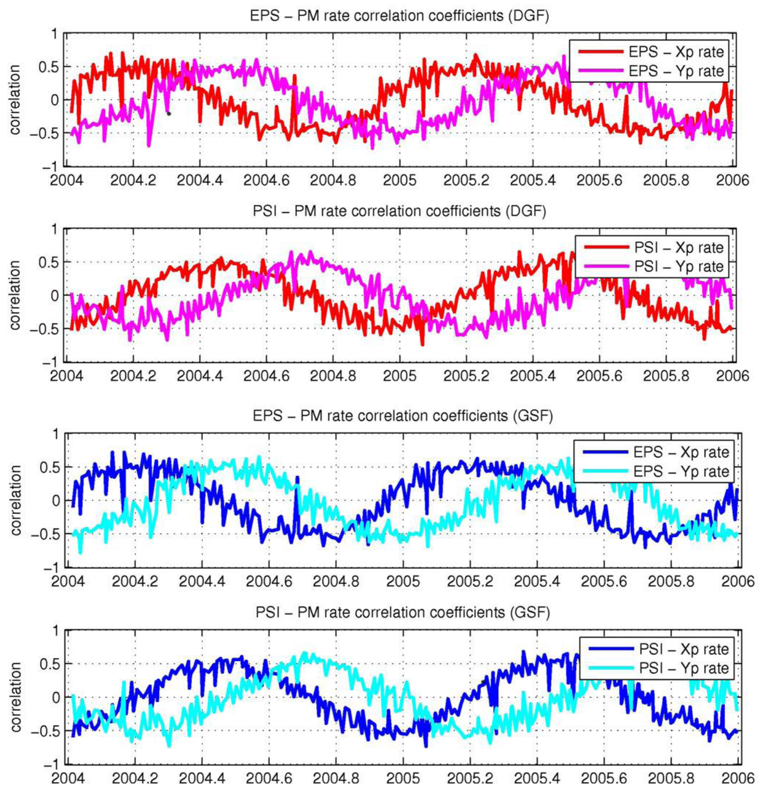


Fig. 1.1.5: Correlation coefficients between nutation offsets and terrestrial pole rates, estimated from the session SINEX files, submitted to the IVS by DGFI (upper panel) and the NASA Goddard Space Flight Centre (lower panel).

would be a considerable improvement if the deficiencies of the a priori nutation model would only consist of the free core nutation (with a period of about 432 days). This would stabilize the nutation estimates and thus lead to more stable polar motion rate estimates for each session. Preliminary results for the nutation estimates are illustrated in Fig. 1.1.6, while Fig. 1.1.7 shows a bar plot of the WRMS of the differences of session-wise dX and dY pole rate estimates with respect to the corresponding IGS parameter values.

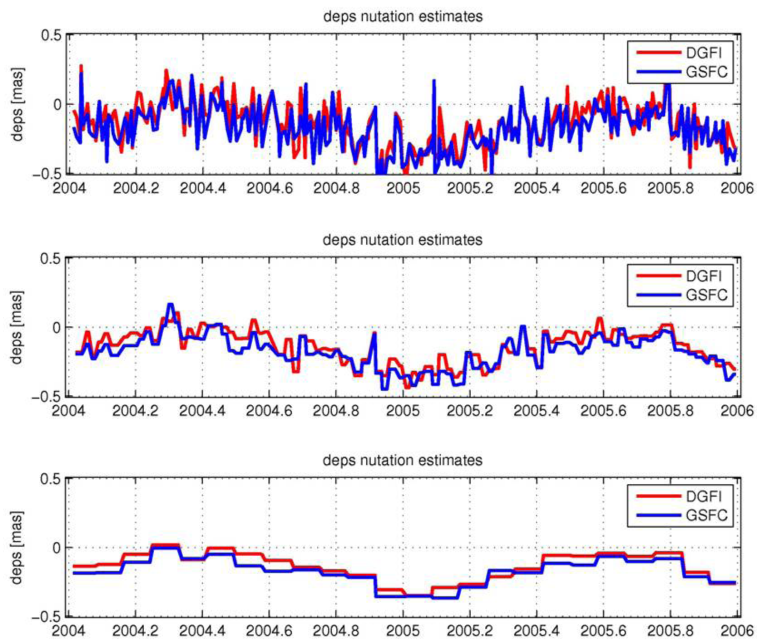


Fig. 1.1.6: Δε estimates with respect to the IAU2000A model, derived from SINEX files submitted to the IVS by DGFI (red) and GSFC (blue); The three graphs show the session-wise (upper panel), weekly (2–4 sessions, panel in the middle) and monthly (8–16 sessions, lower panel) estimates.

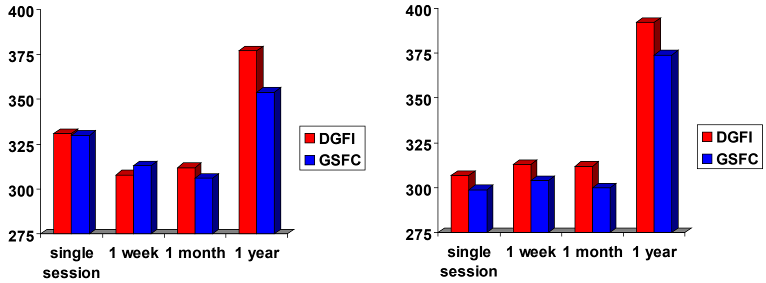


Fig. 1.1.7: WRMS [μas] of the differences of session-wise dX pole rate (left) and dY pole rate (right) estimates of the years 2004 and 2005 with respect to the corresponding IGS values; The WRMS values were computed for the approaches with session-wise, weekly and monthly nutation estimates, derived from SINEX files submitted to the IVS by DGFI (red) and GSFC (blue).

Although the results for the dX pole rate are promising, the dY pole rate estimates deteriorate by this approach. This is probably due to small shortcomings of the IAU2000A nutation model in the shorter periods, like in the 13.661 period with an amplitude of about 0.06 mas, which was found by an analysis of the session-wise nutation estimates. Therefore, before repeating these tests, further short-period correction terms with respect to the IAU2000A nutation model will be computed, using the full VLBI session series from 1984 to present in a first step, which will be optionally applied to the a priori nutation model.

1.2 Fundamentals of geometric reference systems

Investigations on the realization of the TRF origin by SLR

Satellite Laser Ranging (SLR) provides a direct and unambiguous distance measurement between space objects and terrestrial ground stations and uses the geocentre as dynamic origin for computing satellite orbits. SLR is therefore the most precise and unique observation technique to realize the origin of the terrestrial reference frame. Results derived from the SLR observations to LAGEOS showed in numerous studies that the standard deviations for the *z* component are larger by a factor of about 3 compared to the *x* and *y* components. This is consistent with theoretical considerations, as the origin in *z* is determined only by the disturbed satellite motion, whereas the origin in *x* and *y* is additionally determined by the Earth rotation.

We analysed SLR data to satellites in different altitudes to investigate the impact on the realization of the TRF origin. The results of this study show that the standard deviations for the *z* component are significantly smaller for satellites with lower altitudes (see Tab.1.2.1), which confirms the theoretical considerations. Based on these results, we suggest that for future realizations of the terrestrial reference frame also the data of satellites with lower altitudes (e.g., Starlette, Ajisai) should be included to stabilize (in particular) the *z* component of the origin (se 3.1).

Table 1.2.1: Standard deviations of the translation parameters derived from weekly SLR solutions using Laser satellites with different altitudes.

	Etalon 1	Lageos 1	Ajisai	Starlette
Altitude [km]	19105	5850	1485	815
Std.dev. Tx [mm]	12.1	1.1	0.7	0.9
Std.dev. Ty [mm]	15.8	1.0	0.7	0.8
Std.dev. Tz [mm]	61.0	2.9	1.1	1.2
Tx,y : Tz	1:4.4	1:2.8	1:1.5	1:1.4

Terrestrial reference frame from consistent data sets

ITRF2005 is the first terrestrial reference frame that was computed from weekly solutions/normal equations. This allowed to handle discontinuities properly and to investigate the influence of station position variations on the reference frame. But because the data sets were not consistent concerning their modelling, e.g. with respect to atmospheric and ocean loading, it was not possible to interpret the time-variable effects of station positions as geophysical signals.

In contrast to the ITRF, the data sets provided in the GGOS-D project (see 1.1) are fully consistent between the different techniques (SLR, VLBI and GPS), concerning their modelling and parameterization. This allows to compare the time-variable effects with results from geophysical models and to estimate additional parameters in the TRF combination such as seasonal signals.

We computed preliminary intra-technique solutions and an inter-technique solution using the same procedure as for the ITRF2005 computation. Since the time series of station positions show some clear seasonal variations, the question arises whether the reference frame can be improved by estimating an annual signal in addition to the positions and velocities. For this task we investigated the form of the seasonal variations for all stations in order to decide whether they can be approximated by a sine/cosine function (see Fig. 1.2.1 for two examples of a mean seasonal signal).

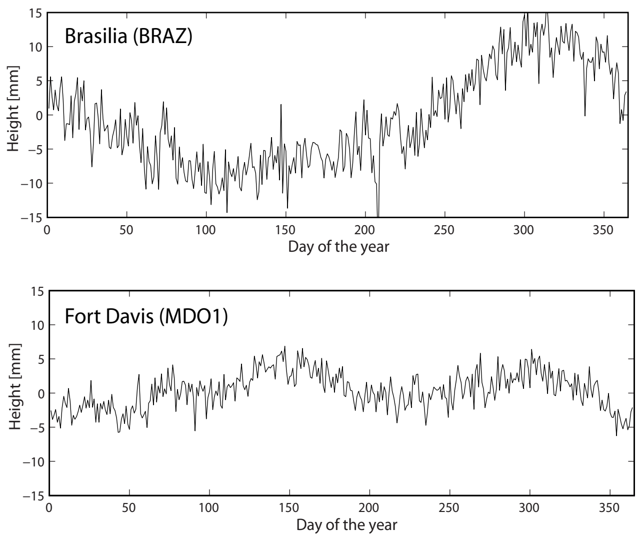


Fig. 1.2.1: Examples of a mean seasonal signal of the height component at two stations, computed from the GPS data of GFZ.

Investigations on the local ties for combining daily normal equations

The work concentrated on the combination of daily normal equations resulting from GPS and VLBI analysis. Common parameters of both space techniques are station coordinates, Earth orientation parameters (EOP) and troposphere parameters. As the observations of the two techniques do usually not refer to the same reference point, the station coordinates can only be combined by introducing terrestrial measurements, so-called local ties, which are archived and provided by the IERS. The agreement between the local ties and the coordinate differences derived from the space geodetic techniques for some stations is often relatively poor. Therefore a selection of suitable local ties is necessary to avoid a deformation of the station networks within the combination.

In daily VLBI sessions, often only a few telescopes co-located with GPS are participating. The diagram in Fig. 1.2.2a gives an overview of how many daily combinations are possible with a certain number of local ties which differ from the space geodetic techniques by less than 20 mm. The maximum number of local ties per session is 8, and for 14 % of the sessions with two or less local ties, no solution is possible. Instead of the local ties obtained by terrestrial measurements, local ties computed from a combined multi-year solution (TRF) of GPS and VLBI data can be applied. This has the advantages that local ties are available for all co-location sites and that they are consistent to the space geodetic techniques. It enables a larger number of local ties per session to be introduced into the combination of daily normal equations, as can be seen in Fig. 1.2.2b. In maximum 11 local ties per session are used, and about 7 % of the sessions cannot be solved. The number of included local ties is crucial for the stability of the combined solution. Fig. 1.2.3 shows how the stability of the terrestrial pole of VLBI depends on the number of introduced local ties, if the terrestrial pole coordinates are not combined and the no-net-rotation (NNR) datum is defined using only GPS stations.

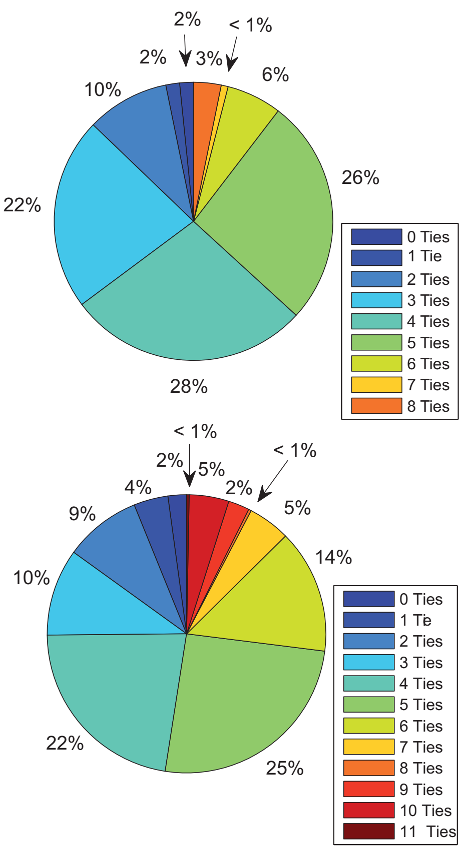


Fig. 1.2.2: Number of daily combinations (in %) with a certain number of local ties (a) using local ties derived from terrestrial measurments, (b) using local ties computed from a TRF solution. Altogether 326 sessions were investigated.

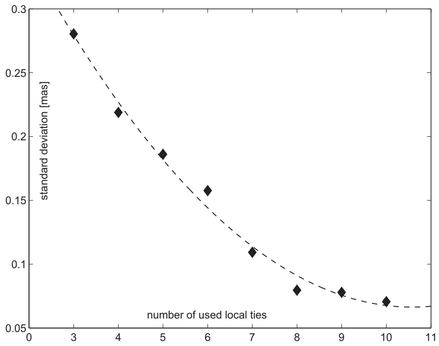


Fig. 1.2.3: The standard deviation of the x pole coordinate from VLBI as a function of the number of introduced local ties (the no-net-rotation datum being defined by GPS stations only).

A combination of the terrestrial pole values serves as an additional global tie. Hence, for sessions with only two local ties a solution can be obtained combining the pole coordinates. Thus, 97% of the daily combinations can be solved if station coordinates and EOP are combined.

Two Working Groups (WG) were established for the second realization of the ICRF (ICRF2) as a joint project of the International Astronomical Union (IAU), the International Earth Rotation and Reference Systems Service (IERS) and the International VLBI Service for Geodesy and Astrometry (IVS). The IVS Working Group for ICRF2 was set up during the IAU General Assembly 2006 in Prague. It will deal with all efforts related to the observational data. DGFI actively takes part in the IVS WG by submitting all types of results necessary in this context.

DGFI contribution to the second realization of the ICRF (ICRF2)

Presently, it is assumed that the positions of the extragalactic radio sources are constant in time. Therefore, only one position for each source is estimated from VLBI observations over the whole data span (suitable data exist since 1984). Although this assumption is sufficient for most of the sources, it is no longer suitable for all of them. This is why the first goal of the IVS WG is to identify such sources by an effort to examine time series of estimated source positions. Tests are currently done at DGFI to estimate such time series for each single session, using a NNR datum over all sources per session with respect to a CRF solution computed at DGFI.

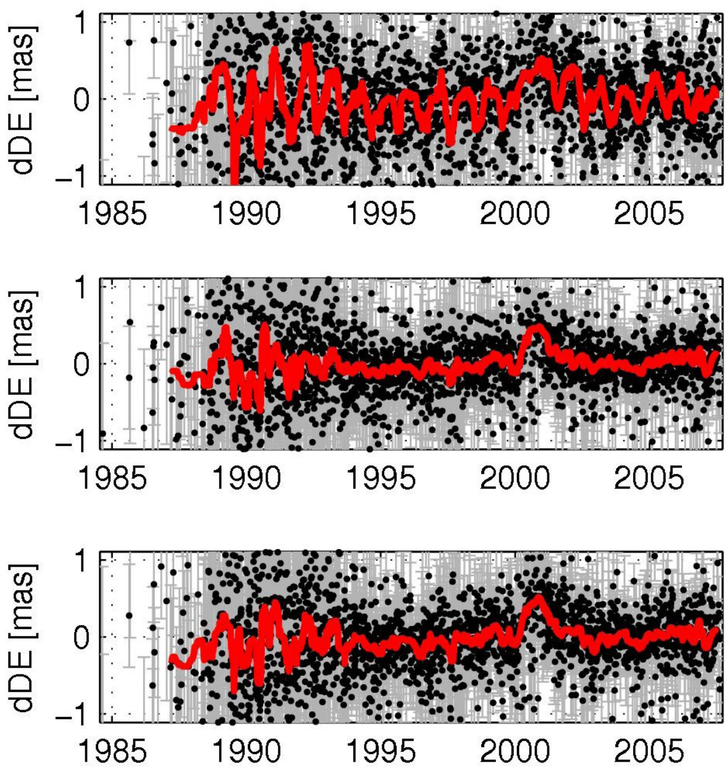


Fig. 1.2.4: Time series of declination components for the source 1741–038: positions are estimated for each session, with only NNR datum applied (upper panel); with a deformation model also estimated, which is often used in the IERS and the astrometric community (for declination: ddDE·(DE-DE0) and dz, for right ascension: ddRA·(DE-DE0), panel in the middle); estimated with NNR datum and a simpler but very effective deformation model, developed at DGFI (for declination: dz·cos(DE), lower panel). Although still under investigation, the DGFI model seems to fit the data very well.

Fig. 1.2.4 shows the time series of declination components of the source 1741-038, with only NNR conditions used in the datum equations for each single session. An annual signal can clearly be seen, which is possibly caused by atmospheric mismodelling in data analysis (this is especially the case for sources with small declinations). If some deformation parameters are estimated simultaneously (panel in the middle: 'IERS approach', lower panel: 'DGFI approach'), this signal is absorbed.

Analysis of systematic effects in CRF solutions and dependencies between CRF and TRF

In 2006, the effect of various analysis options on a VLBI-determined CRF was investigated at DGFI:

- different troposphere mapping functions and gradient models,
- choice of the data set (neglecting sessions before 1990 and 21 astrometric sessions),
- handling of sources that may not be assumed to have time-invariant positions,
- handling of the station network (estimate the station positions per session, as linear functions of time (over 20 years), or fix them to a priori values).

The biggest, clearly systematic effects in the estimated source positions up to 0.5 mas were found to be caused by different gradient models (esp. the selection of the a priori values and the constraints). The choice of the data set does generally not have a significant influence. This holds also (with several exceptions) for different options how to treat sources which are assumed to have time-invariant positions. Furthermore it turned out that fixing station positions to values not consistent to the solution itself can noticeably affect CRF solutions.

At DGFI, a VLBI solution was computed, in which a TRF, a CRF and EOP were simultaneously estimated with a non-biased NNR and NNT datum for the CRF. Using such minimum datum conditions, biases can be avoided which are due to fixed reference frames or other relevant parameters of the observation equations. With such a solution, dependencies between VLBI determined CRF and TRF can be studied very clearly. The most important results are: (1) There are generally dependencies of TRF and CRF because of models with 'geometric meaning' in CRF and TRF domain (e.g. gradient modelling). (2) There are dependencies of single objects because of an insufficiently redundant observation geometry, which can have two reasons: (2a) Stations can be isolated from the rest of the network, like the stations on the southern hemisphere (e.g. O'Higgins, Antarctica or Hobart, Australia) or the stations in Japan; (2b) Some satations and/or sources were not included in sufficiently varying network arrangements, (like Haystack, USA or Crimea, Ukraine). (3) There are stations which observed in too few sessions (like Kwajalein Atoll, USA).

Transformation between ICRS and ITRS

The transformation between the space-fixed reference system ICRS and the Earth-fixed system ITRS includes traditionally two intermediate systems, the celestial and terrestrial intermediate systems, the common third axis of which is the celestial intermediate pole (CIP, formerly celestial ephemeris pole). The first axis of the celestial intermediate system in the equator is now the "celesital intermediate origin" (until 2006 "celestial ephemeris origin"), which was substituted in 2003 for the vernal equinox. At a reference epoch it coincides with the (true) equinox. Its subsequent position is determined by the condition that its motion relative to an inertial system has no component along the equator, and thus the rotation vector of the celestial intermediate system has no component about its third axis.

The precession and nutation matrix **Q** transforming from the ICRS to the celestial intermediate system has in the parametrization of the IERS Conventions (2003) the representation

$$\mathbf{Q} = \mathbf{R}_3(s)\,\mathbf{Q}' \quad \text{with} \quad \mathbf{Q}' = \mathbf{R}_3(-E)\,\mathbf{R}_2(d)\,\mathbf{R}_3(E).$$

E, d are the longitude and the orthogonal complement of the latitude of the CIP with respect to the ICRS. The matrix **Q**' is represented by the Cartesian coordinates *X, Y* of the CIP, for which Poisson series are given. The IERS Conventions (2003) give as well a Poisson series for the small angle *s*, by which the first axis is turned within the true equator into the celestial intermediate origin. (A Poisson series is a combination of Fourier and power series, in which the individual terms are products of powers and trigonometric functions of time with different periods.)

Alternatively following the traditional way, the matrix **Q**' can be replaced by the product of the precession matrix **P** and the nutation matrix **N**, which transforms from the ICRS to the true equator system with the first axis in the true vernal equinox. Then the angle *s* of the rotation which has to be carried out afterwards around the third axis is the angle between the true equinox and the celestial intermediate origin. This angle is the integral of the third coordinate of the rotation vector of the true equator system. While the secularly changing parameters of the precession matrix **P** are pure power series of time and the periodically changing parameters of the nutation matrix **N** are pure Fourier series (in a generalized sense) of time, the angle *s*, as a result of matrix multiplication, differentiation and integration, is a rather complex Poisson series.

The necessary analytical deviations and numerical computations were continued.

1.3 Fundamentals of physical parameter determination

Recent activities in topic 1.3 deal with the estimation of the geopotential V from GRACE data. An appropriate procedure requires the involvement of the highly-precise KBR (K-band range, range rate) measurements between the two GRACE satellites, i.e. the low-low inter-satellite measurements SST.

Integral equation approach

We decided to develop a method based on the integral equation approach as proposed and applied by Mayer-Gürr et al. (J Geod, 78, 2005). The observation equations for the range ρ and the range rate $\dot{\rho}$ are given as

$$\rho + v = (\boldsymbol{x}_1 - \boldsymbol{x}_2)^T \boldsymbol{e}_{12}. \tag{1}$$

and

$$\dot{\rho} + v = \dot{\boldsymbol{x}}_{12}^T \boldsymbol{e}_{12}. \tag{2}$$

$\boldsymbol{x}_1, \boldsymbol{x}_2, \dot{\boldsymbol{x}}_1, \dot{\boldsymbol{x}}_2$ are the position vectors and the velocities of the two GRACE satellites in an inertial system; furthermore, $\boldsymbol{e}_{12}$ means the line-of-sight unit vector and $\dot{\boldsymbol{x}}_{12} = \dot{\boldsymbol{x}}_1 - \dot{\boldsymbol{x}}_2$ is the relative velocity. *Fredholm's integral solution* of Newton's equation of motion $\ddot{\boldsymbol{x}}(t) = \boldsymbol{b}(t; \boldsymbol{x}, \dot{\boldsymbol{x}}, V(\boldsymbol{x},t), \boldsymbol{f}, ...)$ reads

$$\begin{aligned} \boldsymbol{x}(\tau) &= (1-\tau)\boldsymbol{x}(t_A) + \tau\,\boldsymbol{x}(t_B) \\ &\quad - T^2 \int_0^1 K(\tau,\tau')\,b(\tau'; \boldsymbol{x}, \dot{\boldsymbol{x}}, V(\boldsymbol{x},\tau'), \boldsymbol{f}, ...)\,d\tau' \end{aligned} \tag{3}$$

with $\tau = (t-t_A)/T$ being the normalized time variable, $T = t_B - t_A$ is the total time span of an arc between the times t_A and t_B. The kernel $K(\tau, \tau')$ is defined as

$$K(\tau,\tau') = \begin{cases} \tau(1-\tau') & \text{if } \tau \le \tau' \\ \tau'(1-\tau) & \text{if } \tau' \le \tau \end{cases} ; \tag{4}$$

$\boldsymbol{f}$ is the vector of the non-conservative accelerations. The solution (3) has to be introduced into the observation equations (1) and (2) for the position vectors $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ of the two GRACE satellites. Our objective is the estimation of the boundary position vectors $\boldsymbol{x}(t_A)$ and $\boldsymbol{x}(t_B)$ as well as the parameters describing the geopotential $V(\boldsymbol{x},t)$.

Matrix representation of the integral along the arc

If we assume that the total number of equally spaced observations within an arc is given as N the integral expression in Eq. (3) reads

$$\boldsymbol{h}(\tau_i) = T^2 \int_0^1 K(\tau_i,\tau')\,\boldsymbol{b}(\tau'; \boldsymbol{x}, \dot{\boldsymbol{x}}, V(\boldsymbol{x},\tau'), \boldsymbol{f}, ...)\,d\tau' \tag{5}$$

for $i = 1,..., N$. Expanding the acceleration vector $\boldsymbol{b}$ into a polynomial and collecting the elements $h_j(\tau_i)$ with $j = 1,2,3$ in a vector $\mathbf{h}_j = [h_j(t_1), ..., h_j(t_N)]^T$, Eq. (5) can be rewritten as

$$\boldsymbol{h}_j = \boldsymbol{K}\boldsymbol{b}_j, \tag{6}$$

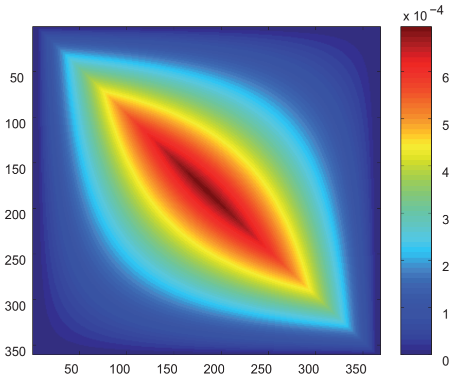


*Fig. 1.3.1: Absolute values of the elements of the matrix **K**. The maximum value of each row/column appears along the diagonal; the absolute maximum is at the centre of the matrix, i.e., at the centre of the arc.*

i.e., the convolution is transferred to a matrix multiplication. If we further assume an observation sampling rate of 5 seconds, an arc length of 30 minutes and a polynomial of degree 8, the matrix ***K*** is of size 360 x 360 as shown in Fig. 1.3.1.

The procedure described before was tested with simulated data sets. We used three kinds of observations for the gravity field reconstruction, namely (1) error-free range observations, (2) error-free range-rate observations and (3) range-rate observations considering orbit errors (the absolute orbit error is set to 3 cm, the relative orbit error to 1 mm). We estimated spherical harmonic coefficients of the geopotential up to degree 70. Fig. 1.3.2 shows the results for geoid heights estimated from the second observation type. Based on the results from the different observation types we notice that

1. the geoid errors from error-free range and range-rate observation are ±1.34 mm and ±0.50 mm (Fig. 1.3.2), respectively (it seems that better results can be obtained with the range-rate observation type),

2. there are some systematic differences between the results of the orbit integrator and from the matrix ***K***; this could be the reason why the geoid error of error free case is not very small,

3. from the geometrical point of view, the arc length should not be longer than 30 min, otherwise the approximation of the orbit due to Eq. (6) is too inaccurate,

4. further investigations are necessary for the integral equation approach, especially for the non-error-free case.

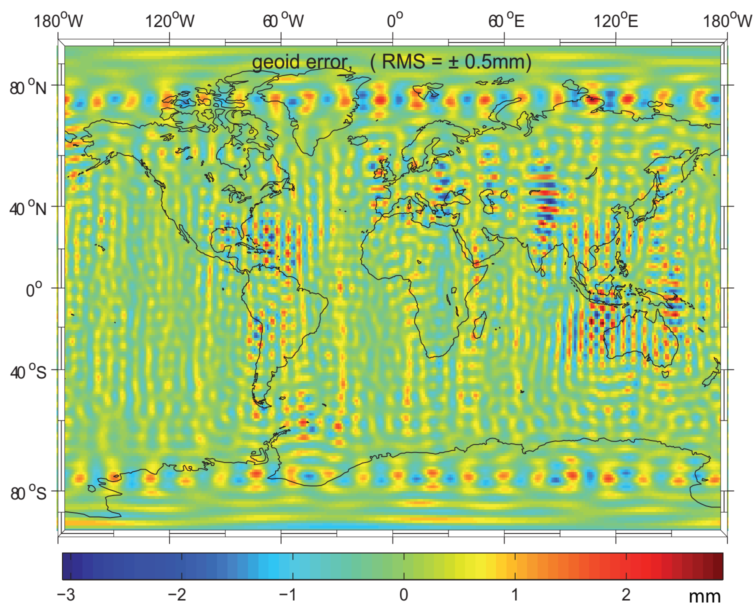


Fig. 1.3.2: Geoid error of the gravity field up to degree 70 estimated from simulated error-free range-rate measurements.

Sea surface height profiles for a highly resolving marine gravity field

Encouraging results were achieved for the modelling of highly resolving gravity fields by using sea surface height profiles from TOPEX and ERS-2 satellite altimetry in combination with gravimetric data from GRACE. The novel approach is based on the fact that the sea surface is – in the first order – in balance with gravity and nearly coinciding with an equipotential surface of the Earth gravity field. Consequently, the potential differences between two points of a sea surface height profile are very close to zero. The deviations between equipotential surface and sea surface, known as mean dynamic topography (MDT) are in the order of ±1–2 metres. From the geostrophic approximation and the mean surface velocity of water it can be concluded that also the slope of the MDT is rather small. Thus the MDT has smooth, large-scale signatures. It is therefore justified to account for the slowly varying offset between the mean sea surface and an equipotential surface by a low-degree polynomial set up for limited lengths of the altimeter profiles. In the present approach polynomials of degree 5 are used to account for the along-track potential residuals due to MDT.

The approach was applied in two test areas in the South Atlantic which are shown in Fig. 1.3.3. with their bathymetry and the satellite ground tracks. Long period averages of TOPEX and ERS-2 data were computed after a careful harmonization and cross-calibration. The successive mean sea surface heights constitute altimeter profiles along the nominal ground tracks with a spacing of around 7 km. The cross-track spacing is much higher (at the equator about 80 km for ERS-2 and 311 km for TOPEX) and can be seen in Fig. 1.3.3. For the sequence of profile points observation equations were set up with (“observed”) zero potential differences and the low-degree polynomials to account for the MDT.

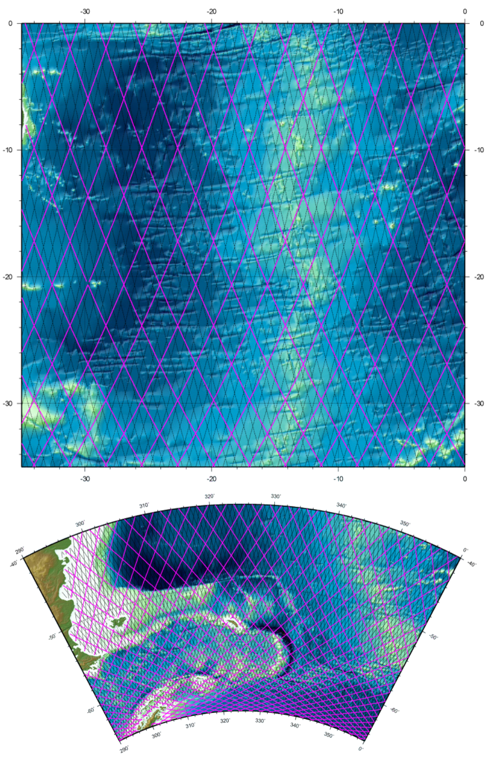


Fig. 1.3.3: The two test areas in the South Atlantic for modelling a detailed gravity field by using sea surface height profiles from satellite altimetry. The first test area (on top) is below the equator and includes the Mid-Atlantic ridge. The second area (bottom) is characterized by the South Sandwich Trench. Ground tracks of TOPEX are shown in red, those from ERS are shown in black.

The GRACE normal equations initially set up for a spherical harmonic series up to degree and order $N = 160$ were extended by spherical spline functions allowing for a regional improvement of the marine gravity field. The spline functions were located on a uniform grid with a spacing of about 37 km, corresponding to a sphercial harmonic degree of $N = 540$.

The normals of altimetry and GRACE observations were accumulated and solved for the parameters of the marine gravity field and the coefficients of the MDT polynomials. To validate the result the regional gravity field solutions were compared with

- a GRACE-only solution (IGG Bonn), already available in terms of a global spherical harmonic series (up to $N = 160$)
- independent data from a high resolution geoid model (EIGEN-GL04c, up to $N = 360$) and
- marine gravity anomalies (Sandwell & Smith, Version 15.1 available on a 2’×2’ grid).

Fig. 1.3.4 summarizes the comparison for the gravity anomalies. The altimetry data did not only stabilize the GRACE-only solution (the striping disappeared), but also led to a dramatic increase in spatial resolution. The anomalies of Mid-Atlantic ridge and the South Sandwich Trench become clearly visible. Geoid

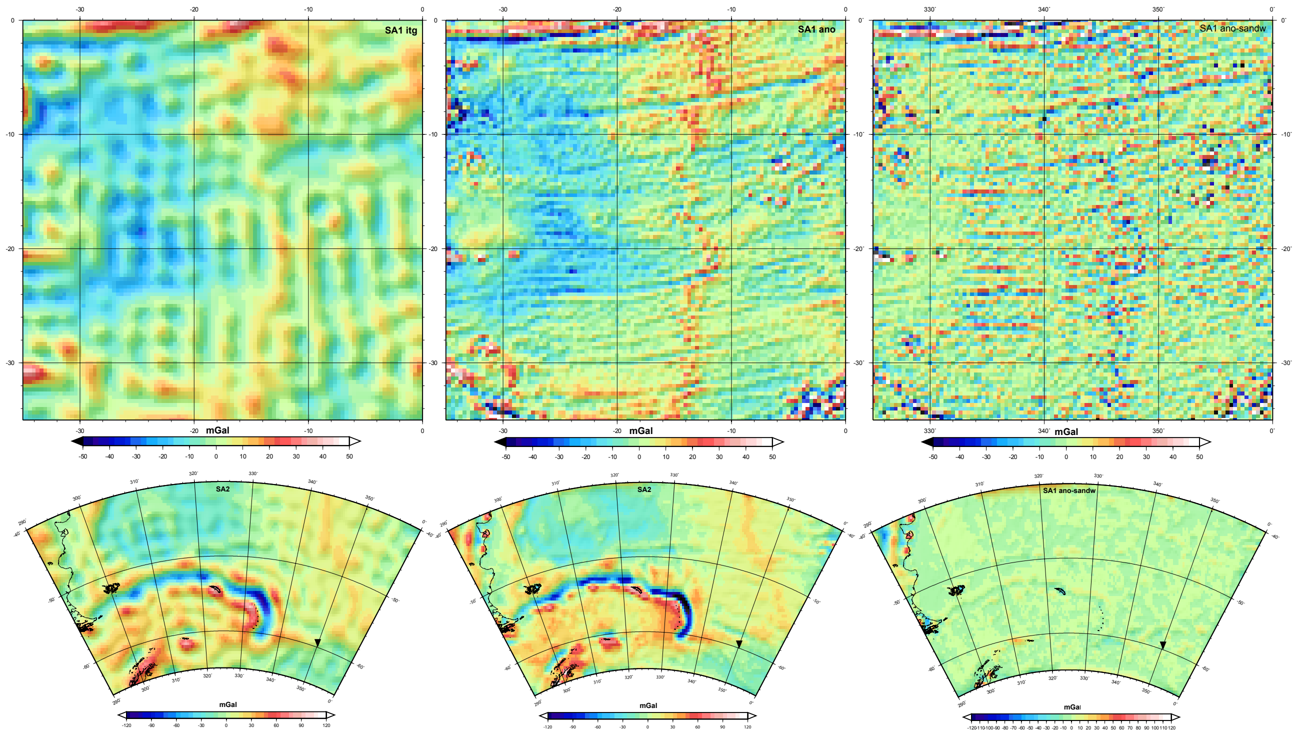


Fig. 1.3.4: Left: gravity anomalies of the GRACE-only solution of IGG. In particular area SA1 (top) shows the well-known meridional artifacts of GRACE gravity fields. Centre: gravity anomalies of the solution combining GRACE and Altimetry. The altimetry data did not only stabilize the GRACE-only solution (the striping disappeared), but also led to a dramatic increase in spatial resolution. The combined GRACE+Alti gravity field exhibits many details of the geophysical structure correlated with the ocean bottom topography. Right: Gravity anomaly differences versus the Sandwell & Smith marine gravity data, V. 15.1 (averaged to 1/3° grid).

height differences with respect to EIGEN-GL04c show an excellent agreement with RMS-values of ±0.14 m (for the northern test area) and ±0.44 m (for southern test area). The new combination approach recovers not only the high resolution geoid, but gives also reasonable estimates of the MDT. For the southern test area Fig. 1.3.5 confronts an oceanographic estimate of the MDT with the values of the polynomials used to accomodate the deviations between sea surface and equipotential surface (expressed in metre units).

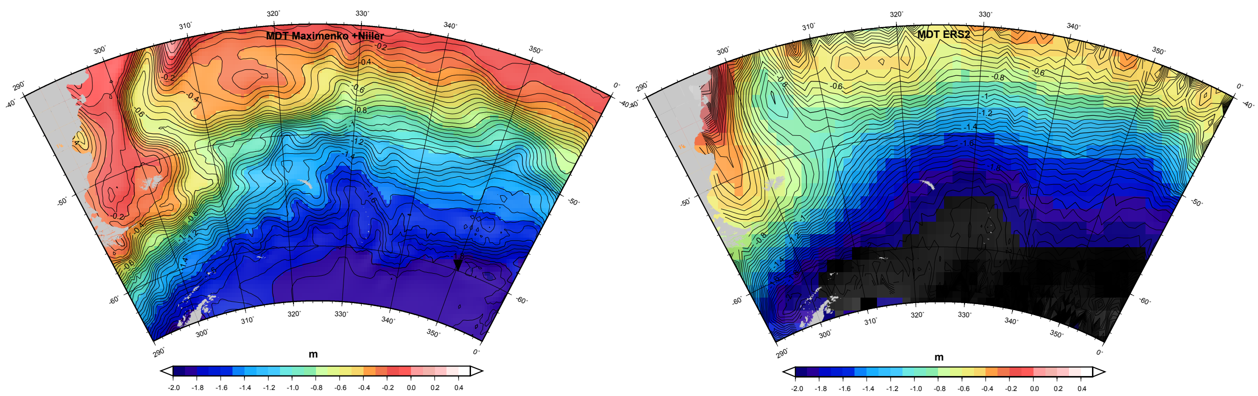


Fig. 1.3.5: Mean Dynamic Topography (MDT) for the southern test area, dominated by the Antarctic Circumpolar Current (ACC) with strong West-East surface flow (along the contour lines). Left hand, an oceanographic MDT of Maximenko et al. (2003). On the right the values of the polynomials estimated to account for the potential differences between sea surface and equipotential surface (expressed in metre units). The structure of both estimates is quite similar, but the mean on the right is about 0.4 m lower.

1.4 Combination of geometric and gravimetric observations

The objective of the combination of geometric and gravimetric observations is the consistent determination of time-dependent parameters of the rotation, the shape and the gravity field of the Earth within a global geometric and gravimetric reference frame. The overall intention is to obtain a higher and more accurate resolution of the solved-for parameters defining the geometric and physical reference frames in time and space.

In two research fields, intensive investigations started: An analysis of models and parameters which have to be considered to reach higher accuracy and consistency in the modelling, and the development of tools for the automatic processing.

Parameter sensitivity of gravimetric, altimetric and geophysical observations

Up to now, polar motion has been modelled only from changes in Earth geometry. In more rigorous Earth rotation analyses, global mass redistributions and motions have to be considered as estimation parameters which can be obtained from gravimetric, altimetric and geophysical observations. Therefore it was tested how accurate individual contributions of polar motion can be determined from known mass displacements and movements within and between the following subsystems of the Earth: atmosphere, ocean and continental water. Currently, modern geometric observation techniques such as VLBI, SLR and GPS allow to specify polar motion with a precision at the level of a few millimetres. This accuracy cannot be reached by gravimetric, altimetric and geophysical observation techniques up to now. Special priority in recent interdisciplinary research is focussed on the identification of atmospheric, oceanic, hydrological and solid mass redistributions, which shall lead to a consistent modelling.

Parameter space extension when modelling LEO satellite observations

Future works shall focus on the combination of all relevant geodetic observations and parameters into one consistent estimation procedure. Geometric observations (SLR, GNSS, VLBI), satellite altimetry, and satellite gravity mission data (such as GRACE) are the input for a simultaneous least-squares adjustment of point positions, Earth orientation, sea surface, and gravity field parameters. Since the integral signals of mass variations observed by GRACE result from regional effects such as ocean variability, variations in continental water storage or seasonal snow cover, regional signal representations come into question. Thus, besides the spherical harmonic (SH) representation, we also rely on approaches which allow the representation of spatio-temporal data in a multi-dimensional space spanned by base functions either directly derived from the data or locally supported within the region where a specific effect occurs, e.g. the oceans. Consequently, the parameter space has to be extended by SH coefficients and / or the coefficients of the regional representation.

Parameter space extension for modelling the vertical reference frame

The precise modelling of the Earth's gravity field is based on the combination of gravimetric terrestrial (including marine and aerial) data and satellite derived global geopotential models. However, the adequate integration of these two kinds of data requires additional parameters to fix the biases caused by the vertical datum inconsistencies in the terrestrial data, i.e. a global vertical datum unification has to be achieved. Therefore, besides gravity acceleration, deflections of the vertical, and geopotential differences, the mixed formulation of the so-called geodetic gravity boundary problem (GBVP) requires the introduction of the ellipsoidal height *h*. This height is determined, in the frame of the geometrical terrestrial reference system, on the sea surface by satellite radar altimetry and on land by GNSS positioning. The solution of the GBVP under this formulation allows the determination of a global equipotential surface with a specific W_0 value as well as the potential differences $\delta W_j = W_0^j - W_0$ of the individual local vertical datums W_0^j with respect to the global one.

Geodetic boundary value problem for W_0 determination

The introduction of a W_0 value either for a local vertical datum or a global one has been considered until now as irrelevant because the reference level for the measured potential differences can be arbitrarily defined, and the direct determination of an absolute W_0 by observational data is not possible. However, similarly to the geometrical reference system (where coordinates are not directly measurable, but time intervals, distances, and angles), absolute geopotential values can be precisely estimated by introducing adequate constraints. These constraints (mainly the vanishing of the gravitational potential *V* at infinity) are only reliable in the frame GBVP; hence, the determination of a suitable W_0 is exclusively feasible by solving the GBVP. Accordingly, the vertical datum problem is faced by considering the GBVP in two ways:

Global W_0 value

a) The so-called fixed gravimetric GBVP (determination of potential values from the known geometry of the boundary surface and the gravity disturbances as a specific boundary condition) is applied in ocean areas to estimate the geopotential value of the level surface that best approximates the mean sea surface. This value is appointed as the global reference level W_0.

Local W_0 value

b) The local reference levels W_0^j in land areas are estimated by solving the scalar-free GBVP (determination of the boundary surface geometry from the relative gravity boundary conditions). Since the observational data (gravity anomalies, potential differences, deflections of the vertical, etc.) included in the boundary conditions refer to different vertical datums, we obtain as many values W_0^j as height systems (*j*) exist. In this case, the solution of the GBVP in all datum zones shall follow Molodenski's approach; otherwise, uncertainties in the required assumptions for the classical solution (the geoid determination) can be misinterpreted as vertical datum inconsistencies. Once the quasigeoid is properly determined, it can be transformed into a geoid by introducing the desired hypothesis.

Height datum unification

The relationship of each local reference level W_0^j with the global W_0 value can then be established through vertical datum unification strategies. Since a main requirement of a modern vertical reference system is the precise combination of geometrical heights (i.e. ellipsoidal heights *h*) with physical heights (i.e. normal H^N or orthometric heights H^O and height anomalies ζ or geoid undulations *N*), in other words to satisfy $h = H^N + \zeta$ (or $h = H^O + N$) in a global frame, a fundamental constraint for the empirical determination of the δW_j terms is given by

$$\gamma_p h_p - (W_0^j - W_p^j) - T_p^j - 2 \cdot \delta W_j = 0$$

Here, $\delta W_j = W_0^j - W_0$ represents the individual vertical datum discrepancies with respect to W_0, $(W_0^j - W_p^j)$ is the geopotential number of the evaluation point P referred to the individual level W_0^j; T_p^j is the anomalous potential of P; γ_p is the normal gravity of P at the Earth's surface; and h_p is the ellipsoidal height.

Combination of geometrical and physical heights

The evaluation of this equation shall be carried out in three approaches:

a) Coastal approach: at the fundamental points (tide gauges) of the classical height systems. In this case, the ellipsoidal height is provided by GNSS positioning, the geopotential number is zero for the reference tide gauge and near zero for other included tide gauges. The geopotential numbers and the anomalous potential refer to the level W_0^j.

b) Oceanic approach: in the marine areas close to the tide gauges. Here, the ellipsoidal heights are given by the satellite altimetry in combination with tide gauge registrations. The anomalous potential refers to the local level, and the geopotential numbers correspond to the SSTop multiplied by the normal gravity γ_p. The SSTop should refer to the global geoid W_0.

c) Terrestrial approach: at fiducial stations of the geometrical reference frame (ITRF or its densifications). At these points, the ellipsoidal heights are obtained from GNSS positioning and the geopotential numbers are derived from spirit levelling combined with gravity reductions. These geopotential numbers and the anomalous potential refer then to the local level W_0^j.

A variation of this approach takes place at connection points between two classical height systems. There the geopotential numbers and the anomalous potential refer to the two neighbouring vertical datums (i. e. W_0^j, W_0^{j+1}), so that the discrepancy between them is represented by $\delta W_{j,j+1}$, see Fig. 1.4.1.

As an example, Tab. 1.4.1 shows the datum discrepancies δW calculated at the main tide gauges of Colombia following the coastal and oceanic approaches. They are computed with respect to W_0 = 62 636 853.11 m^2/s^2 and by applying three different gravity models for the local solution of the GBVP. The potential differences are divided by the respective normal gravity values to express the results in lenght units; i.e. $\delta H = \delta W/\gamma$.

According to the above, the realization of the global vertical reference system shall be given by a set of very good materialized (reproducible) benchmarks (reference stations), including the reference tide gauges of the classical height datums and the connection points between neighbouring vertical networks. These points

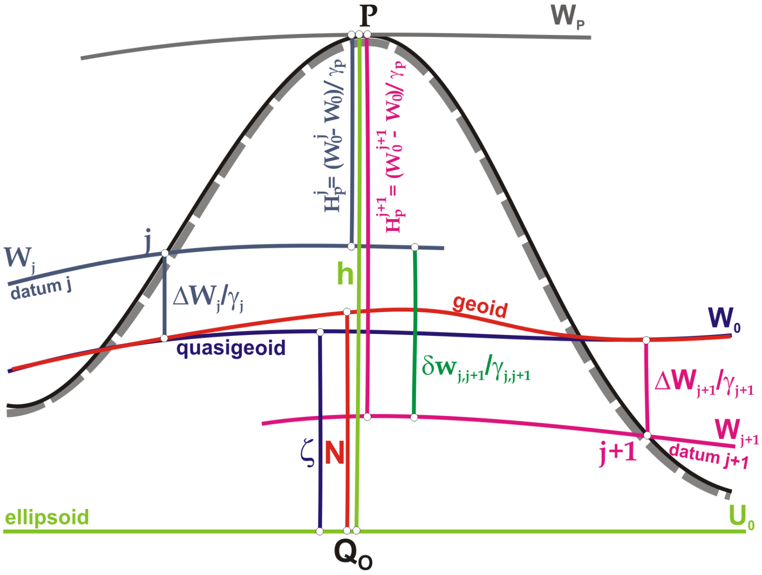


Fig. 1.4.1: Relationship between classical height datums and a global vertical reference system.

Tab.1.4.1: Vertical datum discrepancies at the main tide gauges of Colombia estimated following the coastal and oceanic approaches for the vertical datum unification.

		δH = δW/γ [cm]			
Quasigeoid	**Approach**	**TUMA**	**BTUR**	**CART**	**Average**
EGM96	Coast	76	-46	15	15 ± 61
	Ocean	67	-38	1	10 ± 53
EIGEN-CG03C	Coast	53	-55	18	5 ± 55
	Ocean	40	-44	26	7 ± 45
Local quasigeoid	Coast	-21	-28	-26	-25 ± 4
	Ocean	-25	-33	-23	-27 ± 5

shall be referred to the ITRF, and their geopotential numbers and anomalous potential values must be known. In order to keep the consistency world-wide, the processing of the vertical data has to be carried out in terms of potential quantities; once the vertical networks are appropriately adjusted, each country can introduce the desired physical heights (orthometric or normal heights). In the same way, the anomalous potential shall be determined by applying the Molodenski solution, and then, if it is wanted, the height anomalies can be transformed into geoid undulations.

Towards automatic processing

Another research field of topic 1.4 comprises the development of combination methods for automatic processing. The tendency of shortening the processing intervals cannot be overseen. E.g. ILRS recently recommended the processing and combination of SLR data on a daily basis besides weekly ones. Hence, tools for automatic processing are of urgent interest.

Outlier tools for automatic processing

The variance component estimation (VCE) within the SLR weekly intra-technique combination revealed to be a reliable tool for automatic weighting and outlier analysis of the input solutions. Investigations on this combination strategy were extended to the weekly multi-technique combination and the weekly intra-technique processing including the estimation of lower degree harmonic coefficients.

Weekly multi-technique combination

The processing flow of the weekly multi-technique combination as developed so far is presented in Fig. 1.4.2.

The IAG Technique Services IDS, IGS, and ILRS weekly deliver combined DORIS, GPS, and SLR solutions, whereas IVS computes daily session solutions within the current week. The solved-for parameters comprise weekly position coordinates and daily EOP with their rates. They are given in SINEX format, (box 1 in Fig. 1.4.2. For the a-priori values, the solution of an actual TRF is taken for position and EOP, and in case of prediction, IERS EOP values (2). IERS delivers local tie solutions for the position coordinates of co-location sites, given in SINEX format (3).

After having taken over the individual solution parameters in an internal format (4), the reference coordinates are transformed to the actual epoch of the week (5) taking the necessary information from (4). Identical a-priori parameters are taken over for all individual solutions (6) by using (5). After having selected those local tie files and actual stations per site which are required for the current week as given in (4) and transformed into internal format (7), identical a priori position values are included (8) by using the knowledge of (6).

In (9) a list of core stations is given which are applied for the estimation with internal minimal constraints. Internal minimal constraints are used for unconstrained normal equation systems of individual or local tie solutions. In case of overconstrained solutions external minimal constraints are taken for all position coordinates of that solution. It means that those transformation parameters are included into the estimation process which are required to obtain a minimally constrained solution.

It follows the selection of the core stations for the actual week (10) with the knowledge of (6). It is now possible to compute a weekly VLBI solution with internal minimal constraints from the daily solution within that week (11). In order to create a reasonable basis

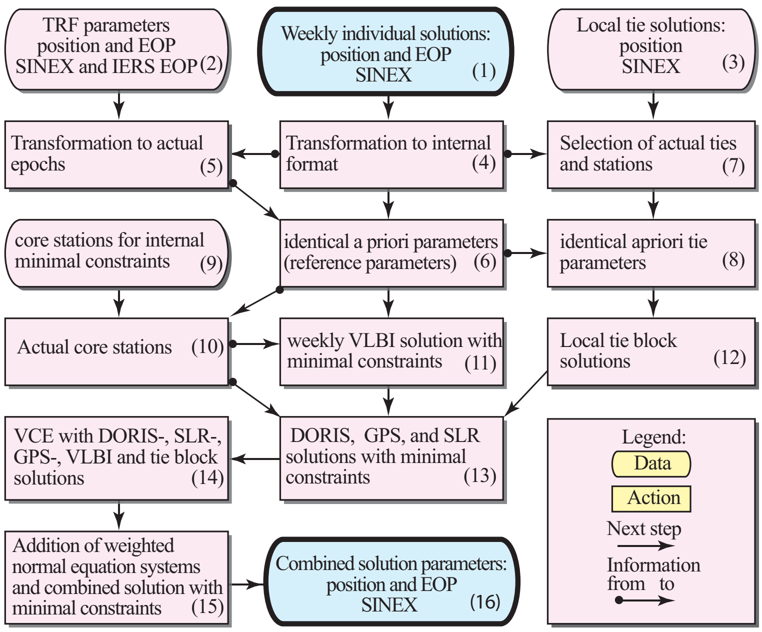


Fig. 1.4.2: Processing flow of the weekly multi-technique combination.

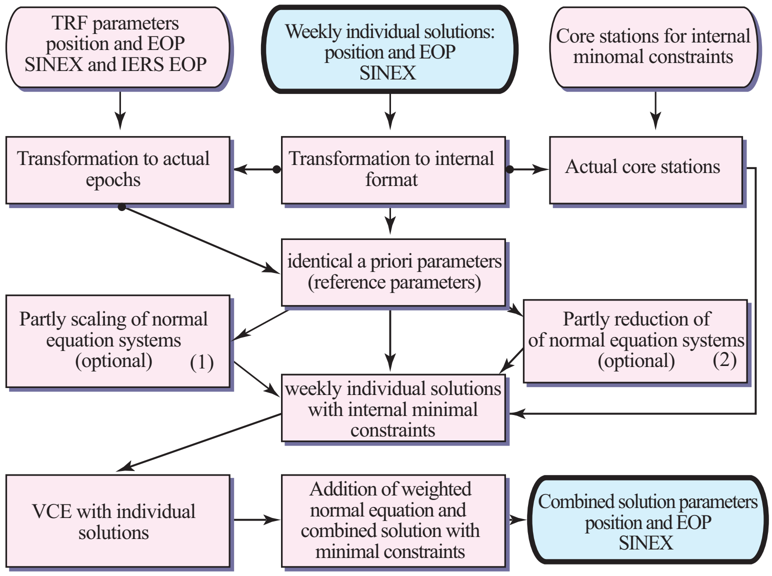


Fig. 1.4.3: Processing flow of the weekly intra-technique combination (SLR).

for the variance component estimation (VCE) later on, the local tie files are comprised to blocks which differ from each other with respect to. the a prori accuracy level. The tie blocks are solved for with external minimal constraints (12). It follows the computation of DORIS and GPS solutions with external minimal constraints, and of SLR solutions with internal minimal constraints (13).

The main estimation part is the VCE (14) of DORIS, GPS, SLR (13), VLBI weekly solutions (11) and tie block solutions (12). The results are used for the weighting of all solutions and for the outlier search and remedy. The additon of all weighted normal eqution systems leads to the combined solution with minimal constraints (15) which is stored in SINEX format (16).

This weekly multi-technique combination process is tested up to action (11). The local tie handling (12) is still under investigation. One of the problems here is the correct modelling of the covariance matrix of the local tie coordinates given.

Weekly intra-technique combination (SLR) with lower degree harmonic coefficients

The processing flow in Fig. 1.4.3 is self-explaning after having read the explainations to Fig. 1.4.2. Additionally, the intra-technique SLR processing is easier to handle, because the problems with local ties and external minimal constraints are dropped. Only the optional actions of partly scaling and partly reducing normal equation systems (boxes 1 and 2 in Fig. 1.4.3) are new features.

Up to now, SLR individual solutions with harmonic coefficients up to degree and order 2 of only one analysis centre are available within the GGOS-D project. In order to combine these solutions with SLR solutions without harmonic coefficient parameters, the optional actions of scaling the harmonic coefficient part of solution (1) and then of reducing this part from solution (2) are applied. Then the VCE combination with the solution having no harmonic parameters was successful. Nevertheless, further investigations are required.

2 Earth System Analysis

The processes of the system Earth are in general described by mathematical and physical models. Today, an increasing number of parameters used to characterize state and temporal evolution of these processes become measurable through observations of precise geodetic space techniques. The present research field "system analysis" shall investigate the interrelationship between geodetic observations and model parameters. The thorough analysis of parameters – most rigorously estimated by combining different geodetic space techniques – promises to overcome the weakness of individual observation approaches as, for example, low sensitivity or insufficient sampling rates. Moreover, system analysis can help to improve the signal-to-noise ratio, to identify model deficiencies, and to introduce novel or extended parameterization with the final goal to obtain a more precise description of processes of the system Earth.

This research field is divided into four topics. The first one focuses on new methods to model the gravity field or the ionosphere by different base functions (wavelets, splines or empirical orthogonal functions) which allow to describe also the temporal variations of these fields. Topic 2.2 is dedicated to the kinematic description of the mean sea surface by combining the data of all available satellite altimeter systems which are to be harmonized and carefully cross-calibrated beforehand. Mass redistributions within or between individual components of the system Earth like the atmosphere, the oceans, and the hydrosphere are subject of the investigations in topic 2.3 in order to study the effect on the Earth rotation, its gravity field, and the Earth figure. In topic 2.4 the actual plate-kinematic models are to be improved and combined with models of continuum mechanics. Site-dependent deformation models for the vertical tectonic motions shall account for the heterogeneous structure of the lithosphere.

2.1 Models of gravity field and ionosphere

The basic idea of the multi-resolution representation (MRR) is to decompose a given input signal, e.g. the geopotential or the disturbing potential of the Earth, into a smoother version (approximation) and a number of detail signals (modules) by successive low-pass filtering. The latter are the spectral components of the MRR because they are related to specific resolution levels, i.e. frequency bands.

As already explained in the last year's annual report we determine spatio-temporal gravity fields from GRACE data using the spherical wavelet approach for the spatial part and a one-dimensional (1-D) series expansion for the temporal variations, i.e. we end up with a four-dimensional (4-D) geopotential model of tensor product type. Modelling the time dependency of each scaling or wavelet coefficient, respectively, by a 1-D Fourier series, a MRR with respect to time cannot be established, and the detail signals of different levels are characterized by the same temporal behaviour, i.e. we do not have a 4-D MRR. But this deficiency can be overcome by substituting B-spline functions for the sine and cosine terms of the Fourier series, because a B-spline expansion allows a 1-D MRR and, thus, a 4-D (spatio-temporal) MRR of the geopotential is established. This approach states that the coarser spatial structures, i.e., the low-level detail signals, are computed for longer time intervals than the finer spatial structures, i.e. the high-level detail signals. However, as a matter of fact long-period spatial patterns of the geopotential are estimable from data sets covering shorter time intervals. In order to overcome this discrepancy we have derived a modified concept explained briefly in the following.

Modified spatio-temporal geopotential model

The MRR of the geopotential (input signal) $V(\mathbf{r},t)$ depending on position vector **r** and time t is generally defined as

$$V(\boldsymbol{r},t) = V_{i'}(\boldsymbol{r},t) + \sum_{i=i'}^{I} v_i(\boldsymbol{r},t) + \Delta V(\boldsymbol{r},t). \tag{1}$$

$V_{i'}$ is the long-period approximation of level i' and ΔV means the short-period unmodelled part of V. The level−i detail signal

$$v_i(\boldsymbol{r},t) = \sum_{k=1}^{N_i} d_{i,k}(t)\ \psi_{i,k}(\boldsymbol{r}) = \psi_i^T(\boldsymbol{r})\ \boldsymbol{d}_i(t). \tag{2}$$

is computed as a series expansion in terms of the level−i wavelet functions $\psi_{i,k}$ collected in the vector $\psi_i(\boldsymbol{r}) = (\psi_{i,k}(\boldsymbol{r}))$.

To model the temporal behaviour of the geopotential we introduce a level−i−dependent 1-D B-spline representation for each scaling coefficient $d_{i,k}(t)$ in Eq. (2). To be more specific, in this 4-D approach we distinguish between the spatial level $i \in \{i',..., I\}$ and the temporal level J_i depending on i. Thus, we expand each time-dependent scaling coefficient by a series

$$d_{i,k}(t) = \sum_{l=0}^{m_{J_i}-1} d_{i,k;J_i l}\phi_{J_i,l}(t) \tag{3}$$

in terms of (temporal) level−J_i normalized endpoint-interpolating quadratic B-spline functions $\phi_{J_i,l}$ with unknown spatio-temporal (4-D) scaling coefficients $d_{i,k;J_i,l}$; furthermore $m_{J_i} = 2^{J_i} + 2$ holds. A visualization of the normalized endpoint-interpolationg quadratic B-splines for level $J_i = 3$ can be found on page 28 in the DGFI Annual Report 2005/2006. Introducing the $m_{J_i} \times 1$ vector $\phi_{J_i}(t) = (\phi_{J_i,l}(t))$ and the $N_i \times m_{J_i}$ matrix $\boldsymbol{D}_{i;J_i} = (d_{i,k;J_i,l})$ of the B-spline functions $\phi_{J_i,l}$ and the spatio-temporal coefficients $d_{i,k;J_i,l}$, respectively, we obtain from Eq. (2)

$$v_i(\boldsymbol{r},t) = (\phi_{J_i}^T(t) \otimes \psi_i^T(\mathbf{r}))\ \mathrm{vec}\boldsymbol{D}_{i;J_i}, \tag{4}$$

where the symbol '$\otimes$' means the Kronecker product; in addition the vec operator orders the columns of a matrix one below the other as a vector. v_i means the detail signal on the spatial level i and the temporal level J_i; it will be denoted as the level −($i;J_i$) detail signal of the input signal. If we subtract a reference signal V_{ref} from the input signal V, we replace on the left-hand side of Eq. (1) $V(\boldsymbol{r},t)$ by the residual geopotential $\delta V(\boldsymbol{r},t)$. If further the summation limits in Eq. (1) are chosen appropriately, the subsignals $V_{i'}$ and ΔV can be omitted.

Estimation of the modified geopotential model

In the following we outline the different steps of our procedure:

- In the *first step* we estimate the unknown parameter matrix $\boldsymbol{D}_{I;J_I}$ from the level-($I+1;J_I$) observation equation

$$\delta V(\boldsymbol{r},t) =: \delta V_{I+1}(\boldsymbol{r},t) = \left(\phi_{J_I}^T(t) \otimes \phi_{I+1}^T(\boldsymbol{r})\right)\mathrm{vec}\boldsymbol{D}_{I;J_I} \tag{5}$$

  where $\phi_{I+1}(\boldsymbol{r})$ is the vector of the level−(I+1) (spatial) spherical scaling functions $\phi_{I+1k}(\boldsymbol{r})$. The estimator of $\boldsymbol{D}_{I;J_I}$ is then used to calculate the level−($I;\ J_I$) detail signal v_I according to Eq. (4) for $i = I$.

- In the *second step* we subtract the estimation v_I from the input signal $\delta V_{I+1} = \delta V_I + v_I$, define the reduced level−$(I;J_{I-1})$ observation equation

$$\delta V(\boldsymbol{r},t) = \left(\phi^T_{J_{I-1}}(t) \otimes \phi^T_I(\boldsymbol{r})\right) \mathrm{vec}\boldsymbol{D}_{I-1;J_{I-1}} \tag{6}$$

and estimate the matrix $\boldsymbol{D}_{I-1;J_{I-1}}$, which allows the computation of the level−$(I-1;J_{I-1})$ detail signal ν_{I-1} according to Eq. (4) for $i = I-1$.

- If we proceed in the same manner, we end up with all detail signals introduced on the right-hand side of Eq. (1).

Time series of the modified geopotential model for Central Europe

In our numerical investigations we analysed residual GRACE geopotential difference observations at orbital height, which were processed from GRACE L1B data via the energy balance approach by members of C.K. Shum's group at the Ohio State University. Applying appropriate background models, we assumed that these observations, given within the total time interval 09/2002 to 07/2005, primarily reflect hydrology variations. We followed the concept presented before by choosing the Blackman spherical scaling (wavelet) function and setting $I = 4$ for the highest (spatial) level I in Eq. (1), i.e., we solved for signal parts until spherical harmonic degree $n = 40$. Furthermore, we set $i' = 2$ for the lowest spatial level and chose appropriate values for the temporal levels J_i defined in Eq. (3), namely $J_2 = 6$, $J_3 = 5$ and $J_4 = 4$. Following Farrell's theory, the geopotential estimations were then transformed into equivalent water heights (EWH). Fig. 2.1.1 shows "snapshots" over Central Europe of the estimated EWHs at selected times within one year; as the reference model we used GGM01C.

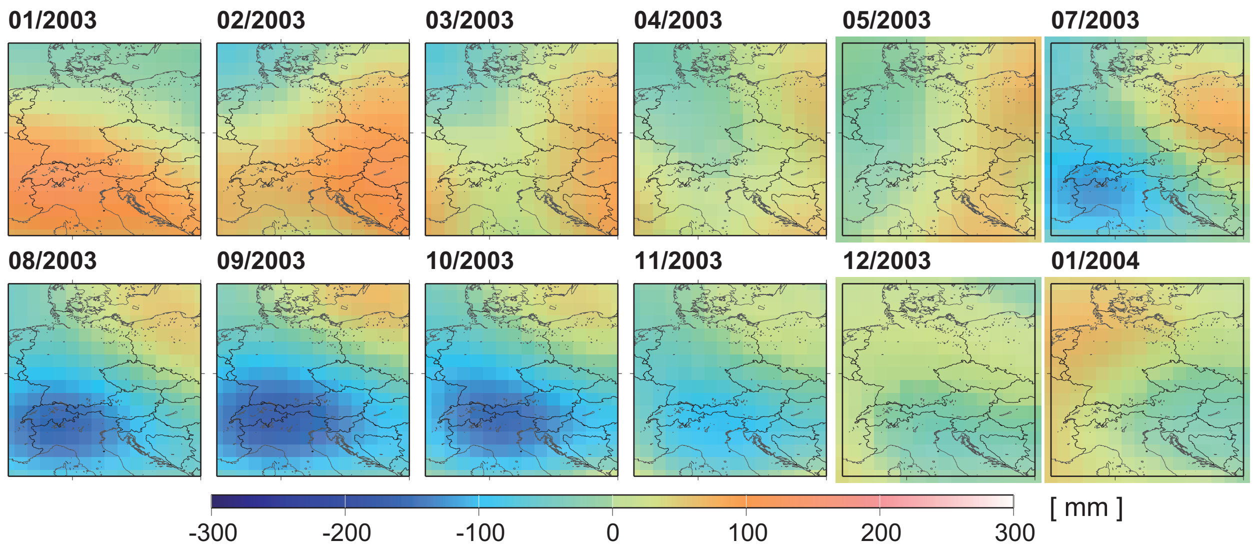


Fig. 2.1.1: Results of estimated EWH variations in Central Europe during 2003 for highest spatial level I=4, i.e., up to degree 40. The severe drought in late summer is clearly noticeable. As temporal level Ji we chose for spatial level i=3 the value J3=5, i.e. we considered for that specific frequency band 34 B-splines within the total time interval 09/2002 to 07/2005.

Modelling the slant total electron content of the ionosphere

Besides modelling the gravity field, in topic 2.1 we also pursue ionosphere reserach. The ionosphere is generally defined as a thick shell of electrons and ions, which envelopes the Earth from about 60 to 1000 km height. In the last year's annual report we presented a 3-D model of the electron density distribution mathematically based on B-spline expansions and physically controlled by the International Reference Ionosphere (IRI) model. In this approach the slant total electron content (STEC), defined as the integral of the electron density along the ray path between the transmitting satellite S and the receiver R, is modelled as

$$STEC(t) = \sum_{k=0}^{K-1}\sum_{l=0}^{K-1}\sum_{m=0}^{K-1} d_{I;k,l,m}(t)\, b_{k,l,m}\,(R,S) \tag{7}$$

with

$$b_{k,l,m}(R,S) = \int_R^S \phi_{I,k}(\lambda)\phi_{I,l}(\beta)\phi_{I,m}(h)\,ds, \tag{8}$$

where the functions $\phi_{I,k}(\lambda)$ $\phi_{I,l}(\beta)$ and $\phi_{I,m}(h)$ are again the normalized endpoint-interpolationg quadratic B-splines of level I depending on longitude λ, latitude β and height h. The time-dependent level$-I$ scaling coefficients $d_{I;k,l,m}(t)$ are estimable, e.g. from GNSS observations. The simple simulated example presented in the last year's annual report was extended to a much more realistic simulation (not shown here). For the integration along the ray path in Eq. (8) we derived an efficient procedure based on the n-point Gaussian quadrature formula.

COSMIC observations of the vertical total electron content

Today there is a variety of approaches to process GNSS observations and to produce ionospheric maps of the vertical total electron content (VTEC) with a temporal resolution of two hours or less. In the following we present a 3-D VTEC model estimated from (occultation) measurements of space-borne receivers flying on low-Earth-orbiting (LEO) satellites, namely the Constellation Observing System for Meteorology, Ionosphere and Climate and Taiwan's Formosa Satellite Mission #3 (COSMIC/FORMOSAT-3), which is a joint Taiwan-U.S. project. It consists of six satellites launched on April 14, 2006. Within the first year their orbital height was changed from 400 km to 800 km.

In our investigations we used electron density values calculated in a pre-processing step from so-called compensated STEC values by L.-C. Tsai from the Centre for Space and Remote Sensing Research at the National Central University in Taiwan. His method does not assume locally spherical symmetry within the ionosphere, but considers the effect of large-scale horizontal gradients and/or an inhomogeneous electron density distribution. Due to the mission characteristics a "measured" VTEC observation means the sum of the integrated value of the calculated electron density along the vertical between bottom of the ionosphere and the orbital height and a model value for the remaining part between the orbital height and the top of the ionosphere. Fig. 2.1.2 shows the distribution of these COSMIC VTEC observations within our selected area of investigation for a specific time interval.

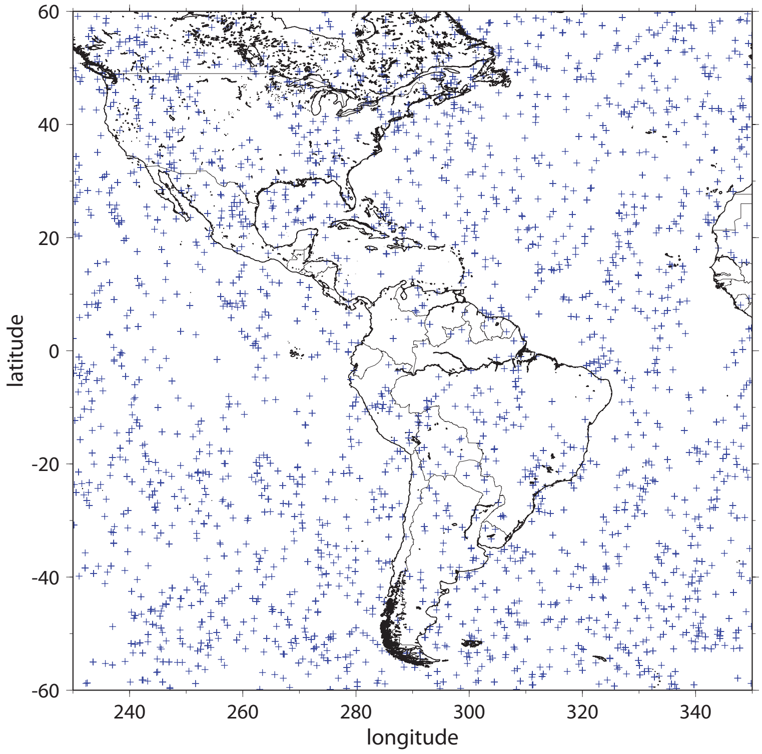


Fig. 2.1.2: Spatial distribution: The blue crosses visualize the geographical positions of altogether 3,637 COSMIC VTEC observations within the time interval between 20/07/06 and 24/07/06.

Modelling the vertical total electron content

In our approach the VTEC observation equation reads

$$VTEC(\boldsymbol{r},t) + e(\boldsymbol{r},t) = VTEC_{\mathrm{ref}}(\boldsymbol{r},t) + \sum_{k=0}^{K-1}\sum_{l=0}^{K-1}\sum_{m=0}^{M-1} d_{I;J;k,l,m}\,\phi_{I,k}(\lambda)\phi_{I,l}(\beta)\phi_{J,m}(t) \quad (9)$$

with unknown level−(*I;J*) scaling coefficients $d_{I,J;k,l,m}$; *e* is the measurement error. As reference model $VTEC_{\mathrm{ref}}$ we chose IRI-2000; cf. Fig. 2.1.4. Furthermore, we set $I = 3$ for the highest (spatial) level value *I*, i.e. with respect to longitude and latitude as well as $J = 5$ for the highest (temporal) level value *J*, i.e. with respect to time. Hence, we solved with $K = 2^3+2 = 10$ and $M = 2^5 +2 = 34$ for altogether $K^2 \cdot M = 3{,}400$ scaling coefficients. The top panel of Fig. 2.1.3 shows the temporal behaviour of the COSMIC VTEC data. The other two panels depict the corresponding VTEC values from the reference model IRI-2000 and the deviations, i.e. the residual VTEC input data. The RMS of the residual VTEC input data amounts to around 3.5 TECU.

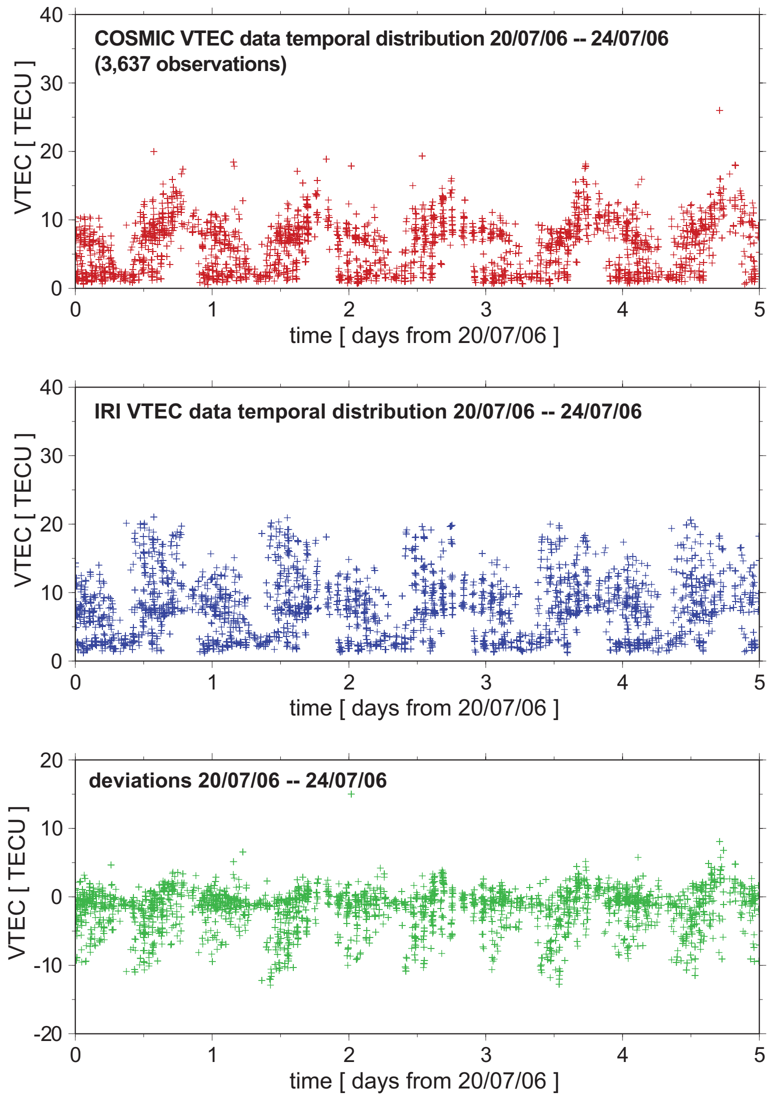


Fig. 2.1.3: Temporal distribution: The three panels show (from top to bottom) the COSMIC VTEC observations, the VTEC reference values from IRI-2000 and the deviations (COSMIC minus IRI-2000) depending on time within the region under consideration.

Estimation of the vertical total electron content from COSMIC observations over America

In the next step we estimated the unknown scaling coefficients $d_{I,J;k,l,m}$ from the residual COSMIC VTEC input data. Generally a scaling coefficient is computable only if observations are given close to the peak of the corresponding scaling function. Hence, in case of large data gaps many scaling coefficients may not be calculable and the corresponding addends can be excluded from the observation equation. If just a few observations support the computation of a coefficient, prior information could be introduced in order to stabilize the estimation process, i.e. to perform a regularization. Fig. 2.1.4 shows exemplarily 24 selected "snapshots" of the residual VTEC estimations between 8:00 and 20:00 UT for July 21, 2006.

Panel a) of Fig. 2.1.5 shows exemplarily the VTEC model data from IRI-2000 for July 21, 14:00 UT. Panel b) visualizes the sum of the reference model and the residual VTEC estimation from the COSMIC data set, i.e. the estimated VTEC data from COSMIC. One of the next steps has to be the validation of our results by using data from ionosondes.

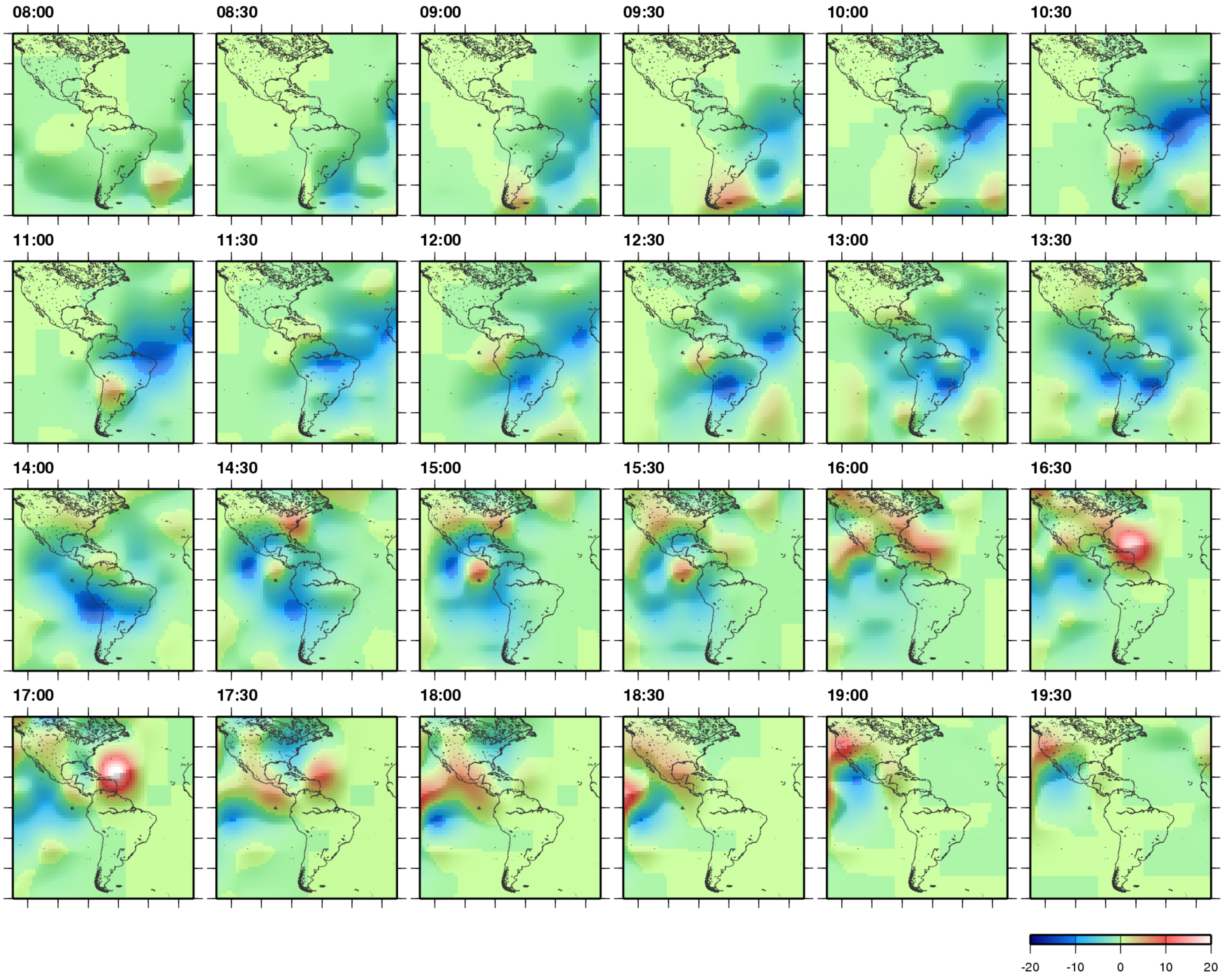


Fig. 2.1.4: 24 residual VTEC estimations for July 21, 2006, 8:00 to 20:00 UT, from the residual VTEC input data shown in Figs. 2.1.2 and 2.1.3 (bottom); all data in TECU.

Since the B-spline expansion (Eq. 9) provides a MRR of the VTEC input data set, a wavelet decomposition procedure can be applied, which means an effective tool for data compression or reduction, respectively. As a numerical example we used the method of hard thresholding, which allows to neglect 2,193 wavelet coefficients. Since we started from altogether 3,400 scaling coefficients the compression rate amounts to 65 %; the corresponding RMS of the differences between the original and the compressed data sets amounts to 0.74 TECU.

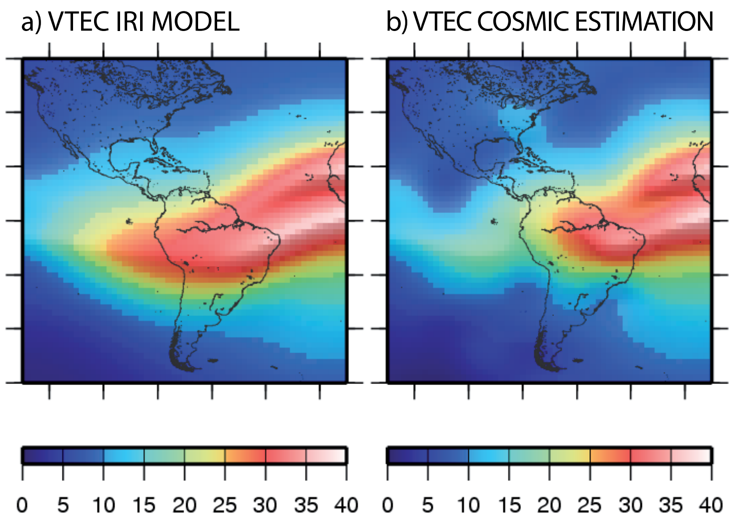


Fig. 2.1.5: VTEC model data from IRI-2000 for July 21, 14:00 UT (a) and the corresponding estimated VTEC model from COSMIC data (b); all data in TECU.

2.2 Kinematics of the mean sea level

The investigations for the kinematic description of the mean sea surface were continued. Numerous upgrades of the satellite altimeter data base led to essential improvements and more consistent data sets and allowed to obtain a more reliable estimate of the long term evolution of the mean sea level.

Upgrade and enhancement of altimeter mission data

In particular the following upgrades of the satellite altimeter data base at DGFI were performed:

- For TOPEX a radiometer replacement product was provided for the NASA distributed data version. Therefore the DGFI data holdings were changed to the NASA version (MDGR-B) and the replacement product was applied.
- The initially distributed data set of Jason-1 was gradually replaced by the reprocessed GDR, version B with orbits now based on the GRACE gravity field model EIGEN-GL03C, a new signal analysis including a mispointing angle, the wet troposphere delay corrected for jumps and side lobe effects of the radiometer, and the inverse barometer correction based on the dynamic MOG2D model.
- The "dynamic atmospheric correction" (DAC) composed of the dynamic MOG2D model (describing the response of the ocean to atmospheric variations within the first 20 days) and a static inverse barometer correction for longer periods was applied to all other missions, except Jason1. As the change to the DAC is rather significant, this harmonization was important to maintain consistency between different altimeter missions.
- For ENVISAT new GRACE-based orbits were gradually made available by DEOS. They were interpolated to the ENVISAT data and replace the inhomogeneous orbit data, provided with the original mission data.
- ERS-2 data were enhanced following the recommendations of DEOS
- Finally, the DGFI altimeter data base was enlarged by the geodetic and ice phases of the ERS-1 mission. Although the data of these phases were not reprocessed by ESA, their compilation is important for the high-resolution gravity field modelling. The ERS-1 data were also enhanced with respect to the deficiencies identified by the science community.

Multi-mission cross calibration

As the complete altimeter data base was considerably affected by the above upgrades, it was justified to repeat the multi-mission cross calibration already presented in the previous annual report. The cross-calibration is based on the discrete crossover analysis (DCA),

- realizing a common least squares adjustment of all single and dual satellite crossover differences performed between all altimeter systems operating simultaneously.
- The total set of these crossover differences establishes a rigid network with high redundancy allowing to estimate radial errors for all satellites with a sufficiently dense sampling – even for TOPEX/Poseidon whose orbit is no longer taken as free of errors (in contrast to the procedure followed so far by other investigations).

The analysis is again performed for a sequence of 10-day periods (coinciding with the repeat cycles 001 – 481 of TOPEX spanning more than 13 years) with 3 days overlap to neighbouring periods. As the radial errors in the overlapping periods coincide to within 1 – 2 mm, the error estimates of the central 10-day periods are used only and are – for each altimeter system – concatenated to time series covering the complete mission period analysed (see bar graphs at the bottom of Fig. 2.2.2). These time series allow for each satellite a rather solid statistical characterisation of the radial errors by empirical auto-covariance functions shown in Fig. 2.2.1

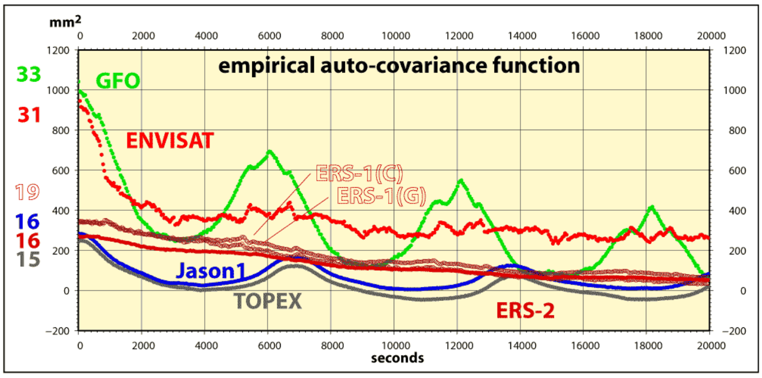


Fig. 2.2.1 Empirical auto-covariance functions for most of the altimeter missions analysed by the multi-mission cross calibration. The large variances (indicated on the left) for GFO (33 mm) and ENVISAT (31mm) can be explained by the inadequate tracking and the inhomogeneous processing respectively. The increase of the auto-covariance approximately after one revolution (outstanding for GFO, but also present for TOPEX and Jason1) indicates the presence of geographically correlated errors.

New relative range bias estimates

To overcome the rank defect of the crossover analysis the sum of TOPEX errors for every analysis period was forced to zero. Therefore the estimated radial errors of TOPEX vary around zero – with a scatter of 1–2 cm. As a consequence, the radial errors of all other satellites carry – on average – the range biases relative to TOPEX. Fig. 2.2.2 shows for every mission and all 10-day analysis periods the mean of the radial errors. Compared to the previous analysis the time series of relative range biases became more stable. A few anomalies, e.g. for ERS-2 around spring 2002 and at the very first cycles of ENVISAT, remain suspicious.

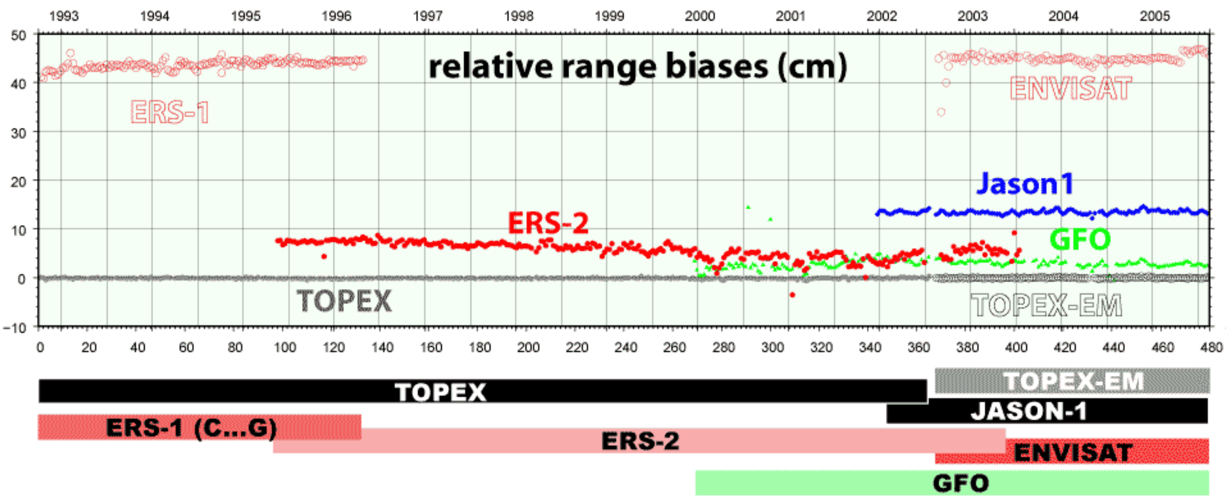
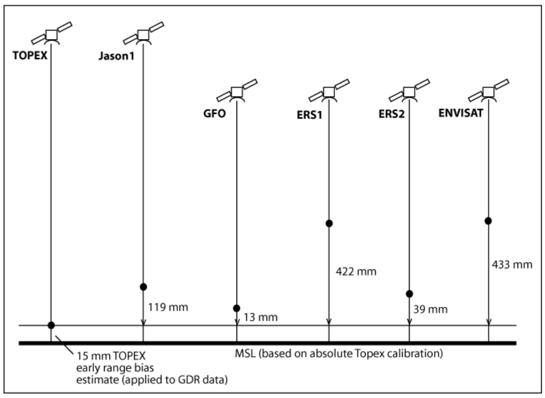


Fig. 2.2.2 Relative range biases (cm) for all missions and 10-day periods re-analysed after completion and upgrades for all mission data. The range biases are relative to TOPEX (later T/P-EM) because the sum of TOPEX (T/P-EM) errors was always forced to zero. The weak annual oscillations of the range bias time series visible in the previous multi-mission cross calibration disappeared. The range biases for ENVISAT, Jason1 and GFO are rather stable, while ERS-1 and ERS-2 show a small, but significant positive and negative trend respectively (c.f. Tab. 2.2.3).

Fig 2.2.3 Relative range biases and bias drifts for the altimeter missions analysed by the multi-mission crossover analysis. The figure on the left indicates the range biases related to TOPEX, which was used as reference by forcing the sum of radial errors for each analysis period to zero. In the GDR data, the TOPEX ranges are already corrected for a range bias of +15 mm, an early estimate of the absolute bias. Therefore the relative range biases between the other missions and TOPEX, listed in the table on the right, are always reduced by 15mm. ERS-1 and ERS-2 show a significant bias drift – with opposing sign. The drift estimate for ENVISAT and the individual phases of ERS-1 appear unreliable due to poor signal analysis and short time periods respectively.



mission-phase	duration [days]	rel. range bias [mm]	bias drift [mm/year]	epoch
Jason1	1338	119.3 ± 0.3	—	
GFO	2022	13.3 ± 1.2	—	
ENVISAT (A)	941	433.7 ± 0.5	-2.1 ± 0.7	2004.5
ERS2	2935	39.2 ± 0.7	-4.7 ± 0.3	2000.0
ERS1	1348	421.8 ± 0.6	+5.3 ± 0.5	1994.5
ERS1-C	456	418.0 ± 1.1	+13.3 ± 2.9	1993.5
ERS1-D	118	416.9 ± 2.8	—	
ERS1-E	168	423.9 ± 1.7	—	
ERS1-F	168	424.8 ± 1.4	—	
ERS1-G	416	428.4 ± 0.6	—	

By a postprocessing, mean values of the radial errors were estimated for all analysis periods in order to determine the radial range biases and their stability. Fig. 2.2.3 shows the results. The relative range biases are widely consistent with independent calibrations and cross-calibrations performed by other groups.

The radial error estimates from the multi-mission crossover analysis were finally applied to the altimeter data so that the corrected sea surface heights from different altimeter missions should be as homogeneous and consistent as possible and possess the most reliable long period stability.

Long period sea level variation

The corrected sea surface heights were subsequently used to study the long period variations of the mean sea level. From previous investigations it was already known that in contrast to the *global* sea level rise of about +3 mm/year the regional sea level variations can be significant larger (about ±20 mm/year) with opposing sign and extended geographical pattern. Obviously such outstanding trends cannot be considered as fixed and extrapolated. Due to balance with gravity, these variations must be considered as a few years' snapshot of long period sea level variation. The trends may be valid for a couple of years, but must be compensated after some time by trends with opposing sign. This is confirmed by the new analysis of long-period variations of the mean sea level as illustrated in Fig. 2.2.4. In general, the mean sea level change for the period 1993–1998 is significantly different from the mean sea level change for the period 1999–2005. In most ocean areas the mean sea level trend for the first 6–year period is indeed compensated by the development of the second 6–year period. However, this compensation does not take place at the central axis of the Gulf Stream. Here the sea level dropped down in both periods. This is a clear indication that in the period 1993–2005 the Gulf Stream became significant weaker – a finding already supported by one of DGFI's first EOF analyses in the North Atlantic.

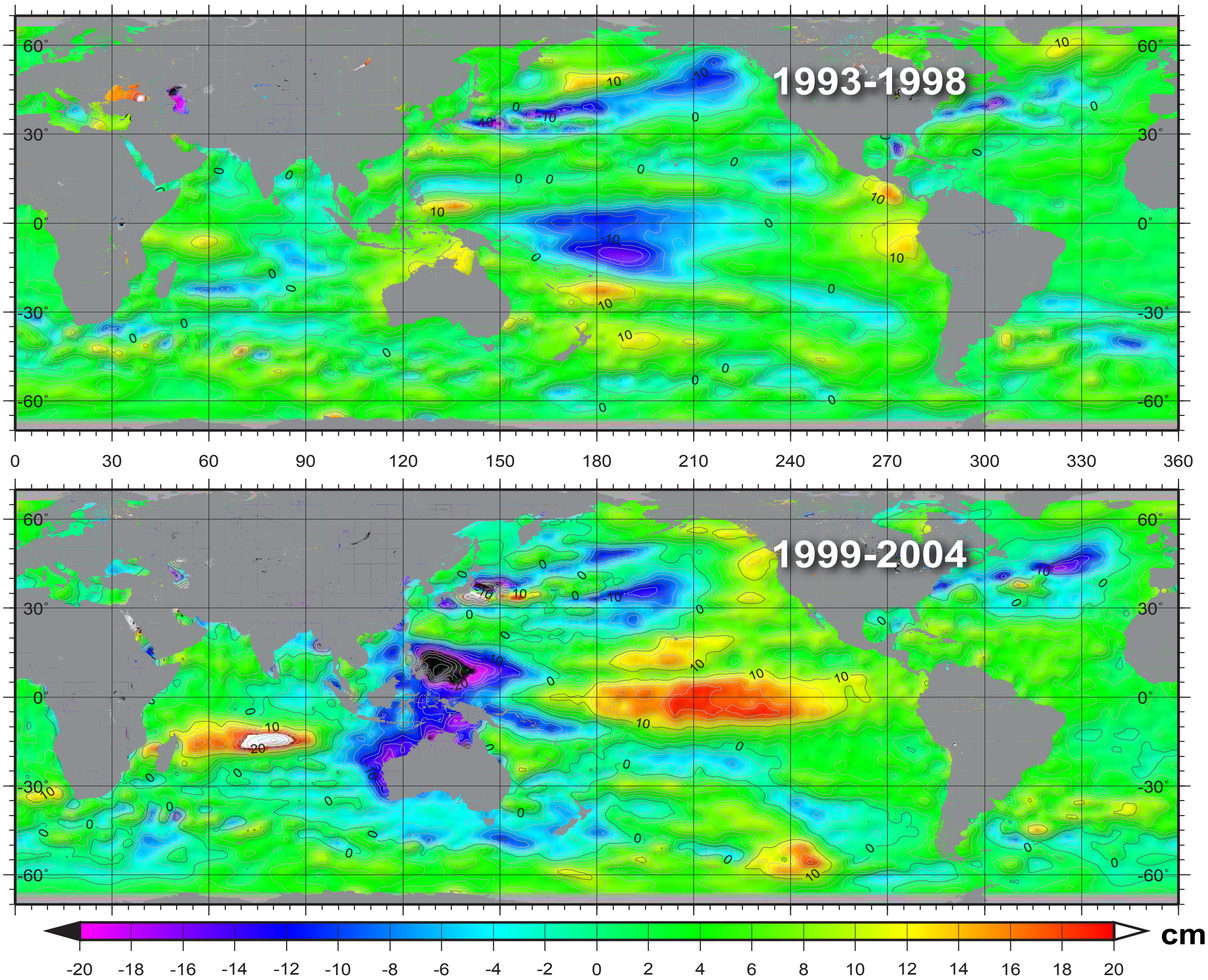


Fig. 2.2.4: While the global sea level rise is estimated at some 3 mm/year, the regional long-period changes of the mean sea surface have significant larger amplitudes with opposing sign and pronounced geographical pattern in the different ocean basins. Within the 6-year period 1993–1998, the sea level in the central Pacific dropped down by up to 15 cm. In the next 6 years (1999–2004), the mean sea level at nearly the same place rose up by more than 15 cm and dropped down in the Indonesian Sea by even more than 20 cm. In most areas, the long-period changes of the first and second 6-year period compensate each other – except for the central axis of the Gulf Stream where the mean sea level dropped down in both periods, an indication for the weakening of the Gulf Stream.

The BIN data structure

In general the altimeter data are segmented in repeat cycles and ascending and descending pass-files, because crossovers can be more easily identified. For time series analysis the pass file oriented data structure is not well suited, because repeated measurements for the same location are distributed over all cycle sub-directories. In order to facilitate time series analysis, the BIN data structure was introduced. It is realized by a re-organisation of sea level anomalies and those corrections applied to compute them. The data of all repeat cycles is stacked into bins, small cells along the nominal ground track. The length of the bins was defined to match the mean distance of 1Hz observations. This ensures that with every cycle just one observation is added to the bin's stack. In this way every bin compiles sea level anomalies for every cycle, a time series covering the whole mission lifetime.

The BIN data structure was used, for example, for the empirical ocean tide analysis (c.f. section 2.3). By an experimental web interface, the data structure was also made available to cooperating partners which used the data for coastal applications and the unification of height systems. Based on the feedback and own experiences with the BIN data structure, it was decided to carry out some modifications:

- The initial length of the bins was too short causing data gaps for some bins. Now, the definition of bins is more precisely adapted to the sampling frequency of different altimeter systems. For altimeter satellites with the same nominal orbit characteristics but different sampling frequency, the bin lengths were unified using the maximum length. For instance, ERS and ENVISAT got both the bin size of ENVISAT. This allows to combine the time series of both satellites if they were carefully harmonized beforehand.
- For some studies it is important to know the ocean depth at the bin centres. Therefore the "bin definition" files were extended by a parameter containing the ocean depth from the GEBCO bathymetry atlas.
- The most important modification was related to the sea level anomalies (*sla*) defined as the difference between the instantaneous sea surface heights (*SSH*) and the mean sea surface height (*MSS*), cf. the Eqs. left hand. As the measurements do not repeat at exact the same position, it is desirable to relate all sea level observations within a bin to its centre. As a first approximation this can be done by sea surface slopes from the mean sea surface model CLS01. Using these slopes and the distance Δl between measurement point and bin centre the sea surface height is transferred to the bin's centre and then used to calculate a sea level anomaly (sla^{cob}) by subtracting the mean sea level at the centre of the bin. Compared to the sea level anomalies at the measurement positions, the sla^{cob}-values should constitute a more consistent time series.
  Unfortunately the CLS01 mean sea surface exhibits errors and does not always provide reliable slope estimates. For land areas, the mean sea surface CLS01 was augmented by the EGM96 geoid and deformed to obtain a smooth transition from ocean to land. Thus, in particular in coastal areas, the slope of CLS01 may be wrong. Therefore, it may be more reliable to estimate the mean sea surface slope from the observed sea surface heights. In order to allow the reconstruction of instantaneous sea surface heights, another residual value is included in the BIN data structure. It is defined as the difference ($sldif_i$) between the sea surface heights at measurement point and the mean sea surface height at the centre of bin.

ICESat Integration in MVA structure

To allow an extensive modelling of the ocean heights and dynamics it is advisable to use data from as many altimeter systems with different orbit and mission characteristics as possible. DGFI maintains a broad data base to store altimeter data from various missions in the so-called MVA structure (multi-version altimetry). A standard data format for all missions is used as well as small parameter files allowing a simple and quick update of single processes (like orbit computation or tidal corrections).

Tab. 2.2.1: Mission Characteristics of ICESat.

Orbit height	~ 600 km
Inclination	94°
Repeat Ground Track	183 days
Diameter of Footprint	~ 70 m
Along-track separation	~ 170 m
Cross-track separation	~ 15 km ... 2.5 km
Wavelength (for surface measurements)	1064 nm
Active since (not continuously)	2003

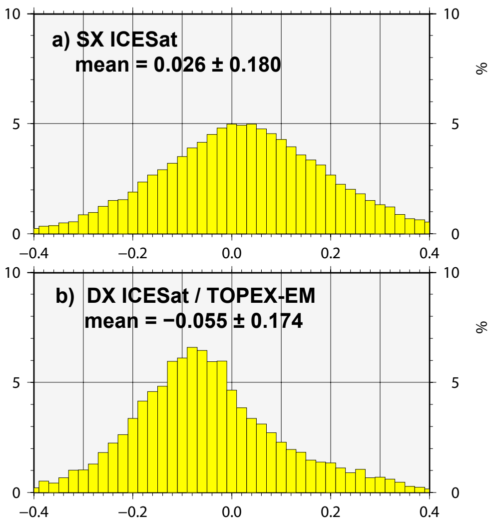


Fig. 2.2.5: Histogram of a) single satellite crossover differences of ICESat and b) dual satellite crossover differences between ICESat and TOPEX-EM.

DGFI started to integrate data from the Geoscience Laser Altimeter System (GLAS), which is flying on board of ICESat (Ice, Cloud, and Land Elevation Satellite) into its data base. The primary goal of ICESat is to measure ice sheet elevations, but the laser also provides heights from land topography as well as ocean elevations.

As ICESat measurements are carried out with a laser (wavelength of 1064nm), the mission has different characteristics than radar altimeters (cf. Tab. 2.2.1). With the higher repetition rate, the smaller footprint and a cross-track separation between 15 km (equator) and 2.5 km (at 80°), the ICESat data will significantly contribute to the mapping of the mean sea level and to the high resolution gravity field modelling.

First analyses of cross-over differences within the ICESat mission and with TOPEX-EM (Fig. 2.2.5) shows a good general agreement of both missions encouraging the use of ICESat GLAS data for further investigations and modelling approaches.

A comparison of ICESat-derived sea level heights with the CLS01 mean sea level is illustrated in Fig. 2.2.6. The differences are in the range of decimetres with a mean of –9.6 cm ± 18.2 cm in ocean regions. These differences include physical differences (different time periods of CLS01 and ICESat measurements) as well as systematic mission biases and single measurement errors (mainly uncertain measurements due to large off-nadir angles).

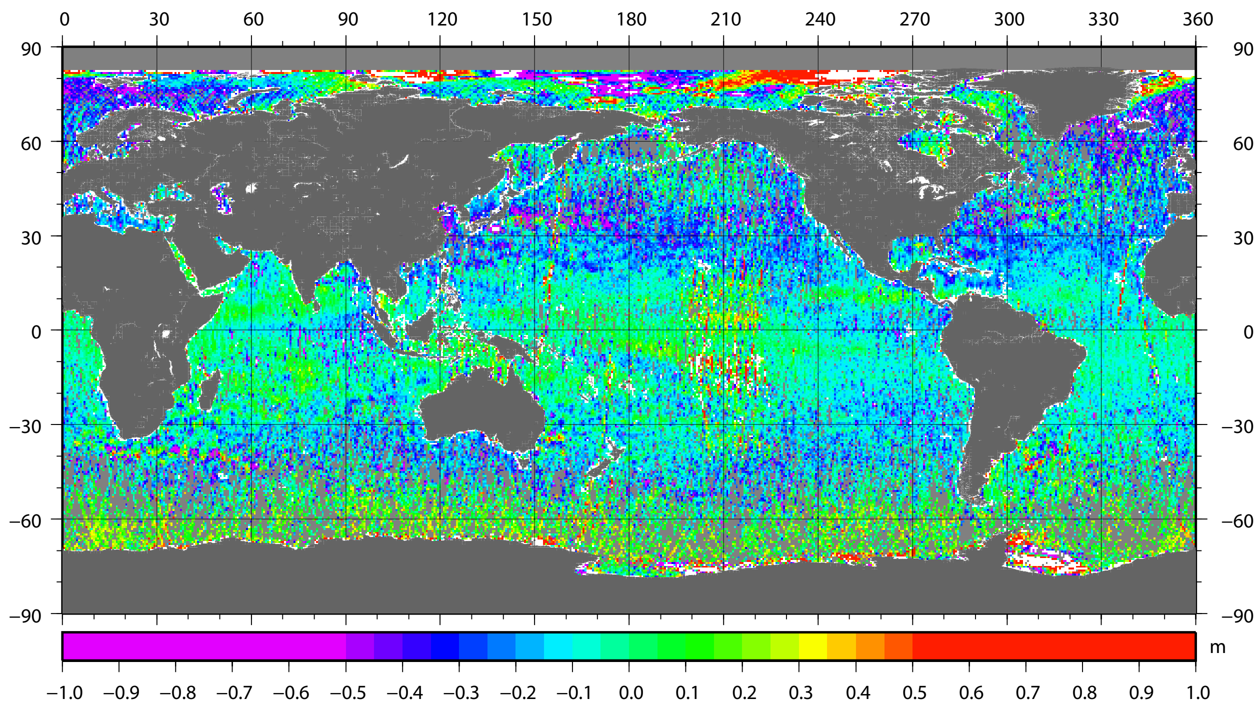


Fig. 2.2.6: Groundtrack and sea level anomalies (with respect to CLS01) of ICESat Laser Period 3B (17.02.-24.03.2005).

2.3 Dynamic processes in the system Earth

Dynamic processes within and between the individual components of the Earth system cause variations of the rotation, the geometry and the gravity field of the Earth. Modern geometric and gravimetric space geodetic techniques make it possible to observe the effects of global and regional mass transports with high accuracy. Since the observations reflect the integral effect of a multitude of underlying geophysical effects, informations from different space and terrestrial observations as well as theoretical models are required in order to separate particular contributions.

Within this topic approaches are developed for an extensive analysis of atmospheric, oceanographic and hydrologic effects on the geodetic observations. This comprehends the assessment of different models, data sets and investigations with respect to their applicability for the geophysical interpretation and refined analyses of geodetic observations.

Parts of the activities within this topic are carried out in the framework of the DFG Priority Research Program SPP 1257 (project: Separation of mass signals by common inversion of gravimetric and geometric observations) and the DFG Research Unit FOR 584 (project: Integration of Earth rotation, gravity field and geometry using space geodetic observations).

Signals of extreme weather conditions in Central Europe from GRACE gravity field variations

During the last five years weather conditions in Central Europe featured strong fluctuations. Heatwaves, droughts, exceptional rain, snowfall, and floodings occurred at irregular intervals. Such phenomena are associated with hydrological mass variations that are reflected by changes of the Earth's gravity field. This way they influence the observations of the satellite gravity field mission GRACE over multiple seasonal scales.

Regional analyses of GRACE observations were performed for seven Central European river basins (Fig. 2.3.1). GRACE gravity

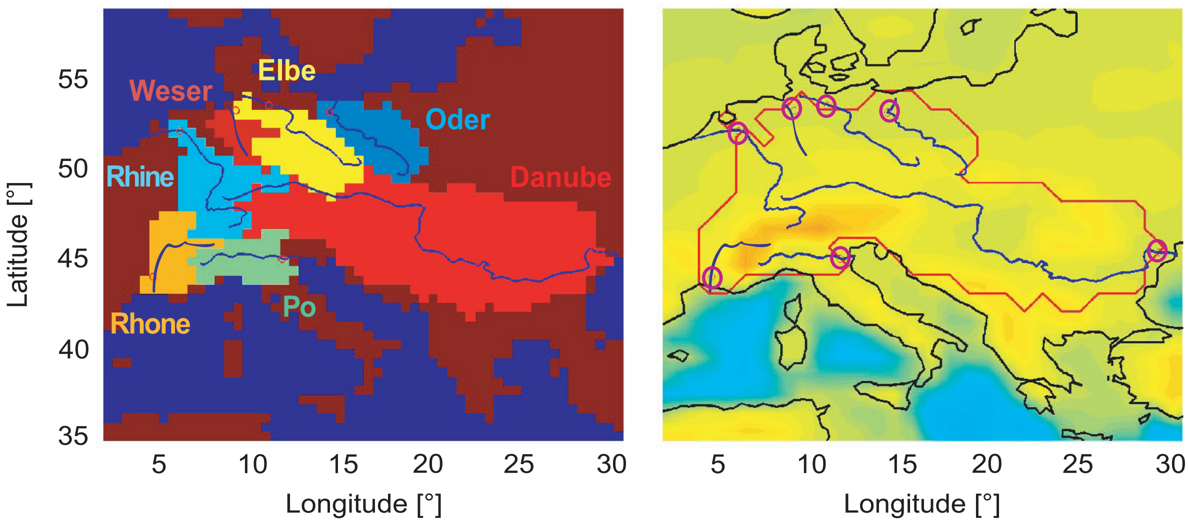


Fig 2.3.1: (left) The area investigated is composed of seven large river basins in Central Europe. (right) The red line is the boundary of the area and purple circles show locations of river gauges used for discharge information.

field variations were derived from a multi-resolution representation (MRR), presented in Topic 2.1 and from monthly mass grids based on global spherical harmonic (SH) solution data products from the processing centres at GeoForschungsZentrum Potsdam (GFZ) and Centre for Space Research (CSR). Observed mass variations are expressed in terms of equivalent water heights (EWHs), averaged over the investigated area and converted into units of km^3 of water. These values represent the total variation of equivalent water with respect to a long-term average over 2003–2005 that was removed in the course of the computations. Resulting water mass variations from the MRR and the SH solutions are displayed in Fig. 2.3.2.

Atmospheric flux convergence and river discharge

Mass variations from integrated GRACE EWHs are balanced with the net effect of river discharge from gauges (outflow) and precipitation (P) and evaporation (E) (inflow) from the convergence of vertically integrated water vapour flux in the examined area. $P - E$ is computed from the atmospheric moisture budget:

$$\mathrm{P} - \mathrm{E} = -\frac{\partial \mathrm{W}}{\partial \mathrm{t}} + \nabla^{\mathrm{T}}\mathbf{Q} \qquad (1)$$

where W is precipitable water and $\mathbf{Q}$ is the vertically integrated water vapour flux. The first term is negligible on monthly and annual timescales, the latter is calculated from six hour atmospheric re-analysis products from the National Centres for Environmental Prediction (NCEP) between 2002 and 2007. The net inflow of water into the examined area A follows from

$$(\mathrm{P} - \mathrm{E})_{\mathrm{A}} = \int_{\mathrm{A}} (\mathrm{P} - \mathrm{E})\, \mathrm{dA} = \int_{\mathrm{A}} \nabla^{\mathrm{T}}\mathbf{Q}\, \mathrm{dA} = \oint_{\mathrm{L}} \mathbf{Q}^{\mathrm{T}}\mathbf{n}\, \mathrm{dL} \qquad (2)$$

In this equation the flux convergence is interpreted as the line integral of the vertically integrated moisture transport along the boundary curve L of the area (red curve in Fig. 2.3.1, right) according to Gauss' Theorem; $\mathbf{n}$ is the unit normal to L. The total discharge from the area is calculated from river gauges (purple circles in Fig. 2.3.1, right) closest to the mouths of the rivers in the examined area. Respective discharge records were provid-

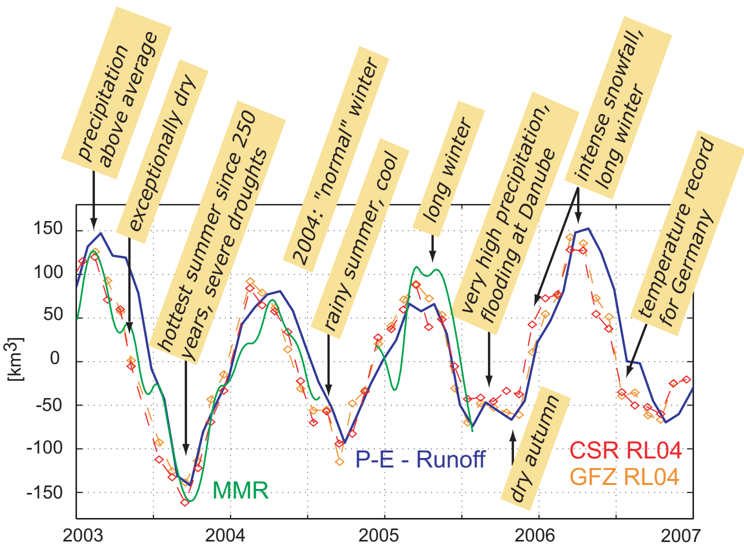


Fig 2.3.2: Observed mass variations in the investigated area in units of km^3 of equivalent water from the MRR approach (green) and two solutions based on global spherical harmonics from GFZ (orange) and CSR (red). The blue curve shows the independent results from geophysical data.

ed by the Global Runoff Data Centre (GRDC). From the P − E and river discharge data the instantaneous amount of water in the examined area is calculated for each time step. The different GRACE solutions and the water mass variations computed from Eq. (2) and the river discharge agree well concerning both the amplitude and the phase of the curves. Some specific features of the curves can be related to meteorological conditions (Fig. 2.3.2). Particularly the severe heatwave during 2003 which caused rivers to drop to record low levels is clearly visible in all GRACE time series. The 2005 flooding in the Danube basin and the intense snowfall during the winter 2005/2006 are reflected by the GRACE observations very well, too.

Occasional discrepancies between the observations and the atmospherical and hydrological data can be expected. On the one hand, the latter data sets are not free from errors, on the other hand, mass variations computed from GRACE observations cannot be viewed as perfect representations of water storage changes either. In general the interpretability of the results in terms of water mass variations is limited due to errors in the models and algorithms applied for de-aliasing (see below) and filtering. Furthermore, the GRACE observations are also influenced by other geophysical processes than continental hydrology. The uncertainties of reduction models and data processing strategies manifest themselves in the discrepancies among the individual GRACE time series which are in the same order of magnitude as the discrepancies between the GRACE solutions and the result from atmospherical and hydrological data.

3D-computation of the atmospheric gravity effect

Short term mass variations within the atmosphere and the oceans would lead to erroneous patterns in the monthly averaged gravity fields from GRACE. Consequently suchlike fluctuations are removed from the observations in the course of pre-processing (de-aliasing). Sub-daily atmospheric mass fluctuations can be computed from three-dimensional air density variations. Due to the orbit characteristics of GRACE, the resulting de-aliasing data set should be available in a spatiotemporal resolution of at least 1.5° and 6 hours.

Since air density is not provided operationally by weather services, this parameter has to be computed from other meteorological output data, in particular from surface pressure, temperature, specific humidity and topography (geopotential height). Due to hydrostatic equilibrium, the computation of density changes in a vertical air column is equivalent to mass changes of the atmosphere. The latter are subsequently transformed into coefficients of the spherical harmonic expansion of the Earth's gravity field via spherical harmonic analysis.

In comparison with the two-dimensional approximation, using only the surface pressure the three-dimensional approach leads to a slight but significant improvement of the atmospheric reduction for GRACE observations for coefficients of degree and order >20.

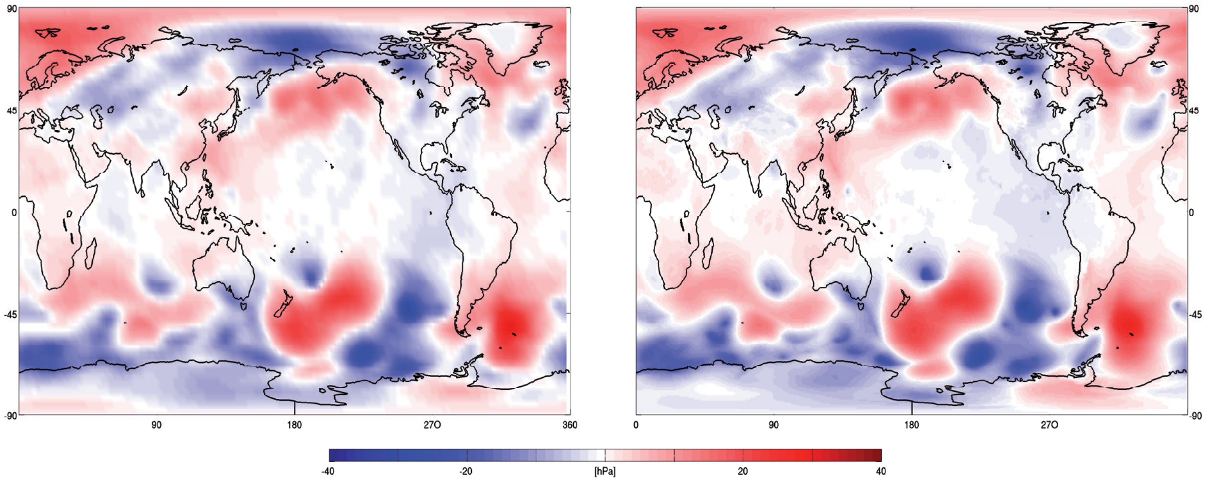


Fig 2.3.3: Surface pressure anomalies for July 1, 2006, 0:00 UTC from NCEP (left) in a spatial resolution of 2.5° and from ECMWF (right) in a spatial resolution of 0.5°. A monthly mean pressure field from July 2006 was subtracted in both cases.

Fig. 2.3.3 compares anomalies of surface pressure for July 1, 2006 from two atmospheric data sets, viz. the re-analyses from NCEP and the operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF). The NCEP re-analyses contain the respective data in a spatial resolution of 2.5° and a temporal resolution of 6 hours. ECMWF data are provided in a spatial resolution up to 0.25°, a temporal resolution of 6 hours and – on request – a vertical expansion of 91 levels which is equivalent to a vertical resolution of approximately 80 km.

Since GRACE is sensitive to sub-daily atmospheric mass variations on spatial scales of up to 500 km, the coarse resolution of the NCEP data limits its applicability for the computation of reasonable atmospheric de-aliasing products.

Mass transports in the Earth system and polar motion

The direction of the Earth rotation axis with respect to the Earth's surface can be determined from geometric observations of modern space geodetic techniques such as VLBI, SLR and GNSS with a precision of better than a millisecond of arc. Polar motion is caused by dynamic processes within and between individual subsystems of the Earth.

Excitation functions from observations and model simulations

In order to validate geophysical data sets from observations and models, forward-modelled effects of atmospheric, oceanic and hydrological mass redistributions and motions on polar motion are compared with geodetic observations. The comparisons are performed on the basis of equatorial excitation functions (EXFs), see Fig. 2.3.4.

Atmospheric EXFs are derived from the re-analyses of NCEP and from the operational analyses of the ECMWF. Oceanic EXFs are computed from model simulations (OMCT, ECCO) and from satellite altimetry. The latter provides accurate information about sea level anomalies (SLA) which are caused by changes of mass and volume of the ocean. Since the volume changes (steric effect) do not influence polar motion, observed SLA must be reduced ac-

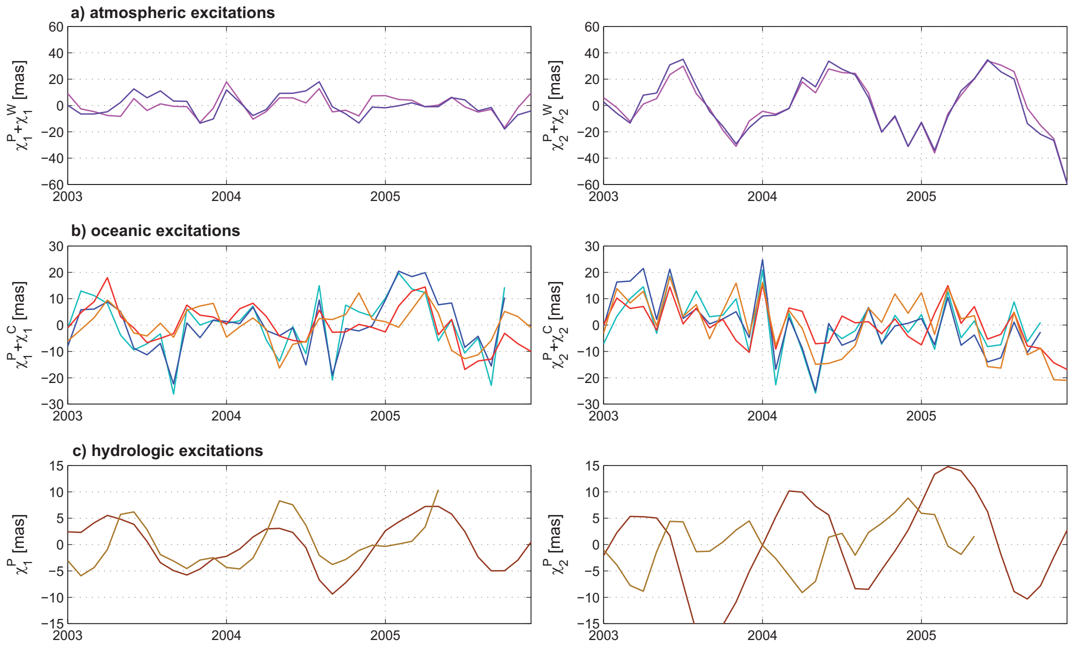


Fig 2.3.4: Time series of polar motion excitation functions for atmosphere, oceans and continental hydrology (note the different scaling): (a) atmospheric excitations from ECMWF (pink) and NCEP (purple); (b) oceanic excitations from TOPEX/Poseidon SLA with steric corrections from Ishii (cyan) and WOA05 (blue) and oceanic excitations from the models OMCT (orange) and ECCO (red); (c) hydrological excitations from LDAS (dark brown) and LaD (light brown).

cordingly. The reduction models are based on fields of temperature and salinity. The EXFs applied in our study are derived from SLA of the TOPEX/Poseidon Extended Mission which were reduced by two models of the steric effect, one provided by Ishii (cyan) and the other one based on own computations from data of the WOA05 (blue). Hydrological EXFs are computed from water storage variations as described by the hydrology models LDAS and LaD.

While the EXFs from the atmospheric data sets agree well, the oceanic EXFs from altimetry feature significantly larger amplitudes than the corresponding curves from the ocean models. This holds especially for the χ_1 component. Conversely, the hydrology models agree quite well in the χ_1 component, but there are huge discrepancies in the χ_2 component.

Comparisons with geodetic observations

In the following the combined effect of atmospheric, oceanic and hydrological EXFs is compared with geodetic observations. In Fig. 2.3.5 (upper panel) the EXFs of the atmosphere-ocean combinations [1] ECMWF + OMCT, [2] NCEP + ECCO and [3] ECMWF + Altimetry (reduced by the steric effect from WOA05) + oceanic motion effect from OMCT are displayed. All of them agree well with the geodetic EXFs.

When the hydrological effect of LDAS is included too (Fig. 2.3.5, lower panel), the agreement is slightly improved although the influence is very small. Correlation coefficients and RMS differences with respect to the geodetic observations reveal that combinations from atmospheric data and ocean models agree better

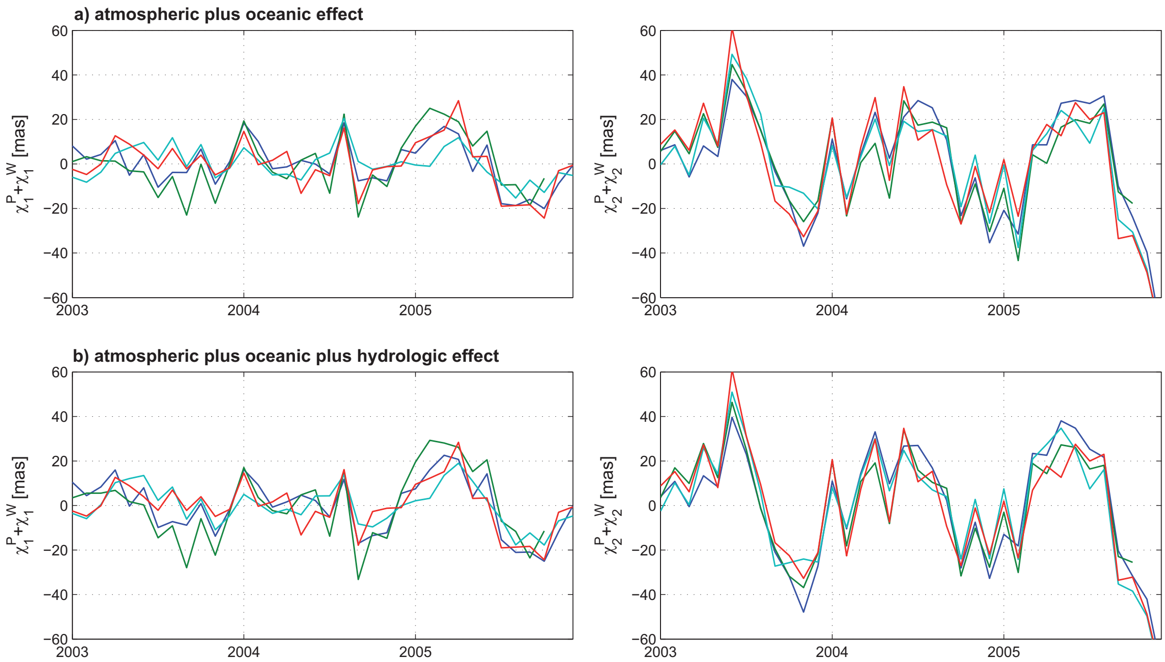


Fig 2.3.5: Upper panel: Combined atmospheric and oceanic excitation functions (blue: combination [1]; cyan: [2]; green: [3], cf. text). Lower panel: Combined atmospheric, oceanic and hydrologic excitation functions (same combinations like upper panel plus hydrologic effect from LDAS). For comparison, geodetic observations are given in red.

with the observed polar motion than combinations including oceanic EXFs from altimetry.

The main reason therefore is that the previous combinations are more consistent, i.e., the phase relations between the data sets match because ocean models are forced by respective atmospheric data. Since mass EXFs from altimetry, motion EXFs from OMCT and atmospheric EXFs from ECMWF are not in phase, artificial signals due to the noncompensation of counteracting signals are likely. Here additional investigations are necessary.

Improvement of ocean tide models using multi-mission altimetry

Global ocean tide models perform rather well in the deep ocean, but tides in shallow water areas are significantly worse known. Better global ocean tide models are needed for modelling of (coastal) sea surface heights and hence the marine gravity potential, which is necessary for processing GRACE observations (in the context of the DFG DAROTA project).

The analysis of altimeter data itself can help to improve the global ocean tide models. The alias effects caused by sparse temporal sampling of satellite altimetry make it difficult or impossible to separate certain tidal constituents and other sea surface variations. The time series of TOPEX and Jason-1 are the longest and most accurate ones and are usually used for tidal analysis. However, accurate tidal models in shallow water areas suffer from the large separation of ground tracks. The time series of altimeter missions with denser ground track patterns (like ERS, ENVISAT and GFO), have extremely long or even infinite alias periods and cannot be used alone to increase the spatial resolution. Thus only the combination of time series of missions with different orbit characteristics mitigates the alias-effects and improves the decorrelation of tidal constituents.

After a careful harmonization and cross-calibration of all altimeter missions a least-squares harmonic analysis was performed for the nodes of a regular geographical 15'×15' grid with normal equations accumulated for every grid node including all measurements inside a spherical cap of 1.125° radius. A Gauss function with a half-weight width of 0.375° is applied for weighting inverse-proportionally to the distance. As the sea surface heights were already corrected using the FES2004 global tidal model only residual tidal signals analysed. Mean value, trend, seasonal variations, the main tidal constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) and the most significant shallow water tidal constituent (M4) were estimated simultaneously.

Harmonic analysis for alias periods of M2, S2, N2, K2, O1, P1, Q1, and M4

The results of this approach can be seen in Fig. 2.3.6 and 2.3.7. Although FES2004 is one of the most accurate tide models, there are significant residual signals on the North-West-European Shelf, particularly near the British coast. For the semidiurnal tides (cf. Fig. 2.3.6) the residual signal meets the decimetre level. The residual diurnal tides (cf. Fig. 2.3.7) are significantly weaker; but in some parts of the area of investigation, the signal is greater than 5 cm. In high latitude areas, the lack of TOPEX and Jason-1 data causes problems for the de-correlation of certain tides as S2, K1, and P1, what can be already seen in Fig. 2.3.6 and 2.3.7 from very large residual signals.

To validate the analysis results, historical bottom pressure records for shallow water sites were used, kindly provided by the British Oceanographic Data Centre (BODC). In order to measure the improvements over FES2004, the time series of the bottom pressure records were first corrected by FES2004. In a second step the residual tide corrections of this analysis were subtracted. The

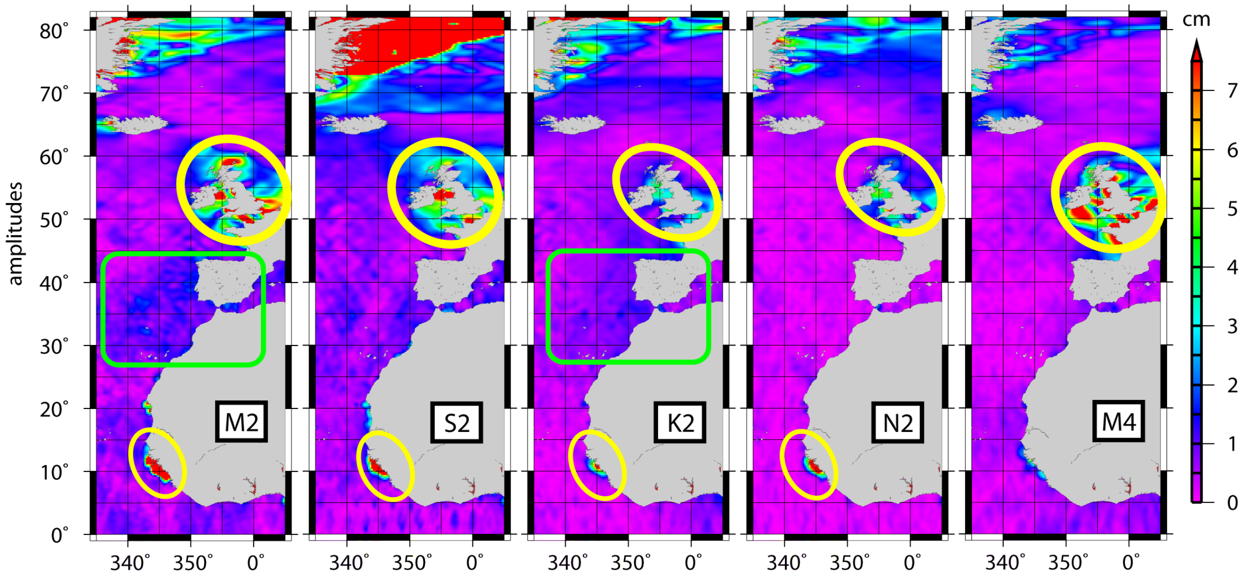


Fig. 2.3.6: Residual amplitudes (cm) of major semidiurnal tidal constituents. The yellow ellipses indicate areas with residuals up to or even above decimetre level. The green rectangles mark areas with large-scale pattern of residuals with 1-2 cm amplitude.

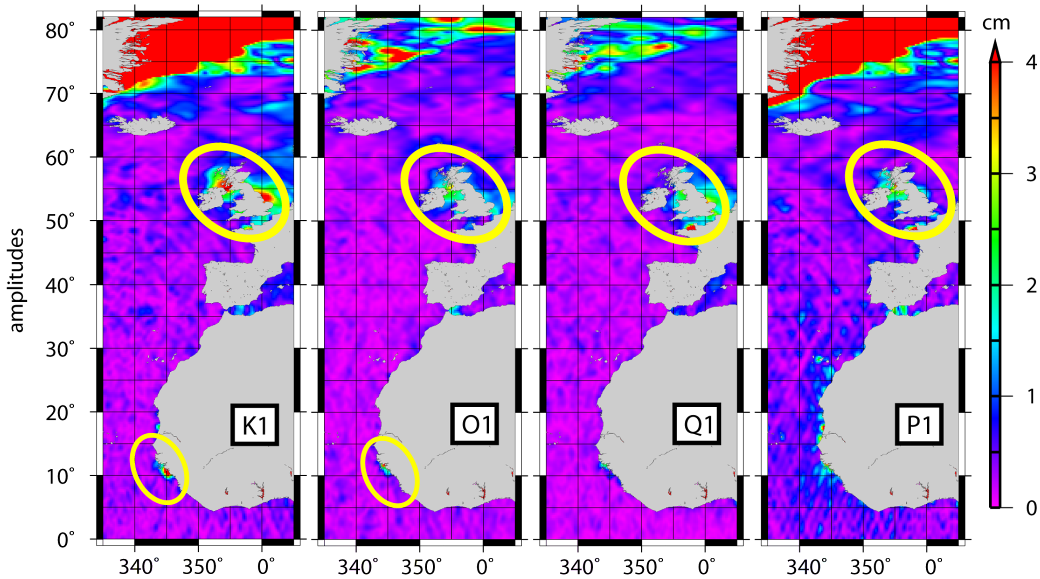


Fig. 2.3.7: Residual amplitudes (cm) of major diurnal tidal constituents. The yellow ellipses indicate areas with residuals up to 5 cm.

relative decrease of variance for each bottom pressure gauge is shown in Fig. 2.3.8.

In conclusion: The global tidal models can be improved by means of direct analysis of multi-mission altimetry. The combined analysis of multi-mission time series significantly helps to reduce the most critical correlations in most parts of the ocean. At higher latitudes, however, the results for the solar constituents are not accurate. To achieve better results in these areas, it is necessary to modify the harmonic analysis or to apply the response method in order to stabilize the estimation by using additional information.

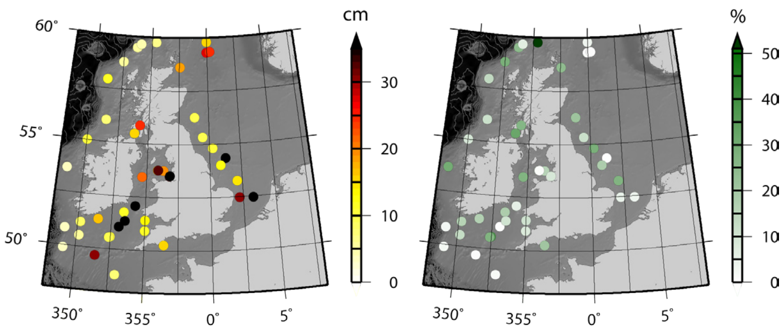


Fig. 2.3.8: Standard deviations (cm) of sea level variability for BODC bottom pressure gauges after subtracting the FES2004 tidal elevations. Right: The reduction of variance (in percent) achieved by applying the residual tide corrections.

2.4 Models of crustal deformation

The research on crustal deformation models at DGFI includes the computation of **A**ctual **P**late **Ki**nematic and crustal deformation **M**odels (APKIM) based on space geodetic observations (GPS, SLR, VLBI, DORIS), as well as investigations on regional horizontal and vertical deformations with emphasis on the vertical component.

Actual plate kinematic and crustal deformation model APKIM2005

For APKIM2005, the rotation vectors of 17 lithospheric plates of the geologic-geophysical model PB2002 (Bird 2003, Fig. 2.4.1) were estimated in a common least squares adjustment of station velocities of the International Terrestrial Reference Frame 2005 (ITRF2005) computed at IGN, Paris. Only sites situated on rigid parts of the plates were included. If various velocities from different space geodetic observation techniques at the same sites are given in ITRF2005, all of them were considered. In this way we come up with a total number of 346 velocity vectors. In the estimation procedure, outliers were eliminated after the 3σ-criterion, in total 41 vectors, which did either not follow the plate rotations or had large uncertainties in ITRF2005.

The geometry of deformation zones between the rigid plates was taken from the PB2002 model, where they are called "orogens". The crustal movements of these areas were represented by continuous deformation models using a least-squares collocation approach. A velocity field in a 1°×1° geographic grid covering the orogenic zones was predicted from the ITRF2005 velocity vectors available in the respective area. A total of five regions were modelled: The Alpine, Persia-Tibet-Burma, Alaska-Yukon, Gorda-California, and Andes orogens. In the Andean region, the North Andes block and the Altiplano plate were included as deformation zones. The deformation of the Alaska-Yukon orogen is shown in Fig. 2.4.2 as an example.

Realization of the NNR kinematic datum

The ITRF2005 velocities are referred to the datum of the geologic-geophysical model NNR NUVEL-1A. This model does not consider any deformation zones and gives average velocities of

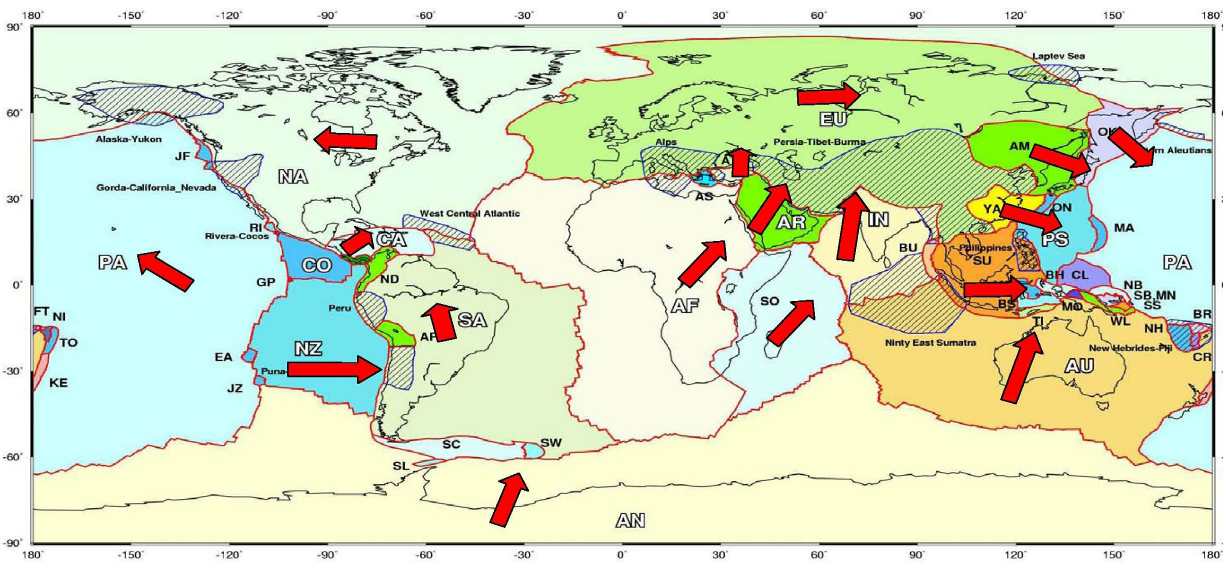


Fig. 2.4.1: Rotation vectors of plates of PB2002 model estimated from ITRF2005 velocities.

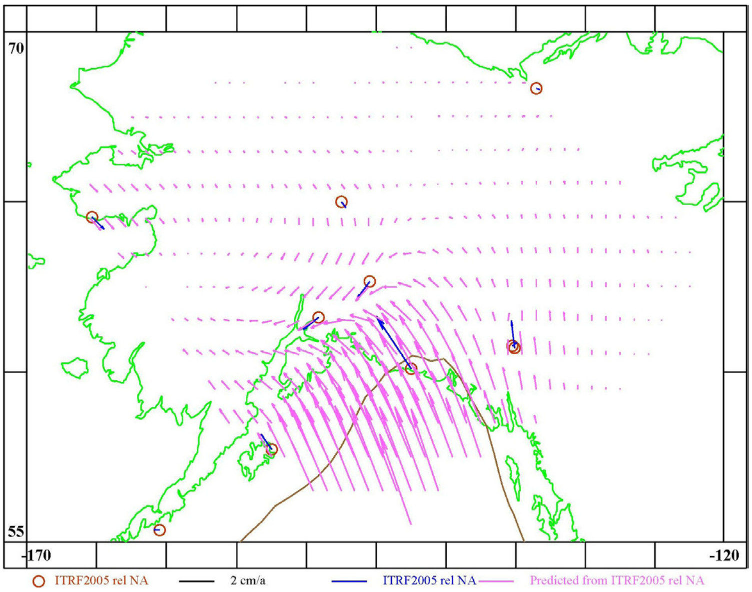


Fig. 2.4.2: Deformation of the Alaska-Yukon orogen predicted from observed velocities.

the last three million years. Therefore it does not fulfill the 'No Net Rotation' (NNR) condition required in geodesy for consistency of station velocities and Earth rotation parameters (ERP). To reduce the velocities to a present-day NNR condition including rigid plates and deformation zones, the common rotation of the complete Earth surface in the ITRF2005 datum was computed. The input data set was a 1°×1° geographic grid of plate motions and continuous (deformation) movements calculated from the preliminary APKIM model as described above. Fig. 2.4.3 shows the Mediterranean area as an example. The global common rotation vector is

$$\omega_X = -0.042 \pm 0.007 \text{ [mas/a]},$$
$$\omega_Y = \;\; 0.031 \pm 0.007 \text{ [mas/a]},$$
$$\omega_Z = -0.023 \pm 0.007 \text{ [mas/a]}$$

This rotation vector is subtracted from all plate rotation and deformation vectors and leads to the NNR APKIM2005 model.

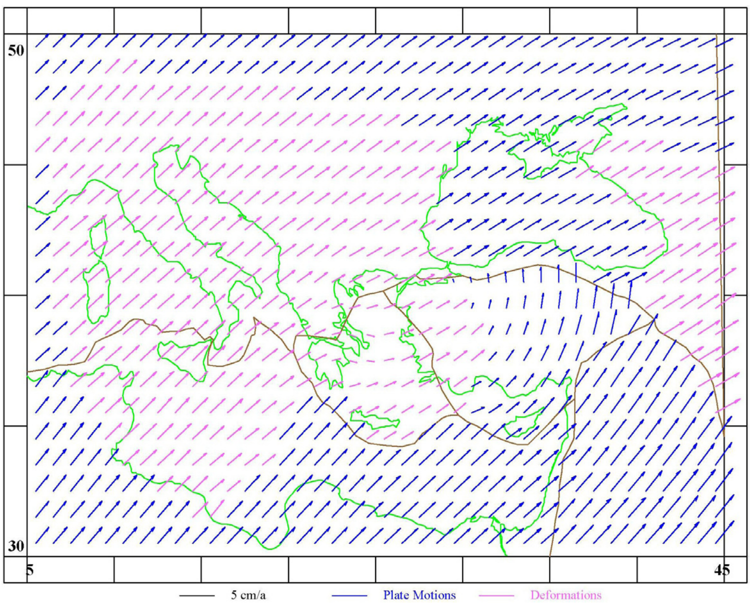


Fig. 2.4.3: 1°×1° plate motion and crustal deformation pattern in the Mediterranean.

Actual plate kinematic and crustal deformation model APKIM2005D

In the same way as the APKIM2005 was computed from the ITRF2005 velocities, an APKIM2005D was derived from the DGFI solution ITRF2005D (cf. topic 3.1). The difference is that the ITRF2005D and the APKIM2005D were computed iteratively. After a preliminary ITRF computation in the ITRF2000 datum, a preliminary APKIM was estimated from those velocities. The NNR velocities of this model served then as kinematic datum constraints for the final ITRF2005D and APKIM2005D.

A comparison of APKIM2005, APKIM2005D and PB2002 rotation vectors is given in Tab. 2.4.1. There are some discrepancies between the two APKIM models which may be caused by the common adjustment of station velocities and ERP in the ITRF2000 datum, i.e. NNR NUVEL-1A. As this datum does not fulfill the NNR condition, the common datum effects of the velocities enter into the ERPs.

Tab. 2.4.1: Comparison of plate kinematic models APKIM2005 (from ITRF2005), APKIM2005D5 (from ITRF2005 DGFI-solution, and PB2002 (geological-geophysical model).

		APKIM2005	APKIM2005D5	PB002
Africa	φ [°]	48.07 ± 0.30	49.30 ± 0.36	50.56
	λ [°]	280.70 ± 0.79	280.47 ± 0.98	286.05
	ω [°/Ma]	0.279 ± 0.002	0.273 ± 0.002	0.291
Amur	φ [°]	52.76 ± 22.86	56.80 ± 7.83	44.33
	λ [°]	268.57 ± 21.93	259.09 ± 8.71	261.62
	ω [°/Ma]	0.268 ± 0.031	0.286 ± 0.016	0.308
Antarctic	φ [°]	61.11 ± 0.46	60.95 ± 0.44	63.00
	λ [°]	239.53 ± 0.70	239.55 ± 0.93	244.26
	ω [°/Ma]	0.243 ± 0.004	0.242 ± 0.005	0.238
Arabia	φ [°]	48.88 ± 0.56	49.48 ± 0.83	46.67
	λ [°]	3.76 ± 2.07	4.83 ± 3.27	353.80
	ω [°/Ma]	0.599 ± 0.019	0.596 ± 0.029	0.593
Anatolia	φ [°]	39.99 ± 0.19	40.02 ± 0.22	40.93
	λ [°]	27.97 ± 0.33	28.33 ± 0.42	27.25
	ω [°/Ma]	2.021 ± 0.116	2.021 ± 0.137	1.210
Australia	φ [°]	32.75 ± 0.14	33.20 ± 0.19	33.86
	λ [°]	36.70 ± 0.30	36.25 ± 0.47	33.17
	ω [°/Ma]	0.639 ± 0.002	0.633 ± 0.003	0.646
Caribbea	φ [°]	32.59 ± 2.80	46.46 ± 1.84	34.04
	λ [°]	241.07 ± 10.10	227.03 ± 18.15	272.42
	ω [°/Ma]	0.186 ± 0.022	0.160 ± 0.021	0.291
Eurasia	φ [°]	53.43 ± 0.39	54.53 ± 0.36	50.63
	λ [°]	264.25 ± 0.48	262.87 ± 0.52	247.72
	ω [°/Ma]	0.259 ± 0.001	0.258 ± 0.001	0.234
India	φ [°]	48.19 ± 2.31	51.29 ± 0.64	45.51
	λ [°]	19.12 ± 10.97	-3.90 ± 15.63	0.34
	ω [°/Ma]	0.588 ± 0.048	0.524 ± 0.024	0.545
North America	φ [°]	-4.29 ± 0.60	-1.93 ± 0.44	-2.41
	λ [°]	275.80 ± 0.24	278.09 ± 0.23	274.11
	ω [°/Ma]	0.194 ± 0.002	0.205 ± 0.002	0.207
Nazca	φ [°]	45.06 ± 0.91	44.63 ± 1.25	47.80
	λ [°]	259.93 ± 0.42	260.32 ± 0.52	259.87
	ω [°/Ma]	0.652 ± 0.008	0.655 ± 0.012	0.743
Okhotsk	φ [°]	-37.38 ± 0.39	-37.33 ± 0.10	63.04
	λ [°]	314.43 ± 0.95	311.85 ± 0.44	107.32
	ω [°/Ma]	0.874 ± 0.116	0.738 ± 0.034	0.641
Pacific	φ [°]	-63.21 ± 0.11	-63.80 ± 0.15	25.32
	λ [°]	110.46 ± 0.49	111.23 ± 0.67	235.57
	ω [°/Ma]	0.671 ± 0.001	0.667 ± 0.002	0.116
South America	φ [°]	-14.56 ± 0.89	17.20 ± 1.11	49.76
	λ [°]	238.98 ± 1.55	241.50 ± 2.28	266.73
	ω [°/Ma]	0.123 ± 0.002	0.115 ± 0.002	0.348
Somalia	φ [°]	51.34 ± 0.96	-52.37 ± 1.34	45.17
	λ [°]	274.73 ± 2.28	272.21 ± 3.49	286.80
	ω [°/Ma]	0.308 ± 0.006	0.308 ± 0.009	0.476
Sunda	φ [°]	43.16 ± 4.67	33.32 ± 5.42	66.85
	λ [°]	276.25 ± 1.94	278.45 ± 1.57	209.52
	ω [°/Ma]	0.392 ± 0.033	0.490 ± 0.076	0.393
Yangtze	φ [°]	56.59 ± 9.94	55.17 ± 12.08	69.07
	λ [°]	261.77 ± 13.46	259.99 ± 14.09	262.28
	ω [°/Ma]	0.315 ± 0.006	0.320 ± 0.005	0.998

Model for vertical load deformations in consideration of crustal inhomogenities

Mass redistributions in various components of the Earth system exert time-variable surface loads on the solid Earth. The resulting variations of the Earth's geometry, which can be in the order of a few centimetres, are reflected by vertical displacements of geodetic markers. The largest load deformations emerge in continental regions due to atmospheric surface pressure anomalies and hydrological mass variations.

Most approaches for the conversion of surface loads into deformations of the solid Earth follow a simple theory based on load Love numbers which are associated with a site-independent weighting function (Green's function). Since the load Love numbers are global values, this procedure does not account for inhomogeneities of crustal material. However a distinct relation between regional characteristics of the crust and the Earth's reaction on surface loads might be expected. Consequently this approach appears to be in need of improvement. We discuss an alternative method in which the common Green's function is substituted by a site-dependent exponential function $F(\psi_{PQ})$ considering different densities of crustal material. $F(\psi_{PQ})$ is defined by

$$F(\psi_{PQ}) := 10^{-17} a\, e^{-b\psi_{PQ}} \tag{1}$$

Local exponential load function instead of global Green's function

where ψ_{PQ} is the spherical distance between the geographical location of the mass load Q and the geodetic marker P. The choice of different numerical values for the parameters a and b allows to account for regional discrepancies of crustal densities. The parameter a which is in the unit of m/kg provides a measure of the vertical deformation of a grid cell on the Earth's surface if loaded by 1 kg. The parameter b determines the decay of the curve, i.e., the effect of a load on neighbouring cells as a function of their spherical distance. Fig. 2.4.4 illustrates the principle of the approach. In a first approximation the parameter a shall be related to the density of the actually loaded grid cell whereas the parameter b is associated with the (mean) density of surrounding cells. Consequently the two parameters are considered to be independent.

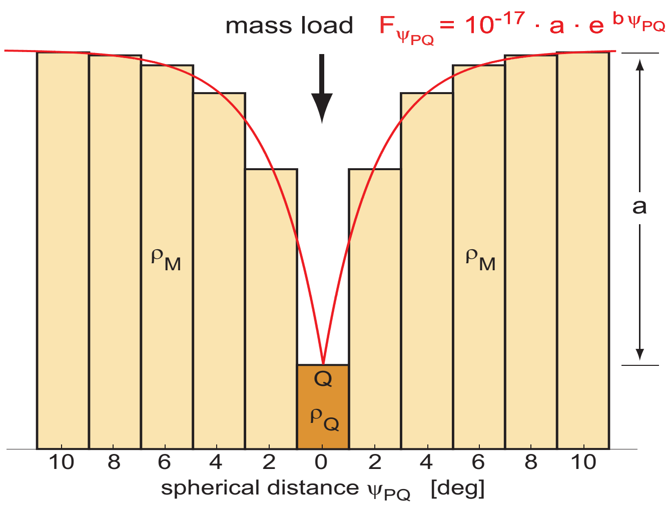


Fig. 2.4.4: Principle of the site dependent approach. Parameter a is related to the density ρ_Q of the loaded grid cell, parameter b is related to the mean density ρ_M of the surrounding cells.

Numerical results

Numerical values of the parameters a and b are estimated by least-squares adjustment for cells of 2°×2° using geodetic observations of vertical site displacements from weekly solutions of the global GPS station network of the International GNSS Service (IGS). These station position time series are based on the weekly combined IGS solutions provided for the ITRF2005 computation. They are available since 1996. Altogether 105 globally distributed GPS stations with a total of 29500 weekly observations of vertical deformations were considered.

On the basis of the crustal model Crust2.0 regions are predefined for which identical parameters are determined in order to reduce the number of unknowns. The model Crust2.0 provides global information on crustal material, thickness and density for 2°×2° blocks. In the model the crust is composed of soft and hard sediments, upper, mean and lower mantle. Density values range from 2.60 to 2.95 g/cm³ which are discretized in steps of 0.01 g/cm³.

It is assumed that loads are effective on grid cells within a radius of 10°. In order to decide which parameter b_i is effective for a certain cell, the mean density values of the cells within a circle of 10° around this cell are computed. This leads to a smoothing of the density values which implies that there are less parameters b_i than a_i. First numerical experiments showed that each parameter a_i and b_i should be covered by at least 20 stations in order to minimize the influence of measurement errors on the parameter estimation. For the parameter estimation, seven different parameters a_i and five different parameters b_i are applied.

The numerical values of the parameters are estimated by least-squares adjustment. The observation equation reads

$$d_r(P) = \sum_{\substack{k=1 \\ \psi_{PQ_k}<10°}}^{N} 10^{-17} q_{Q_k} A_{Q_k} (a_{ik} e^{b_{ik}\psi_{PQ_k}}) \qquad (2)$$

where $d_r(P)$ is the vertical deformation at point P, q_{Qk} is the surface load in kg/m² and A_k is the area of the loaded grid cell k.

Load forces

Pressure fields of atmosphere (re-analyses of the National Centres for Environmental Prediction, NCEP), continental hydrosphere (Land Dynamics Model, LaD) and oceans (Estimating the Circulation and the Climate of the Ocean, ECCO) are considered as forcing. As approximate values for the unknowns we introduce the afore mentioned values $a = -12.5$ and $b = -35$ which result from the fit of function $F(\psi_{PQ})$ to the traditional Green's function. After five iterations, convergence is reached. The adjusted parameters agree quite well with the approximate values, and in principle the results match the expectations: For cells with low densities the deformation is stronger and the function is steeper than for cells with higher densities.

Load forces

In order to validate the numerical results, model time series from both the traditional and the site-dependent approach are compared with GPS observations. Fig. 2.4.5 shows the model time series for three stations on different continents and the respective GPS observations. The green dotted lines are the curves that result from the Green's function approach applying identical forcing. Analyses reveal that in general the proposed approach is more effective for explaining characteristic features in the observations. For none of the stations in our study, the agreement between observations and model results deteriorates when the site-dependent weighting functions are applied instead of the Green's function. The largest discrepancies between both methods (RMS differences up to 2 mm) are apparent in regions where high annual vertical displacements are observed, e.g., in Siberia, the arctic regions of North America and the Gulf Stream region. But on the other hand there are regions where the improvement is marginal, e.g., Europe and South-East Asia.

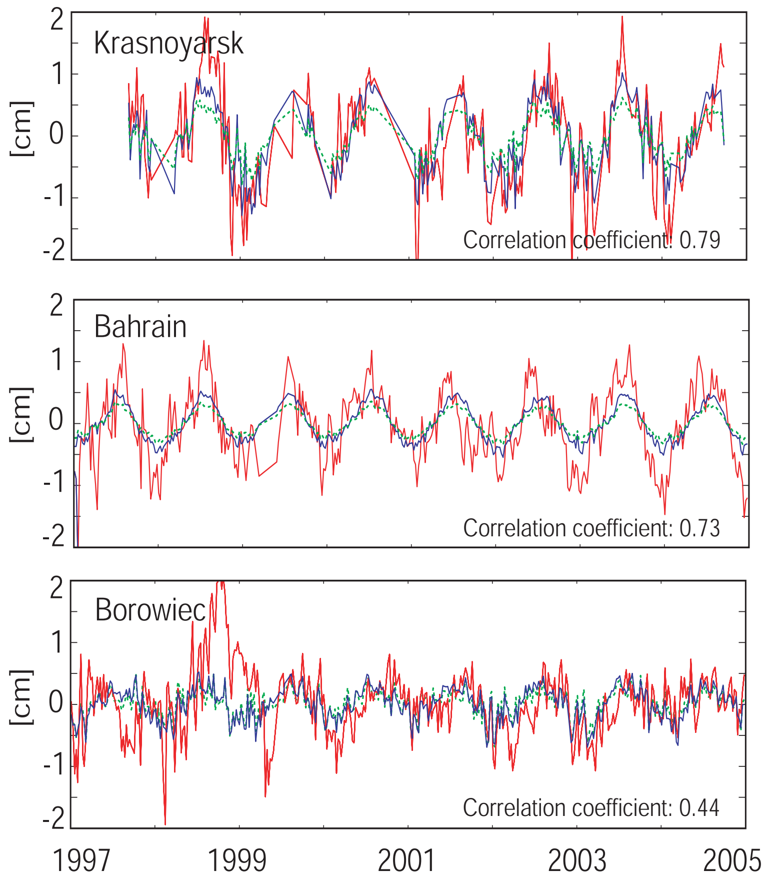


Fig 2.4.5 Model time series for three stations on different continents (blue), respective GPS observations (red) and corresponding correlation coefficients. Green dotted lines are the results from the Green's function approach.

3 International Scientific Services and Projects

DGFI has participated for many years in the activities of international scientific services and projects. It operates data centres, analysis centres and combination centres of several services of the International Association of Geodesy (IAG) and participates in various international projects. In the International Earth Rotation and Reference Systems Service (IERS), DGFI is one of the three official Combination Centres for the realization of the International Terrestrial Reference System (ITRS) and a Combination Research Centre (CRC). In the International GNSS Service (IGS) DGFI operates the Regional Network Associate Analysis Centre for SIRGAS (RNAAC-SIR). For the International Laser Ranging Service (ILRS), DGFI acts as one of the two Global Data Centres (EUROLAS Data Centre, EDC), as an Analysis Centre (AC), and as a Combination Centre (CC). In the International VLBI Service for Geodesy and Astrometry (IVS), DGFI operates an Analysis Centre (AC). DGFI also got the leading role for the installation of the International Altimetry Service (IAS). In IAG's Global Geodetic Observing System (GGOS), DGFI participates in particular in the Working Group on Conventions, Analysis and Modelling. Furthermore, DGFI is active in some international projects by operating permanent GPS stations and data analysis, e.g., in the IGS Tide Gauge benchmark monitoring project (TIGA) and in the European Union's Territorial Cooperation (INTERREG) Alpine Space Project for detection and control of crustal deformations in the Alpine region (ALPS-GPS QUAKENET). The results from these activities enter directly into the basic research (Chapters 1 and 2) and vice versa.

3.1 ITRS Combination Centre / IERS Combination Research Centre

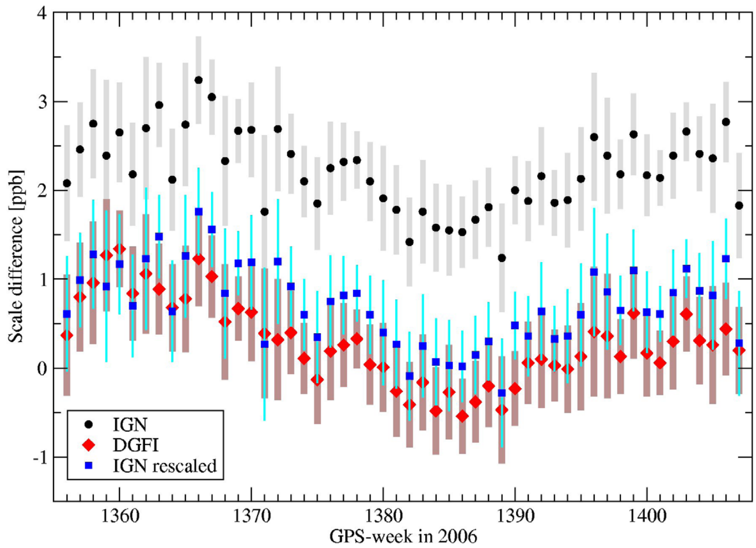
The ITRS/IERS activities include the following items:

− Final ITRF2005 solution of DGFI (ITRF2005D)
− Comparison of the computation strategies of IGN and DGFI
− Study of effects of different ITRF computation strategies

General remarks on the ITRF2005

In June 2006 DGFI finished the computation of a preliminary ITRF2005D solution. A comparison between the preliminary solutions of IGN and DGFI showed a good agreement for station positions and velocities after similarity transformations, but a significant difference in the SLR scale. This is due to different computation strategy and handling of local ties (see below). The analysis of weekly SLR solutions in 2006 and 2007 showed that the scale is in good agreement with the ITRF2005 solution of DGFI, whereas there is a significant scale bias of about 2 ppb compared with the IGN solution (see Fig. 3.1.1), equivalent to a difference of 1.3 cm in SLR station heights. This scale discrepancy was extensively discussed within the IERS and the IAG Services, in particular with the ILRS. It was argued by IGN that there is a "real" scale bias between VLBI and SLR, which is not visible in the DGFI computations. As a consequence the ITRF2005 scale of the IGN solution was defined by VLBI only (because of the longer time series of VLBI observations and non-linear effects in the SLR scale time series of IGN), whereas the scale of the DGFI solution was defined by a weighted mean of SLR and VLBI data. Despite of this unresolved inconsistency in the scale definition of the ITRF2005 and without an overall agreement on this subject, the ITRS Product Centre released the IGN solution as official ITRF2005 in October 2006, which was not accepted by the ILRS. Consequently, the ILRS wrote in November 2006 an "Objection to the ITRF2005 realization" to the IERS chair. The ILRS also decided to use the old ITRF2000 as reference frame, instead of the ITRF2005. As a compromise, IGN provided a second (rescaled) ITRF2005 solution for SLR users in December 2006.

Fig. 3.1.1: Scale of ITRF2005 solutions of IGN and DGFI with respect to weekly SLR solutions (ILRSA).



Final ITRF2005 solution of DGFI (ITRF2005D)

The general concept of the ITRS Combination Centre at DGFI is based on the combination of normal equations and the common adjustment of station positions, velocities and EOP with the DGFI software DOGS-CS. Major updates and changes for the computation of the final DGFI solution are the following:

- Handling of local ties: In the preliminary solution all selected local ties were introduced at the reference epoch 2000.0 of the ITRF2005. In the final solution we introduced the local ties exactly at their observation times if this information was available. For the other ties with unknown observation times we used the reference epoch 2000.0. For the final solution we selected additional local ties by an iterative procedure. In a first step we selected co-locations with an agreement of better than 1 cm (1.5 cm in the case of co-locations with DORIS) between the space geodetic solutions and the local tie measurements. Then we performed a second iteration with a threshold of 3 cm to increase the number of co-locations for the inter-technique combination. Tab. 3.1.1 shows the number of co-locations which were used for the ITRF2005D solution. During the iterations also the weighting factors between the different techniques were re-estimated.

- Realization of the geodetic datum: The origin (translation parameters and their rates) is realized by the contributing SLR solutions, and the scale and its time variation by SLR and VLBI.

Tab. 3.1.1: Number of co-locations between different techniques used for the ITRF2005D combination. In the first iteration, local tie vectors with differences to the space geodetic solutions below 1 cm (1.5 cm for co-locations to DORIS) were selected, in the second iteration the threshold was 3 cm for all co-locations.

Techniques	1. Iteration	2. Iteration
	# co-locations	# co-locations
GPS – VLBI	26	8
GPS – SLR	18	9
GPS – DORIS	18	9
VLBI – SLR	6	4
VLBI – DORIS	7	1
SLR – DORIS	9	0

The orientation of the ITRF2005D is realized by no-net-rotation (NNR) conditions with respect to ITRF2000 using "good" reference stations to ensure consistency with the Bureau International de l'Heure (BIH) orientation at 1984.0. The kinematic datum of the final ITRF2005D solution is given by an actual plate kinematic and crustal deformation model (APKIM) derived from observed station velocities. The new model APKIM2005 was computed iteratively from the ITRF2005D velocities (see topic 2.4). Fig. 3.1.2 shows the residuals of the ITRF2005D station velocities with respect to APKIM05D5 for 56 core stations used to realize the kinematic datum. All these stations have long data time series and are not located in deformation zones. The RMS of the residuals is about 0.4 mm/yr and 0.6 mm/yr for the North and East components, respectively. The kinematic datum of the preliminary DGFI solution was defined with respect to ITRF2000 (consistent with the geological-geophysical model NNR NUVEL-1a), which serves also as the reference for the IGN solution.

The ITRF2005D solution comprises station positions, velocities and daily EOP estimates as primary results. In addition, epoch position residuals and time series of translation and scale parameters are obtained from the combination. Fig. 3.1.3 and 3.1.4 show the horizonal and vertical station velocities of the ITRF2005D solution. The terrestrial pole coordinates of the ITRF2005D solution with respect IERS C04 are displayed in Fig. 3.1.5. There is a significant improvement since mid of 1999, when GPS-derived pole coordinates were included in the combination.

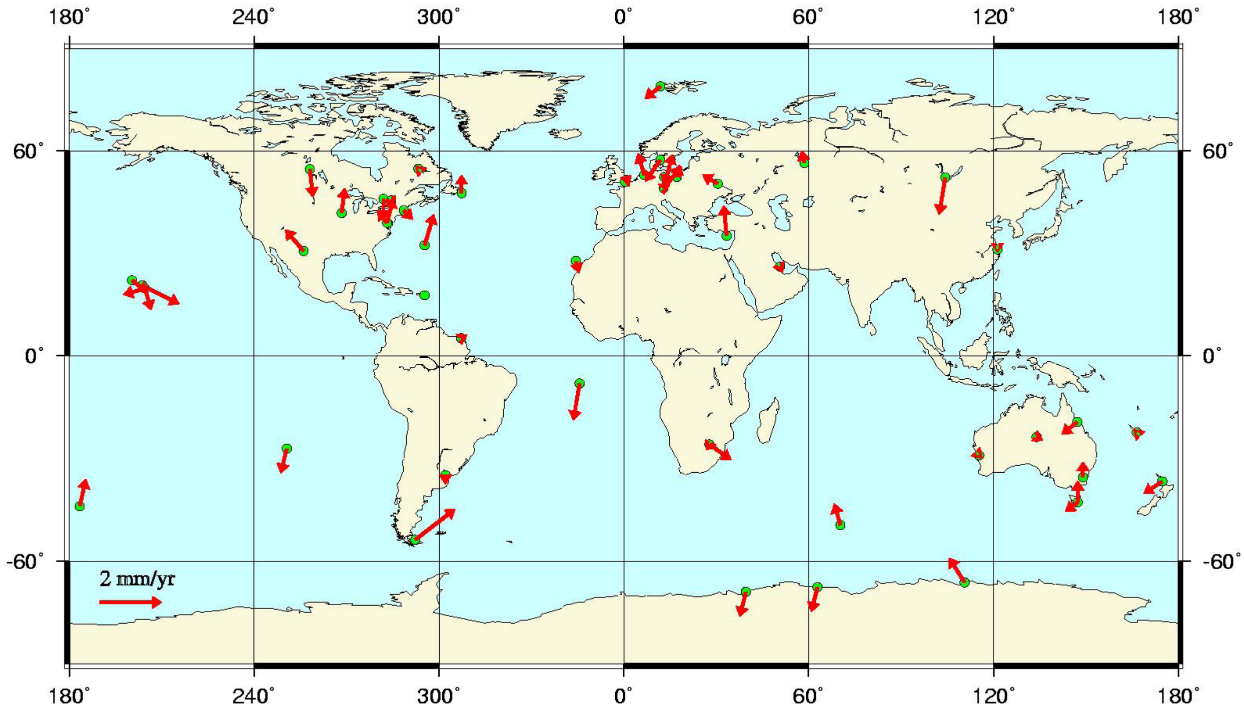


Fig. 3.1.2: Station velocity residuals for the 56 core stations used to realize the kinematic datum of the ITRF2005D solution with respect to APKIM05D5.

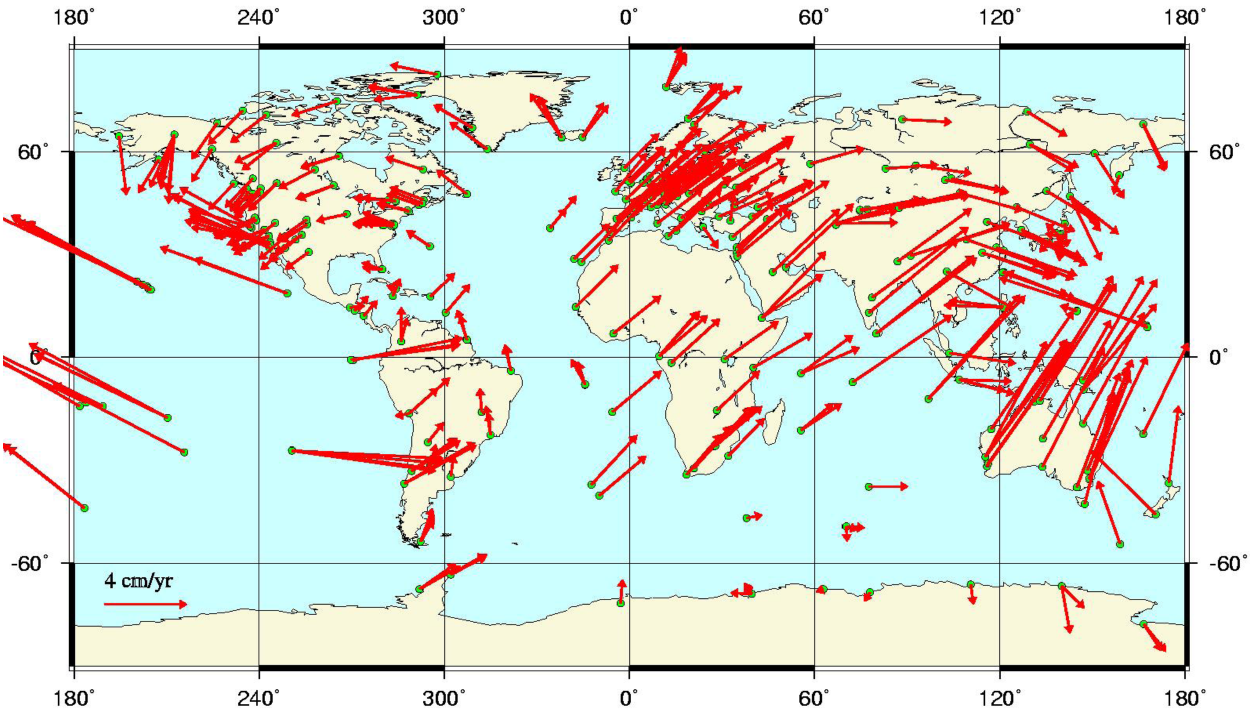


Fig. 3.1.3: Horizontal station velocities of the ITRF2005D solution. Note that only velocities with σ_{vel} below 1 cm/yr are shown.

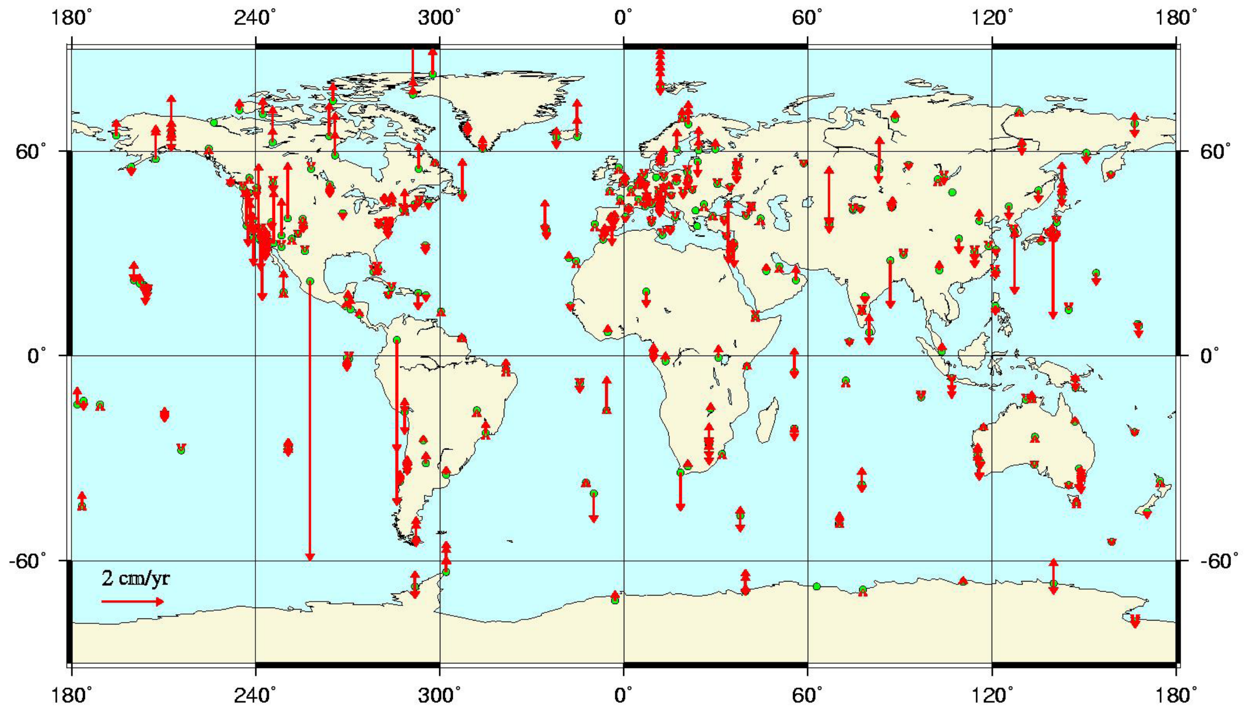


Fig. 3.1.4: Vertical station velocities of the ITRF2005D solution. Note that only velocities with σ_{vel} below 1 cm/yr are shown.

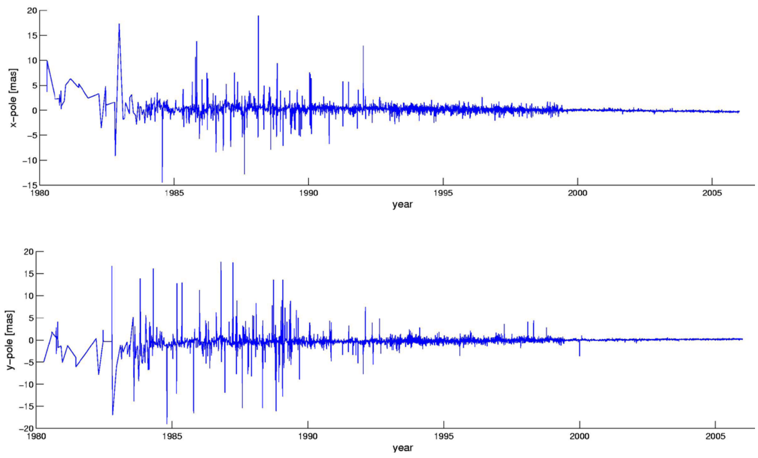


Fig. 3.1.5: Terrestrial pole coordinates of ITRF2005D solution with respect to IERS C04 series.

Comparison of the computation strategies of IGN and DGFI

The computation strategy of IGN is based on the solution level by simultaneously estimating station positions and velocities as well as similarity transformation parameters with respect to the combined frame. The general concept of DGFI is the combination of normal equations and the common adjustment of station positions, velocities and EOP. A comparison of the combination strategies of both ITRS Combination Centres is given in Tab. 3.1.2.

Tab. 3.1.2: Comparison of IGN and DGFI combination strategies.

	IGN	DGFI
Software	CATREF	DOGS-CS
Time series combination	Stacking of minimum constrained solutions 7 transformation parameters	Accumulation of normal equations Without transformation
Inter-technique combination	Combination of per-technique solutions 14 transformation parameters IGN set of local ties	Accumulation of per-technique normal equations Without transformations DGFI set of local ties
ITRF2005 datum		
– Origin	SLR	SLR
– Scale	VLBI	VLBI+SLR
– Rotation	3 NNR conditions w.r.t. ITRF2000	3 NNR conditions w.r.t. ITRF2000
– Rotation rate	3 NNR conditions w.r.t. NUVEL-1A	3 NNR conditions w.r.t. APKIM2005

Effect of different ITRF computation strategies

A comparison between the IGN and DGFI solutions for ITRF2005 shows a good agreement for station positions and velocities after similarity transformations, but a significant difference in the SLR scale. The difference between both ITRF2005 solutions is nearly 1 ppb (offset) and 0.13 ppb/yr (rate), which accumulates to nearly 2 ppb in 2007 (see Tab. 3.1.3). The scale difference is not visible in the pure SLR intra-technique solutions of IGN and DGFI. This indicates that the difference between both ITRF2005 solutions originates from the inter-technique combination.

Tab. 3.1.3: Scale differences between the pure intra-technique and the ITRF2005 solutions of DGFI and IGN.

	Intra-technique solutions (IGN–DGFI)	ITRF solutions (IGN–DGFI)
SLR scale **offset [ppb]** **drift [ppb/yr]**	 −0.17 ± 0.06 0.01 ± 0.02	 0.86 ± 0.12 0.13 ± 0.03
VLBI scale **offset [ppb]** **drift [ppb/yr]**	 0.16 ± 0.05 0.01 ± 0.02	 0.12 ± 0.03 0.03 ± 0.03

Effect of co-location sites and handling of local ties

The selection and the weighting of local tie information is a critical issue for the combination of different space techniques, since the distribution of "good" co-location sites is relatively sparse (see Fig. 3.1.6).

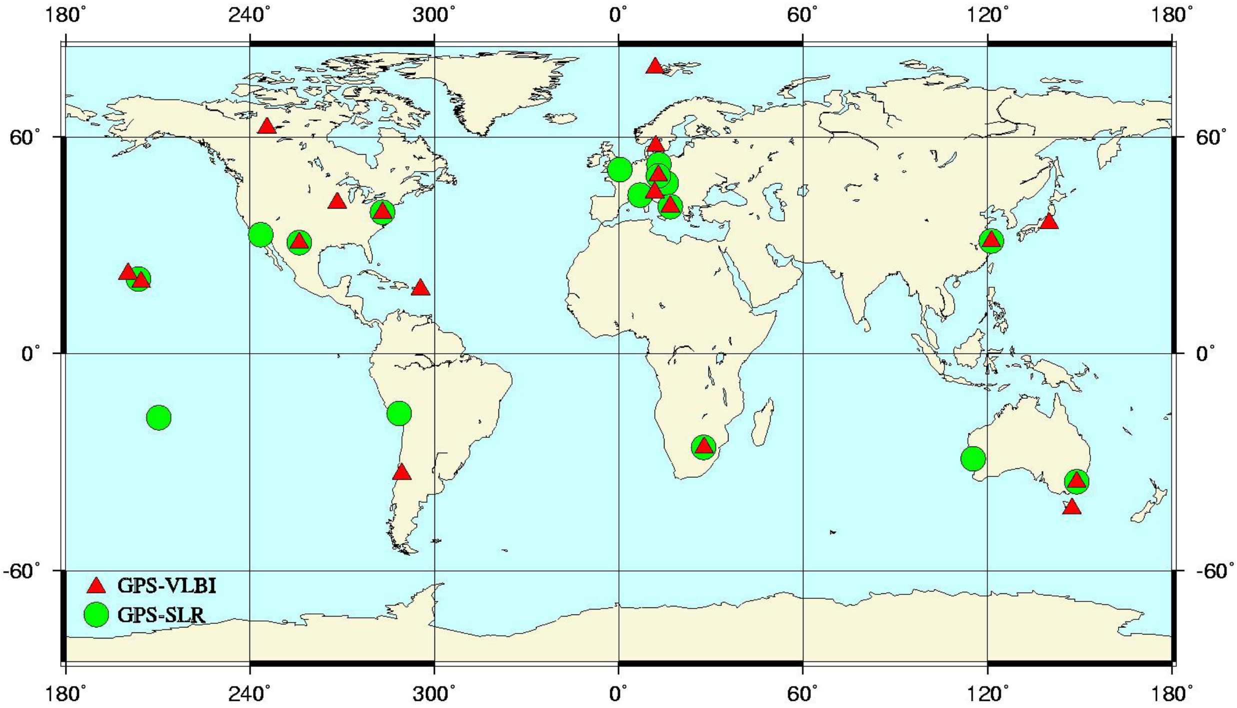


Fig. 3.1.6: Co-location sites between GPS, SLR and VLBI.

Co-location sites between SLR and GPS

The geographical distribution of SLR tracking stations is particularly problematic in the Southern hemisphere. Fig. 3.1.7 shows the observation statistics of the eight available co-location sites of SLR and GPS. Among them there are two stations with very few SLR data (Easter Island and Conception), and another one is (Arequipa) was affected by post-seismic deformation after the earthquakes in June 2001. Tab. 3.1.4 shows the different sets of co-location sites used by IGN and DGFI.

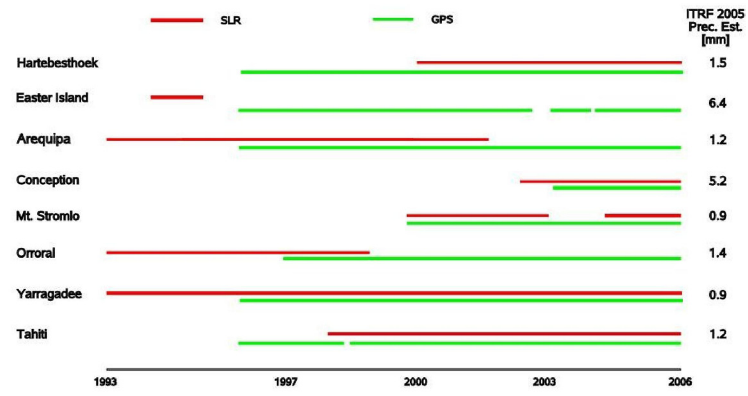


Fig. 3.1.7: Observation periods for SLR and GPS co-location sites in the Southern hemisphere.

Tab. 3.1.4: SLR and GPS co-location sites in the Southern hemisphere used by IGN and DGFI for the ITRF2005 inter-technique combination.

Site name	DGFI	IGN
Hartebeesthoek	used	used
Easter Island	not used	used
Arequipa	used	used
Conception	not used	used
Mt. Stromlo	used	down-weighted
Orroral / TIDB	used	down-weighted
Yarragadee	used	down-weighted
Tahiti / PAMA	used	down-weighted

Tab. 3.1.5: Scale differences between SLR and VLBI observations obtained from two solutions: solution 1 with the local tie selection used by DGFI and solution 2 with the IGN selection (see Tab. 3.1.4).

Solution type	delta Scale offset [ppb]	delta Scale rate [ppb/yr]
Solution 1	0.26 ± 0.41	0.03 ± 0.09
Solution 2	1.05 ± 0.44	0.11 ± 0.10

We investigated the effect of a different local tie selection on the combination results by means of Helmerttransformations. Tab. 3.1.5 shows the effect on the scale of SLR and VLBI. We performed two solutions with different sets of co-location sites. If the co-location sites TIDB, STR1, YAR1 and TAHI are down-weighted (as done in the IGN solution), there is a scale difference between SLR and VLBI, which is not visible with the local tie set used by DGFI.

The fact that IGN and DGFI provided each one solution for ITRF2005 using different software and combination strategies provided for the first time the basis for a through validation and quality control of the terrestrial reference frame results. The major problem is the significant difference in the SLR scale, which is subject of further analysis. IGN and DGFI agreed to perform further test computations to assess the effect of differences in the combination strategies. Since the availability and spatial distribution of high-quality co-location sites is not optimal, the handling of local ties is a very critical issue within the inter-technique combination.

3.2 IGS Regional Network Associate Analysis Centre

For eleven years, DGFI has acted as an IGS Regional Network Associate Analysis Centre for Latin Americaa (IGS RNAAC SIR). Each week a coordinate solution including all available observations of this network is generated and delivered to the IGS Global Data Centres.

RNAAC SIR network status

The number of included stations in the RNAAC SIR processing actually varies between 100 and 110 stations in the daily and weekly solutions. The number of participating permanent GPS stations will still increase considerably, especially in Argentina, Brazil and Colombia. But the distribution of stations over the continent is not yet ideal (see Fig. 3.2.1 and Fig. 3.2.2).

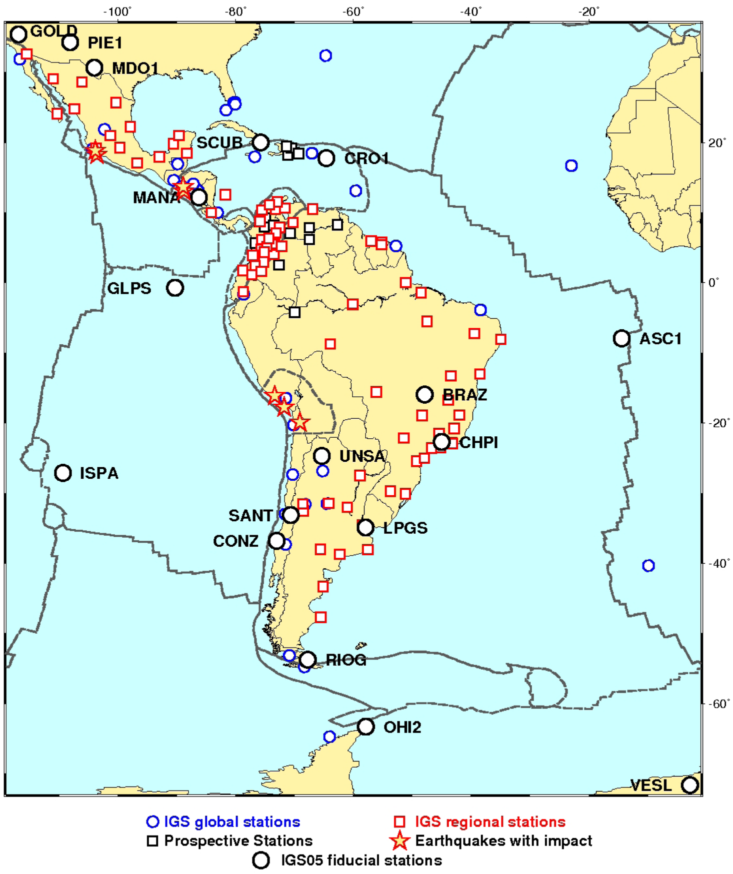


Fig. 3.2.1: The IGS RNAAC SIR network and IGS05 fiducial stations.

Changes in processing of the weekly coordinate solutions

The IGS RNAAC SIR processing at DGFI is done with the Bernese Processing Engine, version 5.0 (BPE). Recently IGS decided to introduce absolute (instead of relative) antenna phase centre variations, as well as the latest ITRF2005 realization for all products. The IGS realization of ITRF2005, the so-called IGS05, and the absolute phase centre variation were implemented at the IGS RNAAC SIR from GPS week 1400 onward.

Country	Stations: IGS Stations	Stations: Regional Stations	Number: IGS	Number: Reg.
Antarctica	OHIG/OHI2, PALM, VESL		3	
Argentina	AUTF, CFAG, CORD, LPGS, RIOG/RIO2, TUCU, UNSA	IGM0/1, LHCL, MECO, MPLA, MZAC, MZAS, PDES, RWSN, UCOR, UNRO, UNSJ, VBCA	7	12
Barbados	BARB/BDOS		1	
Brazil	BRAZ, BRFT, CHPI, FORT	BELE, BOMJ, CRAT, CUIB, GVAL, IMPZ, MANU, MAPA, MCLA, NAUS, NEIA, ONRJ, PARA, POAL, POLI, POVE, RECF, RIOD, SALV, SMAR, UBAT, UBER, UEPP/PPTE, VARG, VIC	4	25
Cape Verde	TGCV		1	
Chile	ANTC, CONZ, COPO, COYQ, EISL/ISPA, IQQE, PARC, SANT, VALP		9	
Colombia	BOGT	ANDS, BERR, BOGA, BUCA, BUEN, CALI, CART, CUCU, DORA, FLOR, IBAG, MEDE, MOTE, NEVA, PERA, POPA, PSTO, RIOH SAMA, TUMA, TUNA, VALL, VIVI, YOPA	1	24
Costa Rica	MOIN	ETCG	1	1
Cuba	SCUB		1	
Ecuador	GALA/GLPS, RIOP	S061	2	1
El Salvador	SSIA		1	
French Guyana	KOUR		1	
Guatemala	GUAT, ELEN		2	
Honduras	SLOR, TEGU/TEG1		2	
Jamaica	JAMA		1	
Mexico	CIC1, INEG, MANZ	CAM2, CHET, CHI3, COL2, CULI, HER2, LPAZ, MERI, MEXI MTY2, OAX2, TAMP, TOL2, UGTO, VIL	3	15
Nicaragua	ESTI, MANA		2	
Peru	AREQ/ARE2		1	
Suriname		PMB1, SRNW, SRZN		3
United Kingdom	ASC1, BRMU, GOUG		3	
USA	AOML, CRO1, GOLD, KYW1, MDO1, MIA3, PIE1, PUR3, RCM5/		9	
Venezuela		BANS, CRCS, MARA		3
		Total Number of sites (10 are identical): 149	55	84

Fig. 3.2.2: IGS RNAAC SIR stations ordered by country.

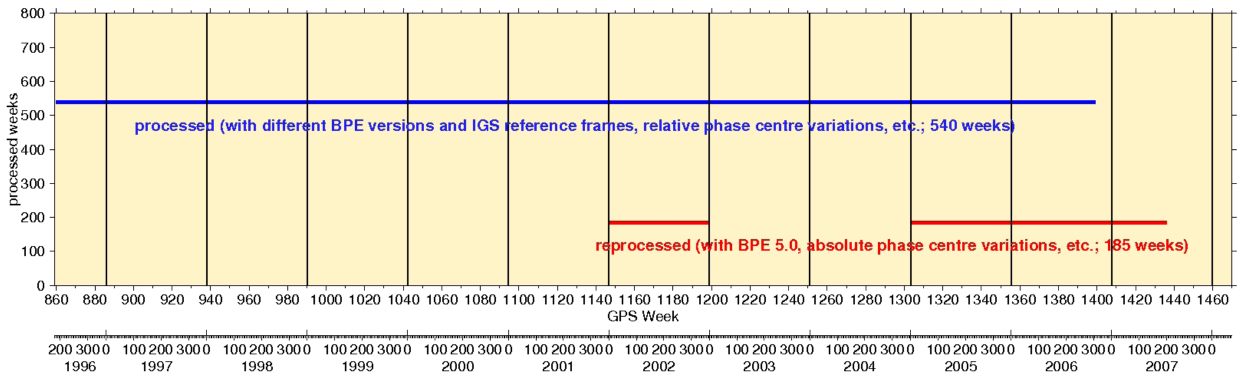
Weekly position solutions

Besides the weekly loosely constrained coordinate solutions for IGS, DGFI provides fixed weekly coordinate solutions as support to all South and Central American countries and Mexico for use in their national networks. These solutions are referred to the IGS05 by applying no net rotation and translation conditions to 18 selected stations of this IGS ITRF2005 realization (see Fig. 3.2.1) lying in the RNAAC region.

Reprocessing of IGS RNAAC SIR solutions

DGFI decided to reprocess all GPS weeks since 1996 to avoid jumps in the time series caused by changing the software (different BPE versions), using different ocean loading models, different elevation cutoff angles, changed IGS reference frames, etc. So far 185 GPS weeks in 2002 and from 2005 onward have been reprocessed (Fig. 3.2.3). This reprocessing with the implemented new decisions of IGS will be continued permanently.

Fig. 3.2.3: Reprocessed GPS weeks (status August 2007).



Combined solutions for estimating the kinematics of the network were computed almost regularly during the past years. The latest realization using the reprocessed weeks was done recently to analyse the changes caused by the new models. As fiducials for the datum realization we adopted positions and velocities of the global IGS solution IGS05. The positions and velocities of its reference stations were not kept fixed, but constrained by no-net-rotation (NNR) and no-net-translation (NNT) conditions so that the network fits optimally with the ITRF2005. This new solution DGF07P01P is preliminary because many stations have less than one year of reprocessed data. The official DGF07P01 solution will be generated soon.

Experimental Analysis Centres for SIRGAS

At the workshop of the SIRGAS Working Group I "Reference System" in Rio de Janeiro, August 16-18, 2006, it was decided to install Experimental Analysis Centres (EAC) for SIRGAS under the responsibility of Latin American institutions. The test phase of the one-year experiment started in October 2006, in order to prove the capability of the EACs to support the IGS RNAAC SIR processing. Five EAC were appointed and have provided their weekly coordinate solutions (not always in the requested time and not for all GPS weeks from two EAC). Several comparisons show promising results with differences in the mm range between the EAC and the RNAAC solutions.

3.3 Operation and applications of permanent GPS stations

In the frame of different international cooperation projects, DGFI installed 13 continuously operating GPS stations in South America and Europe (Fig. 3.3.1). The operation of these stations is supported by local partner institutions, which take care of the functioning of the equipments and the opportune data delivery to the processing centres. Although the tracking data at some stations have many interruptions, the continuous operation of the GPS sites (except Torshavn) improved considerably in the last year (Fig. 3.3.2).

The DGFI permanent stations are integrated in different projects such as the IGS Tide Gauge Benchmark Monitoring Project (TIGA) (stations CART, MPLA, PDES, RWSN, TORS, VBCA), the EC INTERREG IIIB Alpine Space Project (ALPS-GPS QUAKENET) (stations BREI, FHAR, HGRA, HRIE, WART), the densification of the International Terrestrial Reference Frame (RNAAC-SIR, see Topic 3.2) (stations BOGA, CART, MARA, MPLA, PDES, RWSN, VBCA), and the definition and realization of vertical reference systems (SIRGAS-WGIII, see Topic 1.4) (stations CART, MPLA, PDES, RWSN, VBCA). DGFI plans to install two additional permanent GPS stations in Bolivia to increase the density of the ITRF in central South America.

Fig. 3.3.1: Distribution of the continuously operating GPS stations of DGFI.

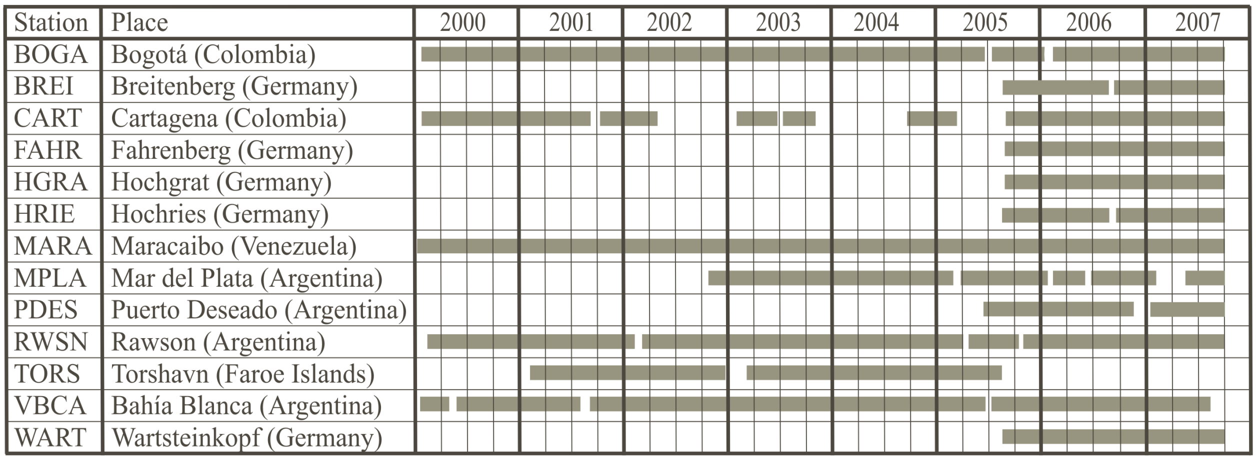


Fig. 3.3.2: Operation of the continuously operating GPS stations of DGFI.

TIde GAuge benchmark monitoring project

DGFI participates in the IGS TIGA Project by operating continuously observing GPS stations at six tide gauges in the Atlantic Ocean and processing a network of about sixty GNSS sites as a TIGA Analysis Centre (Fig. 3.3.3). The weekly processing of this network results in a seven-year time series of station coordinates starting in January 2000 and a multi-year solution of epoch station coordinates with linear and periodic velocities (DGF07P01T). The complete network was re-analysed using the Bernese Software V. 5.0 for the daily data processing with absolute IGS calibration values for the antenna phase centre corrections and satellite orbits referred to ITRF2005. Stations with short time series (less than two years) are excluded. The geodetic datum is defined by constraining 14 IGS stations to their IGS05 coordinates. The SINEX files of the weekly free-net adjustment are provided to the TIGA Associated Analysis Centres (TAAC) and to other users through the web site http://adsc.gfz-potsdam.de/tiga/index_TIGA.html.

Sea level changes and vertical tide gauge motions

GNSS observations give information about vertical displacements of tide gauge stations due to crustal deformation relative to a global terrestrial reference frame. Tide gauge registrations, which are provided by the Permanent Service for the Mean Sea Level (PSMSL, http://www.pol.ac.uk/psmsl/) describe the vertical motion of the sea surface relative to the gauge stations at the coast. The sum of both vertical motions is the sea level change relative to the global reference frame. These relative and absolute vertical motions at 15 stations are presented in Tab. 3.3.1. The distance between the tide gauge and the GNSS station was not taken into account because the local ties (and their variation with time) are not known at all stations. So, we assumed that the difference between the vertical displacements of these relatively close observation points (tide gauge and GNSS antenna) is below the mm/year-level.

To make sure the reliability of these results, they are compared with the sea surface trend derived from satellite altimetry in the marine areas surrounding the tide gauges (Tab. 3.3.1). The sea surface heights obtained from Topex/Poseidon (cycles 1 to 364) are resampled into so-called BINs (small cells along the nominal ground track) to facilitate the time series analysis (see Topic 2.2). The length (~ 7 km) of the BINs is chosen so that for each cycle at least one observation is available. The slope of the CLS01 mean sea surface model is applied to refer all sea surface heights to the centre of the BINs. Afterwards, the sea level trend for each BIN is derived by means of Fourier series analysis, which also considers annual, semi-annual, and quarterly periods as well as an M2 alias period to account for residual errors in ocean tides.

Tab. 3.3.1 shows a good agreement between the vertical trends. The large discrepancies at a few tide gauges are a consequence of the well-known problems associated to

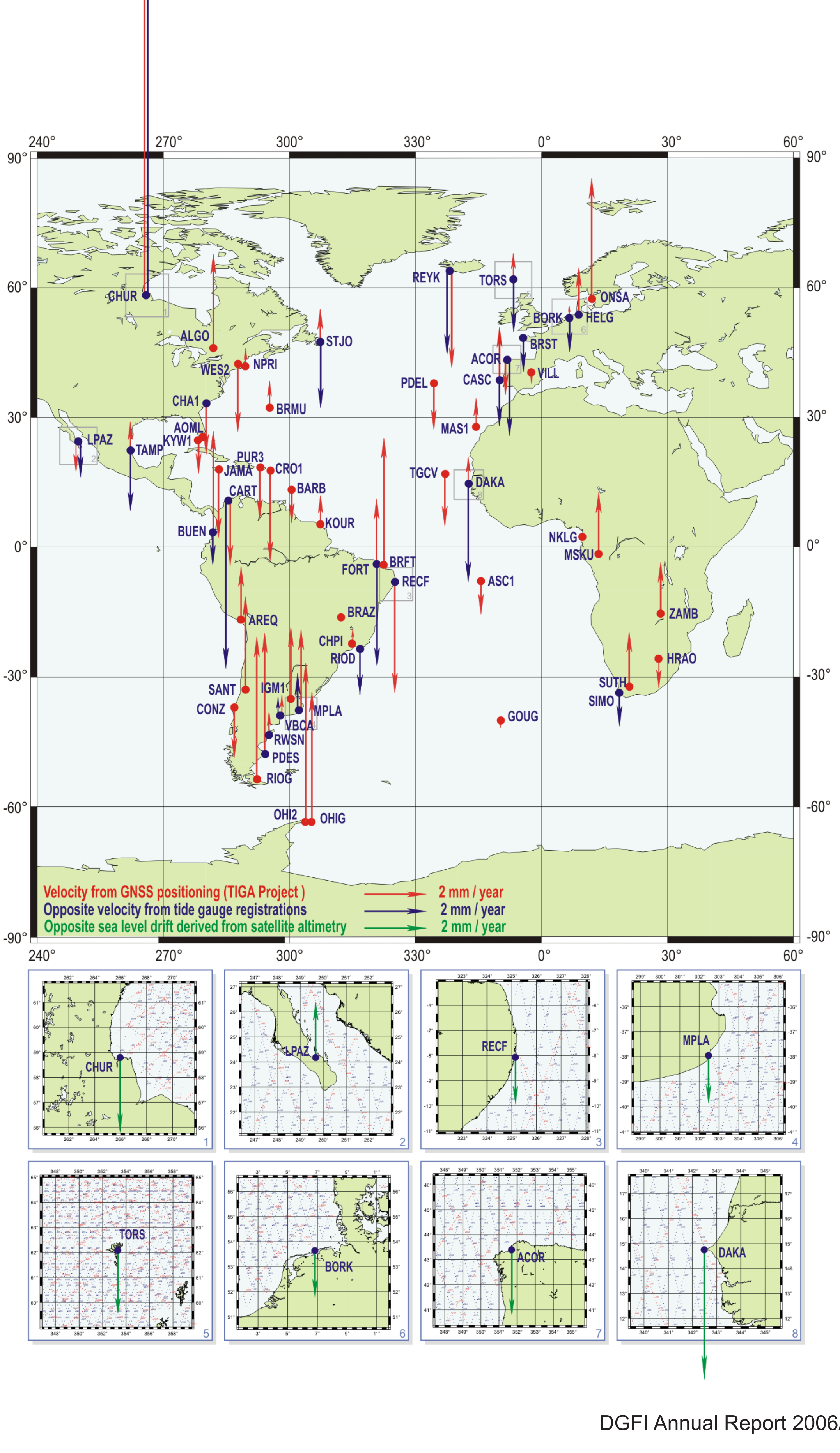
- the tide gauge records because of their regional locations (bays, creeks, etc.),
- the uncertainties of the altimetry observations in coastal areas,
- the dislocation (no coincidence) between tide gauge and altimetry observations, and
- the different time periods covered by the included data (GNSS positioning, tide gauge registrations, and satellite altimetry).

These results validate the balance between sea level trends derived by GNSS + tide gauge and altimetry. They show that sea level changes observed by tide gauges can well be transformed into absolute ones by acting crustal motions determined by GNSS techniques.

Tab. 3.3.1: Comparison of the vertical trends derived from GNSS positioning, tide gauge registrations, and satellite altimetry at some tide gauges.

Site	Tide gauge registrations		GNSS processing		TG + GNSS	Satellite altimetry		(TG + GNSS) – Sat.Alt.
	Time period	dh/dt [mm/y]	Time period	dh/dt [mm/y]	[mm/y]	Time period	dh/dt [mm/y]	[mm/y]
ACOR	1992.0 - 2003.9	2,3 ± 1,9	2000.4 - 2007.0	-1,0 ± 0,0	1,3	1992.8 - 2002.7	2,3 ± 1,5	-1,0
BORK	1949.0 - 1986.9	1,2 ± 0,5	2000.8 - 2007.0	0,3 ± 0,0	1,5	1992.8 - 2002.7	1,6 ± 4,2	-0,1
BRST	1807.0 - 2004.9	1,0 ± 0,0	2000.4 - 2007.0	1,9 ± 0,0	2,9	1992.8 - 2002.7	3,3 ± 1,6	-0,4
BUEN	1941.0 - 1970.9	1,0 ± 0,3	2005.7 - 2007.0	3,1 ± 0,1	4,1	1992.8 - 2002.7	-0,2 ± 1,5	4,3
CART	1949.0 - 1993.9	5,3 ± 0,1	2000.4 - 2007.0	-2,0 ± 0,0	3,3	1992.8 - 2002.7	1,3 ± 1,0	2,0
CASC	1882.0 - 1993.9	1,3 ± 0,0	2000.4 - 2007.0	1,6 ± 0,0	2,9	1992.8 - 2002.7	3,6 ± 0,9	-0,7
CHUR	1940.0 - 2003.9	-9,7 ± 0,2	2000.4 - 2007.0	11,7 ± 0,0	2,0	1992.8 - 2002.7	2,6 ± 5,0	-0,6
DAKA	1992.0 - 2003.9	2,9 ± 1,0	2002.2 - 2007.0	0,8 ± 0,0	3,7	1992.8 - 2002.7	4,4 ± 0,9	-0,7
HELG	1951.0 - 1986.9	0,1 ± 0,5	2000.4 - 2007.0	1,4 ± 0,0	1,5	1992.8 - 2002.7	1,6 ± 4,2	-0,1
LPAZ	1952.0 - 1984.9	1,3 ± 0,3	2005.0 - 2007.0	-0,9 ± 0,1	0,4	1992.8 - 2002.7	-1,9 ± 1,8	2,3
MPLA	1957.0 - 1980.9	-1,3 ± 0,5	2002.7 - 2007.0	2,5 ± 0,0	1,2	1992.8 - 2002.7	1,6 ± 2,6	-0,4
RECF	1948.0 - 1968.9	-0,2 ± 0,4	2000.4 - 2007.0	-3,4 ± 0,0	-3,6	1992.8 - 2002.7	1,6 ± 0,8	-5,2
RIOD	1949.0 - 1968.9	1,4 ± 1,0	2001.6 - 2007.0	0,1 ± 0,0	1,5	1992.8 - 2002.7	0,6 ± 1,4	0,9
TAMP	1952.0 - 1966.9	1,9 ± 3,1	2005.0 - 2007.0	0,9 ± 0,1	2,8	1992.8 - 2002.7	3,1 ± 1,4	-0,3
TORS	1957.0 - 2002.9	1,6 ± 0,2	2001.1 - 2005.5	0,8 ± 0,0	2,4	1992.8 - 2002.7	2,2 ± 1,1	0,2
			Mean value [mm/y]		1,8 ± 1,8			0.0 ± 2.0

Fig. 3.3.3: GNSS vertical velocities of the network processed at DGFI within the TIGA project. It includes opposit vertical velocities (multiplied by −1) obtained from tide gauge registrations and from satellite altimetry data at some selected tide gauges.



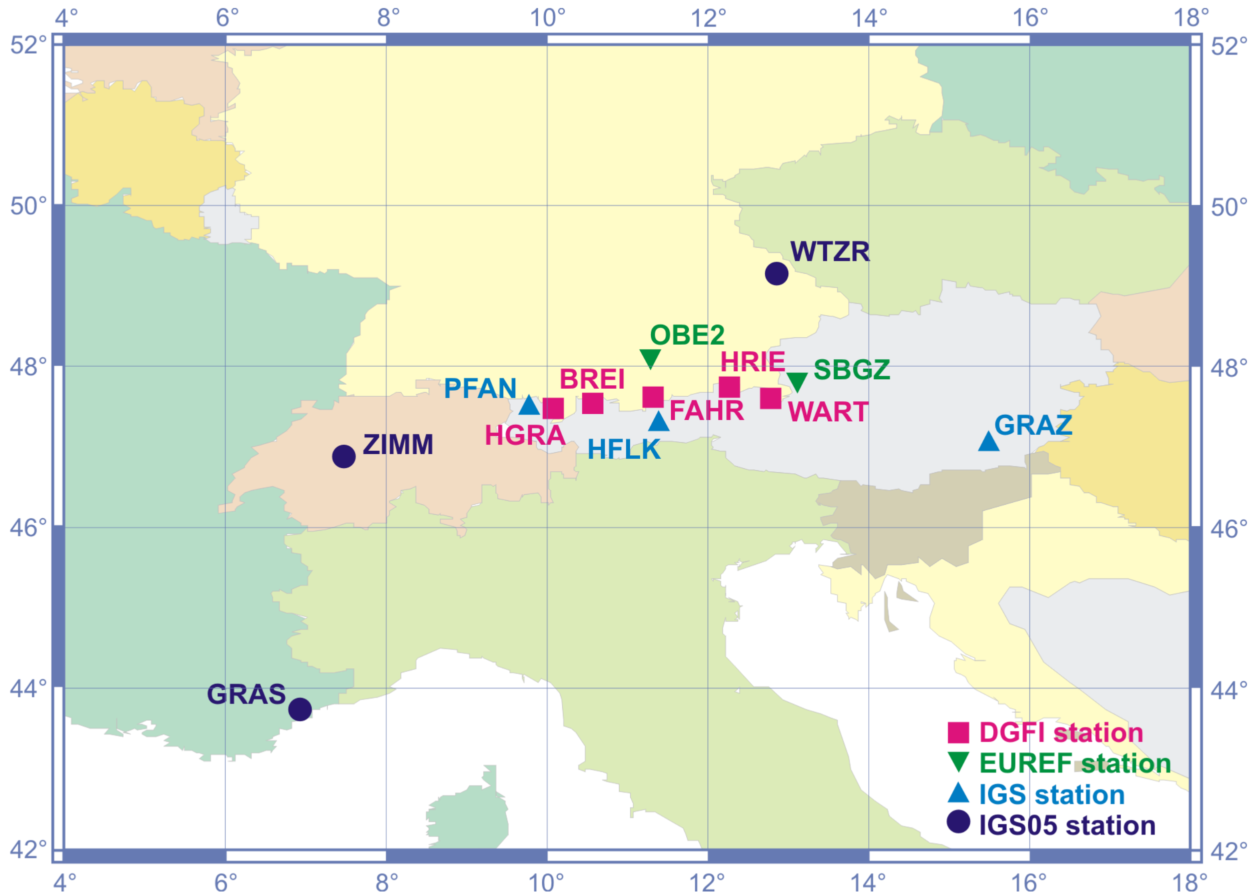
CIP INTERREG IIIB: Alpine Space Programme, Project ALPS-GPS QUAKENET

The objective of the ALPS-GPS QUAKENET project, a component of the Alpine Space Programme established in the frame of the European Community Initiative Programme (CIP) INTERREG IIIB, is to study crustal deformations in near real-time to improve natural disaster prevention in the Alpine region.

To this end, a permanent GPS network of 30 stations was installed. Five of them, which are located along the northern Alps boundary, were set up and are operated by DGFI. The observation data are directly transferred to the operation data centre at DGFI and then forwarded to the GPS QUAKENET project data base in Trieste, Italy. Three data analysis centres process the observations. The results are used to formulate a continental deformation model in the Alpine Region for earthquake hazard reduction, landslides monitoring and meteorological effects.

In order to detect local and regional deformations, DGFI processes its five stations in a small network, which includes three IGS05 reference stations, three IGS global stations and two EUREF stations (Fig. 3.3.4). Station time series (Fig. 3.3.5) and a cumulative solution (DGF07P01A) of this network were derived from daily solutions between October 9, 2005 and July 28, 2007. The obtained station motions mainly reflect the Eurasia plate displacement (Tab. 3.3.2). Regional deformations are not yet significant. They will be estimated when longer time series of more than two years are available.

Fig. 3.3.4: GPS network processed at DGFI to detect local and regional deformations around the DGFI stations included in the ALPS-GPS QUAKENET project.



Tab. 3.3.2: Comparison between the velocities derived from the GPS processing of the DGFI stations included in the ALPS-GPS QUAKENET project (solution DGF07P01A) and the velocities of the Eurasia plate given by the APKIM2005 model

Station	Velocities			
	Component	DGF07P01A [mm/y]	Eurasia Plate, APKIM2005 [mm/y]	Difference [mm/y]
HGRA	V_h	-0,5		
	V_φ	16,7	16,5	0,2
	V_λ	17,7	19,1	-1,4
BREI	V_h	0,9		
	$V\varphi$	15,9	16,4	-0,5
	V_λ	20,6	19,1	1,5
FAHR	V_h	1,5		
	V_φ	15,2	16,4	-1,2
	V_λ	21,0	19,3	1,7
HRIE	V_h	1,6		
	V_φ	16,5	16,3	0,2
	V_λ	20,7	19,5	1,2
WART	V_h	2,5		
	V_φ	16,0	16,2	-0,2
	V_λ	20,0	19,6	0,4

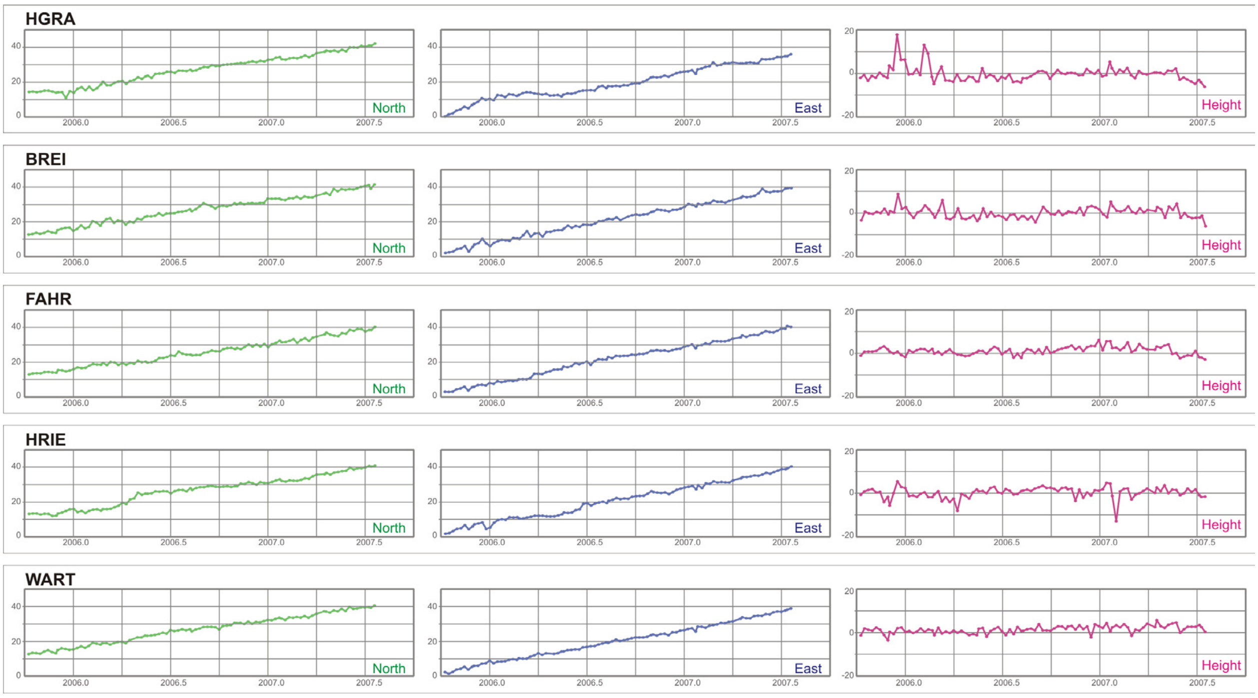


Fig. 3.3.5: Variation [in mm] of the weekly coordinates of the DGFI stations included in the ALPS-GPS QUAKENET project. (Time series between October 9, 2005 and July 28, 2007).

3.4 ILRS − International Laser Ranging Service

DGFI contributes since many years to the ILRS in the maintenance of the global SLR (Satellite Laser Ranging) network as

− Data Centre,
− Analysis Centre,
− Backup Combination Centre.

The ILRS (http://ilrs.gsfc.nas.gov) consists of a Central Bureau, a Governing Board, which controls all activities within the ILRS, and eight Working Groups. The ILRS Analysis Working Group (AWG), for example is responsible for the generation and validation of the offical ILRS products.

ILRS Global Data Centre / EUROLAS Data Centre

The International Laser Ranging Service (ILRS) appointed two ILRS Global Data Centres, the CDDIS at NASA and the EDC at DGFI.

The EDC at DGFI runs three ILRS mail exploders for exchanging informations and results. The EDC exploded 1599 SLR mails (an increase of 102 e-mails in the period of October 01, 2006 to August 31, 2007) and 8725 SLR reports (an increase of 1119) since November 1995 (see Fig. 3.4.1). The third exploder URGENT Mail circulated 137 e-mails (increase of 39 in the last year) since September 2003. A lot of work has been done to avoid the distribution of SPAM, and to update permanently the distribution lists of these three exploders.

The Consolidated Prediction Format (CPF), agreed upon by the ILRS Data Format and Procedures Working Group and confirmed by the ILRS Governing Board in 2006, is used now by most of the ILRS SLR stations. The old IRV predictions are still distributed, but will be stopped at the end of 2007, according to the decision of the Data Format and Procedures Working Group at its last meeting in April 2007 in Vienna.

Since 2006 a new Consolidated laser Ranging Data format (CRD) has been discussed at the meetings of the ILRS Data Format and Procedures Working Group. Both the CPF and CRD are necessary for the upcoming transponder missions. The future activities concerning the CRD were discussed in the Laser Tracking Workshop in Grasse (France) in September 2007.

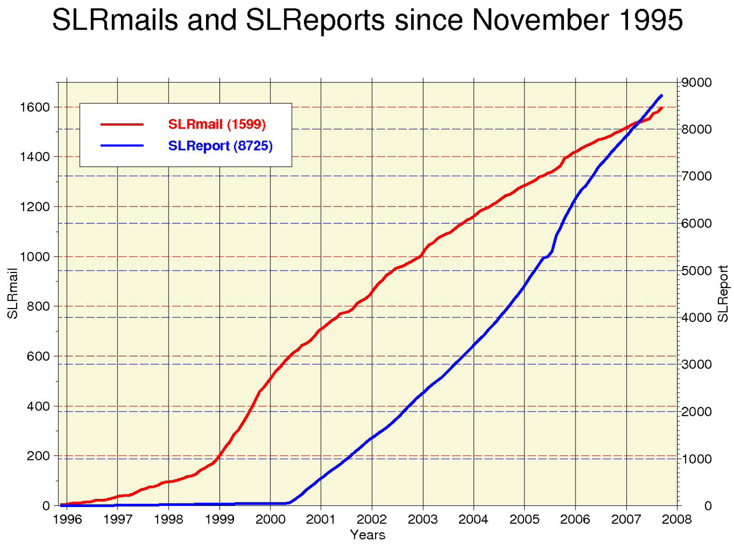
Observation campaigns

The ETALON-1/2, ENVISAT, LARETS and GIOVE-a campaigns were continued, the new campaigns ETS-8, ANDE-RR and TerraSar-X were appointed.

Observed satellite passes

In the time period from October 01, 2006 to August 31, 2007 34 SLR stations observed 33 satellites (including the four moon reflectors). Tab. 3.4.1 shows the EDC data base content at August 31, 2007. This content is compared with that of the CDDIS data base and has to be updated at EDC and/or CDDIS due to missing data.

Fig. 3.4.1: Distributed e-mails by ILRS mail exploders at EDC.



Tab. 3.4.1: Content of ILRS/EDC data base at August 31, 2007 for the product normal points (including Lunar Laser Ranging (LLR) observations to four moon reflectors).

Satellite	number of passes		Satellite	number of passes		Satellite	number of passes	
	Oct.06-Aug.07	Total		Oct.06-Aug.07	Total		Oct.06-Aug.07	Total
ADEOS		671	GLONASS-68		875	GRAVITY PROBE-B		3156
AJISAI	12031	116038	GLONASS-69		945	ICESAT	1810	4080
ALOS		91	GLONASS-70		1430	JASON-1	8008	43363
ANDE-RR A	398	398	GLONASS-71		2617	LAGEOS-1	9919	88796
ANDE-RR P	479	479	GLONASS-72		3260	LAGEOS-2	8087	77652
BEACON-C	6457	50452	GLONASS-74		39	LARETS	4951	16688
CHAMP	2054	11726	GLONASS-75		300	LRE/H2A	1	76
DIADEME-1C		1393	GLONASS-76		301	METEOR-3		409
DIADEME-1D		1585	GLONASS-77		343	METEOR-3M		1756
ENVISAT	6310	30488	GLONASS-78	3	2715	MOON-1	8	405
ERS-1		10524	GLONASS-79		3237	MOON-2	6	315
ERS-2	6458	61202	GLONASS-80		4466	MOON-3	54	2500
ETALON-1	1685	14276	GLONASS-81		275	MOON-4		594
ETALON-2	1602	14382	GLONASS-82		244	OICETS		115
ETS-8	371	371	GLONASS-84		6442	REFLECTOR		3728
FIZEAU		4243	GLONASS-86	56	1311	RESURS-01-3		2011
GEOS-3		2237	GLONASS-87	574	7330	STARLETTE	9494	88349
GFO-1	5697	38778	GLONASS-88		114	STARSHINE-3		48
GFZ-1		5606	GLONASS-89	841	6400	STELLA	5238	53796
GIOVE-A	1093	1503	GLONASS-95	1592	3128	SUNSAT		1864
GLONASS-62		963	GLONASS-99	1264	1264	TerraSAR-X	499	499
GLONASS-63		1952	GLONASS-102	512	512	TIPS		1849
GLONASS-64		81	GPS-35	790	7416	TOPEX/POS.		86423
GLONASS-65		397	GPS-36	734	6635	WESTPAC-1		5620
GLONASS-66		1544	GRACE-A	2534	11167	ZEIA		146
GLONASS-67		4299	GRACE-B	2625	10469	Sum of all	**104235**	**943152**

ILRS Analysis Centre

An ongoing task is the weekly processing of the SLR tracking data to the geodetic satellites LAGEOS-1/2 and ETALON-1/2, which runs mostly automated. The solutions contain station positions, Earth orientation parameters (*X/Y*-pole, LOD) and range biases of selected tracking stations. The results are delivered as SINEX files to the ILRS data centres CDDIS and EDC. This processing includes the computation of pass-dependent biases which are published and daily updated on the DGFI/SLR-group Homepage: ilrs.dgfi.badw.de.

To stabilize the SLR part of the next ITRF, the ILRS/AWG decided to continue the SLR solution back to 1984, using Lageos-1 observations. The computation was done in 15-days arcs, solving for 3 days EOPs, only. Especially before 1990 the distribution of SLR stations was inhomogeneous, and the quality of tracking data was poor. Therefore daily EOPs were not stable enough. The 15-days arcs with 3-day EOPs guarantee a reliable product. Fig. 3.4.2 shows the number of observations per EOP before 1992. There are still parameters with less than 100 contributing observations, which demonstrates the problem of EOP estimation before 1990.

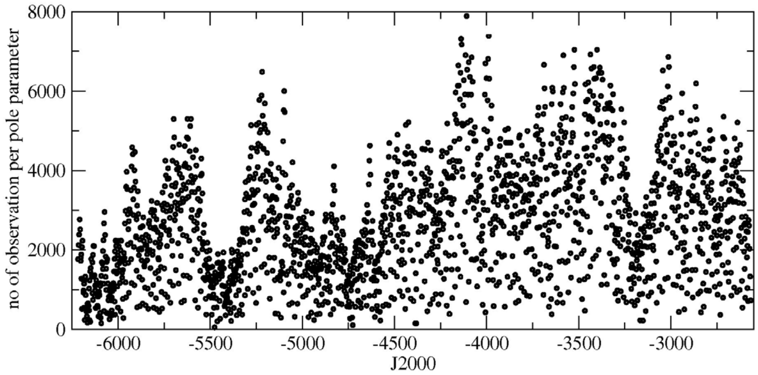


Fig. 3.4.2 Number of SLR observation per EOP-value 1984 to 1992.

Multi-year SLR solution

We re-analysed SLR measurements to LAGEOS 1 & 2 of the global tracking network from January 1993 until July 2007 with the latest version (4.08) of the DGFI software package DOGS-OC. The reference frame, conservative and non-conservative force field parameters are defined according to the IERS Conventions 2003. The solved-for parameters comprise six Kepler elements for weekly accumulated orbital arcs, empirical coefficients for solar radiation and along-track accelaration, daily EOP, as well as station positions and velocities. We applied bias corrections and estimated for some SLR stations range biases according to the latest ILRS table (Status: June 2007). In a first step we computed for the entire time span weekly normal equations for LAGEOS 1 & 2 independently. The free normal equations of both satellites were combined per week with the DGFI software DOGS-CS, and then accumulated to multi-year normal equations. Within the accumulation of the weekly normal equations we introduced new position and velocity parameters for stations with discontinuities according to the ILRS table. For the definition of the reference frame we applied minimum constraints. The origin of the reference frame is defined as a mean geocentre by setting the first degree and order terms of the gravity potential equal to zero, and the scale is defined by the speed of light and GM. The orientation is defined by six NNR conditions to minimize the common rotation and rotation rate with respect to ITRF2005_SLR station positions and velocities. This solution is labelled as reference solution (for further investigations and comparisons, see below).

Effect of range bias estimation on the SLR scale

Encouraged by the discussions about the scale of the ITRF2005 (see 3.1), we investigated the effect of range bias estimation on the SLR scale. For comparisons with the reference solution we computed a test solution over the time period from 1993 until 2007, in which we determined in each weekly solution station-dependent range biases for all SLR stations. We derived time series for the SLR network scale by 7-parameter Helmert-transformations of the weekly solutions with respect to a multi-year reference solution for both solution types (see Fig. 3.4.3 and 3.4.4). A comparison of the results shows some differences between the weekly scale estimations for a few time periods, but the long-term characteristics of both series are very similar. There is only a very small offset and drift between the scale of the reference solution and the test solution. If the range biases are estimated for all SLR stations, the amplitude of the annual signal in the scale is slightly reduced and the R.M.S. variations of the weekly scale estimations are increased by about 15% (see Tab. 3.4.2).

Fig. 3.4.3: Time series of weekly SLR variations for the reference solution.

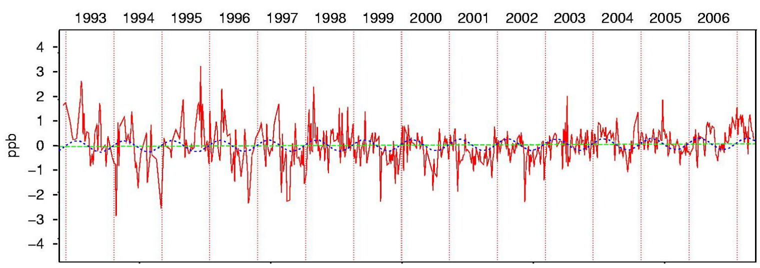
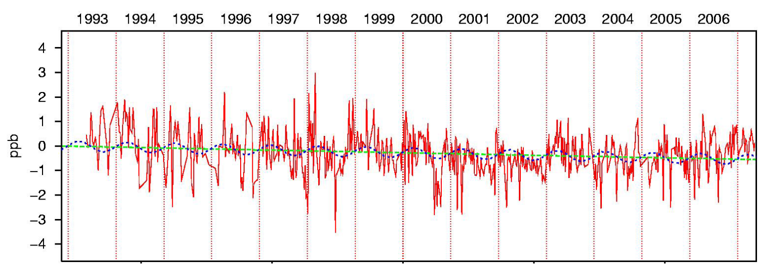


Fig. 3.4.4: Time series of weekly scale variations for the test solution with respect to the multi-year reference solution.



Tab. 3.4.2: Effect of range bias estimation on the SLR scale time series.

	Reference solution	Test solution
Amplitude of annual signal [ppb]	2.6 ± 0.9	2.2 ± 1.1
R.M.S. of scale variations [ppb]	0.79	0.91

Contributions to GGOS-D

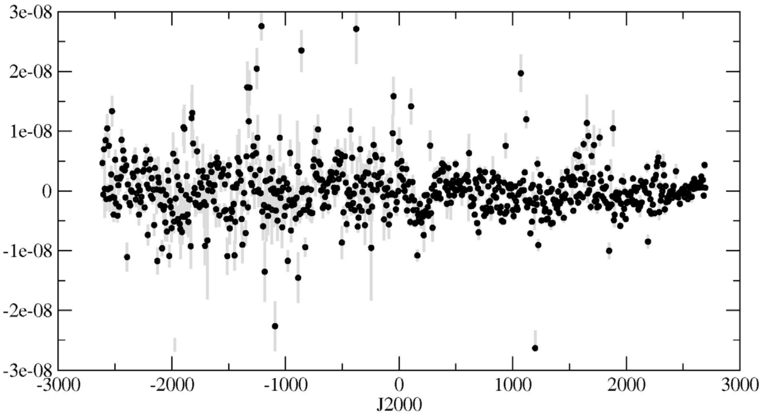
As one of the SLR analysis centres, DGFI contributed to the phase 2 of the GGOS-D project (see 1.1) with weekly loosely constrained sinex files from 1993 to 2007. The parametes of these solutions are:

− daily Earth orientation parameters (*X-, Y*-pole and UT1 at 0:00 UTC)
− weekly stations coordinates at epoch centre of the arc
− weekly range biases for selected, non-core stations
− weekly low-degree harmonics up to 2,2.

We used SLR observations to Lageos-1/2 to generate single satellite orbits. After elimination of internal arc-dependend parameters, the normal equations were added and solved.

Fig. 3.4.5 shows the weekly variations of harmonized C20 values minus 484.165. A clear, but not significant signal can also be seen in the time series of the other coefficients. The analysis of the individual Lageos-1/2 solutions showed a rather good agreement for the gravity coefficients.

Fig. 3.4.5: Weekly C20 from 1993 to 2007, corrections to EIGEN04c values.



Processing of Starlette and Ajisai observations

To stabilize the estimation of station positions and the low-degree harmonics, we processed, first only for a test period, tracking data to Starlette and Ajisai (see 1.1). These satellites are easy targets and hence have a good tracking record. Using the new gravity field and ocean tide models, we could get nearly the same orbital fit (below 2 cm) as for the Lageos satellites. Especially in the period prior to 1990 we hope to stabilze the station position and possibly the EOP solutions.

ILRS Combination Centre (ILRSB)

DGFI as the official ILRS Backup Combination Centre (ILRSB) continued to routinely process weekly combination solutions and to store them at CDDIS and EDC. The variance component estimation (VCE) procedure for automatic weighting and for automatic outlier search and remedy is reliably working. The variance factors since January 2006 are presented in Fig. 3.4.6.

It is clearly to be seen that some ACs are downweighted (variance factors up to 70) especially in summer weeks. An explaination to that phenomenon could not be found.

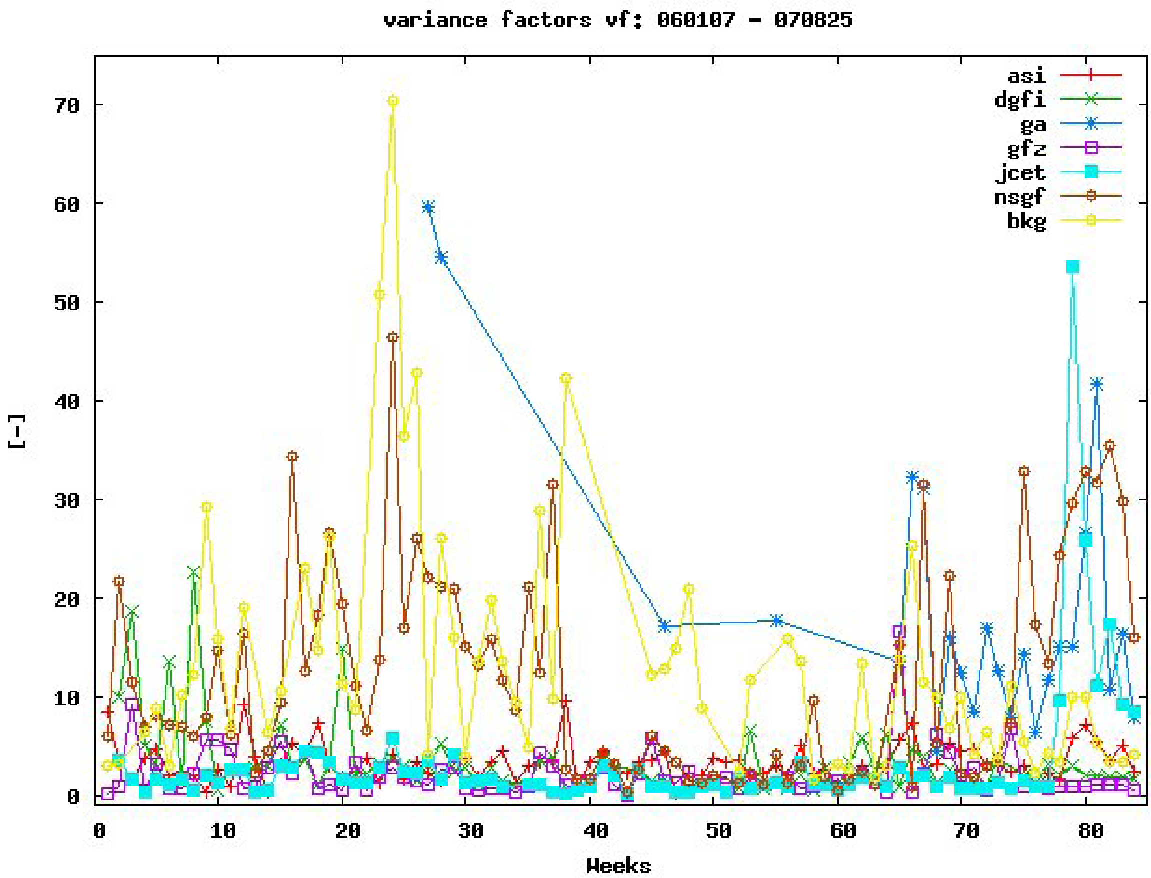


Fig. 3.4.6: ILRSB variance factors for weekly ILRS Analysis Centre solutions from week 060107 (January 7, 2006) to week 070825 (August 25, 2007).

3.5 IVS Analysis Centre

IVS OCCAM working group

The most important effort for DGFI as IVS (International VLBI Service for Geodesy and Astrometry) Analysis Centre is to maintain and refine the VLBI software OCCAM to current requirements in close collaboration within the IVS OCCAM Working Group, chaired by Oleg Titov, Geoscience Australia (Canberra, Australia). Other leading members are scientists from the Vienna University of Technology, Austria, the St. Petersburg University, the Institute of Applied Astronomy, both Russia, and DGFI. The latest updates of the software package are related to the GGOS-D (see 1.1) effort and post-fit analysis tools to analyse station and radio source position time series.

IVS Working Group on the second realization of the ICRF (ICRF2)

The International Celestial Reference System (ICRS) is realized by the coordinates of several hundred radio sources observed by VLBI (for the last realization "ICRF-Ext1", data until 1998 were used). The IERS as well as the IVS aims for a new realization of the ICRS in the next years, which shall, if feasible, be generated by combining several VLBI solutions. For a better understanding of expected systematic differences, the effect of various analysis options on VLBI-determined Celestial Reference Frames (CRF) was investigated in detail by comparing 13 CRF solutions computed with the VLBI software OCCAM 6.1 (least-squares method), using 2847 daily sessions between 1984 and 2006.

IVS Operational Analysis Centre at DGFI

The IVS updated its approach to determine the operational IVS Earth Orientation Parameters (EOP) series from averaging solutions submitted by the different analysis centres (which all used inhomogeneous solution setups, such as different reference frames), to computing them from normal equations, which were derived by adding the SINEX files submitted to the IVS by the different analysis centres (fixing the ITRF2005). These files contain the EOP and station positions for each 24-hour session as decomposed normal equations in the SINEX format (like submitted for the ITRF2005 effort). This approach provides a direct relation of the EOP to one definite TRF throughout the whole series (which can easily be reprocessed if necessary), preferably the ITRF2005, and allows to analyse the input data in a much better way than before.

The DGFI IVS Analysis Centre contributes to this new operational series from its beginning in December 2006 with a recomputed series of datum-free normal equations in SINEX format for VLBI sessions back to 1984 (3000 sessions in the mid of September 2007). Tab. 3.5.1 shows that the data submitted by DGFI are of very high quality: The EOP series computed from these normal equations fit quite well to the IVS EOP series, exemplarily shown for the pole coordinates X- and Y (VLBI internal validation). But, as a comparison of these parameters with the series of the IGS and the IERS (external validation) shows, the DGFI results also fit very well with the contributions of the other IVS analysis centres (see Tab. 3.5.2). Nevertheless, as illustrated by Fig 3.5.1, the IVS and the IGS EOP series still have some significant systematic differences, the origin of wich still has to be clarified.

Besides the submission of the SINEX-files, the DGFI analysis centre significantly supported the group of the IVS analysis co-ordinator in its efforts to homogenize the modelling used in the contributions of the different analysis centres, in order to improve the interpretability of the combined product. The most important result was a homogenization of the pole tide model (see 1.2 'Comparisons of GGOS-D and IVS-standard normal equations in SINEX format').

Tab. 3.5.1: Offset and WRMS of the differences between the pole offsets X and Y since 2005, computed from the SINEX normal equations submitted by DGFI and the IVS EOP series (taken from the IVS homepage, http://vlbi.geod.uni-bonn.de/IVS-AC/combi-sinex/RAPID/HTML/start.html).

	BKG	DGFI	GSFC	IAA	USNO
	(01/2005 - now)	(01/2005 - now)	(01/2005 - now)	(02/2007 - now)	(01/2005 - now)
Offset [µas]	-6.7 ± 3.2	-2.9 ± 2.4	11.1 ± 2.2	24.8 ± 17.5	-7.3 ± 2.9
WRMS [µas]	53.5	39.4	36.1	116.0	47.6

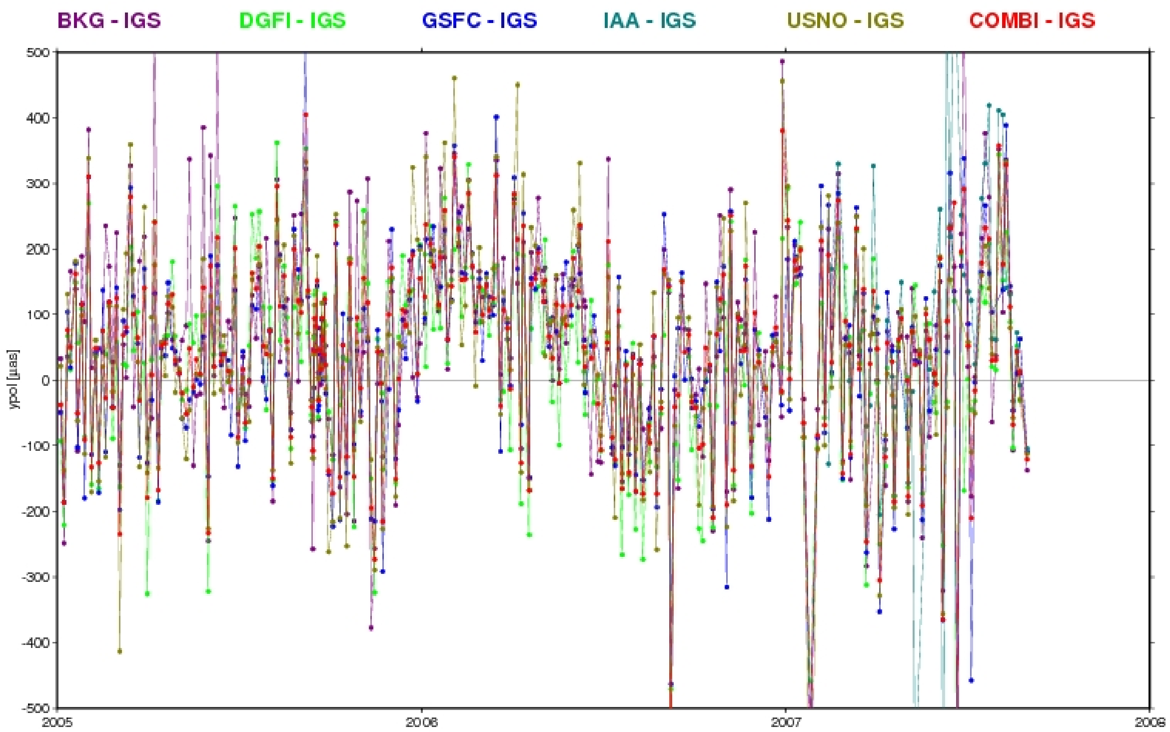
	BKG	DGFI	GSFC	IAA	USNO
	(01/2005 - now)	(01/2005 - now)	(01/2005 - now)	(02/2007 - now)	(01/2005 - now)
Offset [µas]	2.0 ± 3.4	-4.9 ± 2.7	-3.1 ± 2.2	12.2 ± 19.9	2.3 ± 2.5
WRMS [µas]	57.0	45.1	35.4	131.9	41.4

Tab. 3.5.2: Offset and WRMS of the differences between the pole offsets X and Y since 2005, computed from the IVS SINEX normal equations (submitted by the analysis centres as well as the IVS combined), and the IGS EOP series (taken from the IVS homepage, http://vlbi.geod.uni-bonn.de/IVS-AC/combi-sinex/RAPID/HTML/start.html).

	BKG	DGFI	GSFC	IAA	USNO	COMBI
	(01/2005 - now)	(01/2005 - now)	(01/2005 - now)	(02/2007 - now)	(01/2005 - now)	(01/2005 - now)
Offset [µas]	-33.4 ± 7.0	-32.3 ± 6.1	-19.9 ± 6.7	-25.1 ± 25.3	-43.8 ± 7.1	-32.5 ± 6.5
WRMS [µas]	116.1	101.3	111.0	168.0	117.1	109.6

	BKG	DGFI	GSFC	IAA	USNO	COMBI
	(01/2005 - now)	(01/2005 - now)	(01/2005 - now)	(02/2007 - now)	(01/2005 - now)	(01/2005 - now)
Offset [µas]	62.5 ± 8.3	49.2 ± 7.5	52.1 ± 8.0	98.2 ± 25.4	55.3 ± 8.2	50.3 ± 7.8
WRMS [µas]	137.3	124.7	131.1	168.7	135.5	131.0

Fig. 3.5.1: Differences between the Y pole components of the EOP series computed from the SINEX normal equations submitted by all six operational IVS analysis centres (magenta: Bundesamt für Kartografie und Geodäsie, BKG; green: DGFI; dark blue: Goddard Space Flight Centre, GSFC, USA; turquoise: Institute of Applied Astronomy, IAA, Russia; olive-green: United States Naval Observatory, USNO, USA; red: combined IVS EOP) and the IGS EOP series. Even comprehensive analysis of the influence of different analysis options for the computation of the VLBI results did not lied to an explanation of the clear and pronounced bump in the differences between the two series between 2006.0 and 2006.5 (taken from the IVS homepage: http://vlbi.geod.uni-bonn.de/IVS-AC/combi-sinex/RAPID/HTML/start.html).



3.6 Planning and realization of an International Altimeter Service

The intercommission project ICP1.1 'Satellite Altimetry', created in August 2003 at the IUGG General Assembly and hosted by IAG, Commission1 „Reference Systems" completed its work after four years activity on the occasion of the IAG re-organization at the IUGG General Assembly in Perugia.

According to the terms of references of the ICP1.1, an International Altimeter Service Planning Group (IAS-PG) was initiated in 2003 with the objectives to investigate the rationale, feasibility and scope of an International Altimeter Service in order to serve scientific and operational applications of satellite altimetry. In view of the many organisations already providing data and products for satellite altimetry, IAS can only be realized by an integrating effort, e.g., as collaboration between data providers, archive and product centres, research laboratories, space agencies and users. Therefore the group shall strive for an integration, gradually improvement or extension of existing services and a broad support by other scientific entities.

Activities of the International Altimeter Service Planning Group (IAS-PG)

The IAS Planning Group held business meetings in

- 2003, Oct. 13-17, at 8th Meeting of GLOSS Experts at IOC, Paris, France
- 2004, April, at EGU2004 General Assembly, Nice, France
- 2005, April 27 at EGU2005 General Assembly, Vienna, Austria
- 2005, Aug. at IAG General Assembly, Cairns, Australia
- 2006, March at ESA Symposium Venice, Italy
- 2007, March at OST Science Team Meeting in Hobart, Australia

and operated in its initial phase a mailing list and later on a project specific web site (http://www.dgfi.badw.de/wiki/). During its work the IAS Planning Group got official endorsements by the

- Global Sea Level Observing System GLOSS(IOC)
- International Association of Geodesy, IAG
- International Association of the Physical Sciences of the Oceans, IAPSO

The IAS Planning Group

- compiled suggestions and results of discussions.
- drafted a Terms of References (ToR) for an International Altimeter Service, and
- submitted a Call to Participate in an IAS Integrating Office

No applicant to host an IAS Central Bureau

Although there was a broad consensus that an International Altimeter Service would be needed there was no applicant to host the IAS Central Bureau, a minimum body operating at least an information system.

The situation is somehow pending. IAG insisted on establishing at least an IAS Integrating Office (IAS-IO)

- to communicate with, and interface to, mission data providers, centres which process, archive, and analyse altimeter data, and other related services/organizations;

- to provide a single point of contact for information on satellite altimetry and its applications;
- to promote satellite altimetry as a core element of Global Earth Observing Systems

On the other hand there was definitely a need for more intensive coordination among the interested groups.

COSIAS Proposal submitted in respone to the COST open call, March 2007

In March 2007 COST (European Cooperation in the field of Science and Technology) provided an open tender for supporting coordinating activities. Together with 10 scientists from 9 European countries a preliminary proposal for the '*Coordinating operations and science to establish an International Altimeter Service as a core element of the Global Earth Observing System (COSIAS)*' was submitted and passed the first step of the evaluation procedure.

The invitation to prepare a full proposal was adopted, the list of participants and experts was expanded (14 experts, 7 consultants, and 8 early stage researchers) and the scientific program and organisation for the COSIAS action was elaborated in detail (cf. Fig. 3.6.1). The scientific programme of the COSIAS action identified following research tasks:

- GRID technology as a mean to share and coordinate resources from multiple institutions each with their own methods.
- Data quality and consistency. Altimeter data and products of different missions are difficult to compare if different correction models are applied.
- Metadata is required to facilitate the understanding, use and management of data and products.
- The on-line access of altimeter data. It should be interactive and allow to specify content and format upon user request.
- Procedures for faster upgrading and reprocessing and a data management infrastructure will be investigated.

The full proposal even reached the threshold for the second stage assessment, but within the COST ESSEM domain for 'Earth System Science and Environmental Management' it was not ranked among the last two proposal (out of four) that could be funded.

Following suggestions from many colleagues the COSIAS proposal was re-submitted end of September 2007.

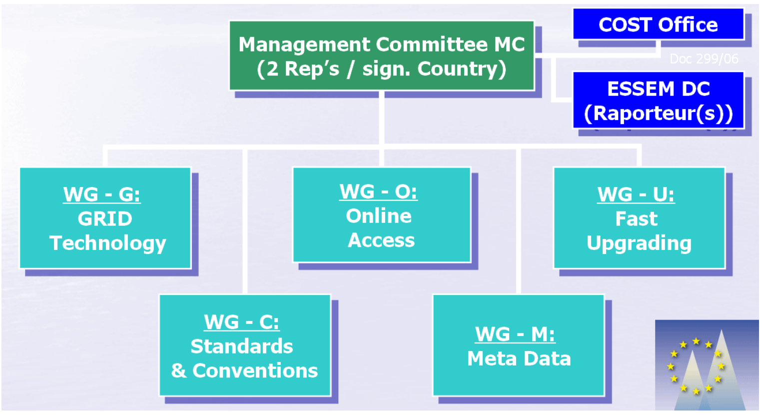


Fig.3.6.1: COSIAS organisation with the Management Committee and Working Groups designated to the 5 topics of the scientific program.

4 Information Services and Scientific Transfer

Scientific research needs to achieve its results within a certain time span and to meet the requests of society. This is especially valid for geo-sciences which describe the planet Earth. Considering the fact of decreasing funds and other restrictions, we have to sustain the permanent and long-term work in the field of geodesy. This requires a system of clear and accessible information. The information can either be provided by personal contacts or by written documents. Research is more and more based on broad cooperation, therefore careful documentation of data and results is requested. The internet has proven to serve as a fast and worldwide accessible tool for information exchange. This tool is fully used, however, for many other requests we still produce printed reports especially for long-term documentation.

The DGFI maintains a homepage (http://www.dgfi.badw.de/) in which all activities of the institute are presented in detail. Moreover links to the IAG entities lead to the international geodetic organisation, especially to the IAG Office, since the second half of 2007 located at DGFI. Other links point to national/international projects. Furthermore, the German Geodetic Commission (Deutsche Geodätische Kommission – DGK) maintains its homepage (http://dgk.badw.de/) informing especially on the commission and its activities but also on various topics of geodesy such as conferences, education in geodesy, job offers in geodetic research, links to other geodetic institutions etc. In this homepage the publications of the German Geodetic Commission (Veröffentlichungen der Deutschen Geodätischen Kommission – DGK) with up to 1000 volumes are listed in detail as well.

4.1 Internet representation

Internet has become an indispensible medium for the exchange of data and scientific information. DGFI set up and maintains several independent Internet sites to solve growing demands to inform about different scientific aspects.

Typo3 Content Managament System

The administration of multiple Internet representations is solved by means of the Typo3 Content Management System (CMS). Typo3 pages are administrated by a data base system, the system ensures a common layout by pre-defined templates and provides simple interfaces to the editors. With Typo3, the Internet sites can be remotely administrated by means of a browser interface – without experiences in Internet specific “mark up” languages like HTML or CSS. Typo3 is an ‘Open Source’ project and as such 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.

Web sites set up and maintained by DGFI

The Typo3 Content Management System is used by DGFI to 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)”, and
- a Geodesy Information System GeodIS.

DGFI used the same system also for Websites, dedicated to

- the new DFG priority program “Mass transport and mass distribution in the Earth system” (SPP1257), and
- the International GSTM/SPP Symposium jointly organized by the GRACE Science Team and the DFG SPP1257 programm on “Mass transport and mass distribution in the system Earth”.

Moreover, the Internet is used to maintain

- several file transfer servers for extensive data exchange, required for DGFI acting as data and analysis centres,
- mailing lists for services and international projects,
- collaborative Internet site for specific projects, and an
- Intranet site to support compilation and distribution of internal information (blackboard, calendar, library).

DGFI home page

The DGFI home page, available under

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http://www.dgfi.badw.de
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informs about structure and results of the actual research programme, ongoing research topics and the national and international projects, DGFI is involved in and the multiple contributions of DGFI to international services. The home page (see Fig. 4.1.1) also provides a complete list of papers and reports published since 1994 by the employees and 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).

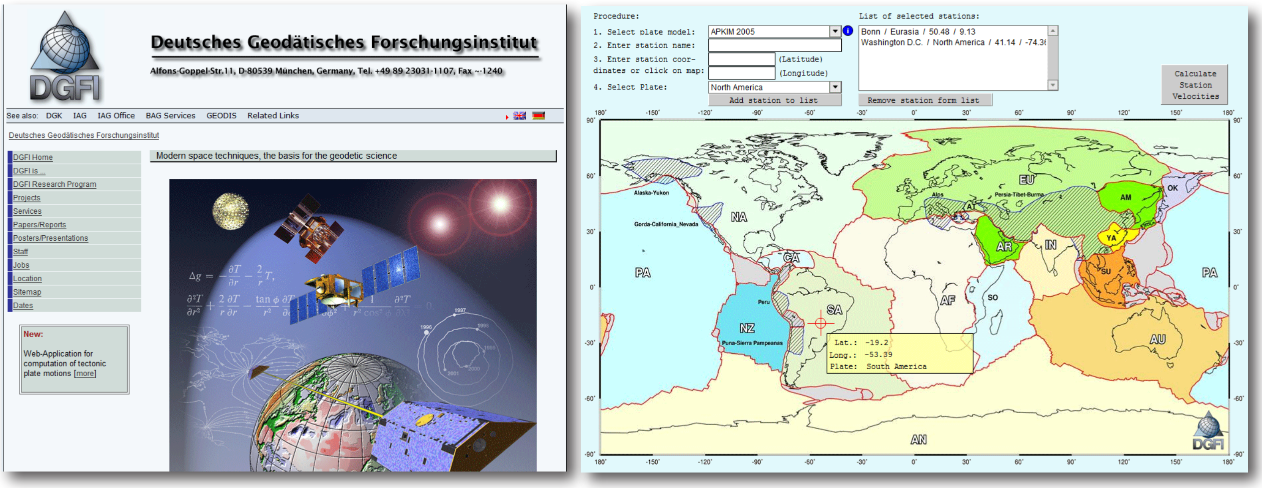

Fig. 4.1.1: Screenshots of the DGFI home page (left) and a new Web application for computations of tectonic plate motions (right).

Internet site for IAG Office

On the occasion of the General Assembly of IUGG at Perugia, Italy, the IAG was reorganized. The position of the IAG Secretary General was taken over by the director of DGFI who acts now also as the director of the IAG Office and is assisted by a small number of assitent secretaries. The IAG Office, now located at the Deutsches Geodätisches Forschungsinstitut (DGFI) got a new web site at

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http://iag.dgfi.badw.de
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in order to support the work of the Office. A Sreenshot of the web site is shown in Fig. 4.1.2

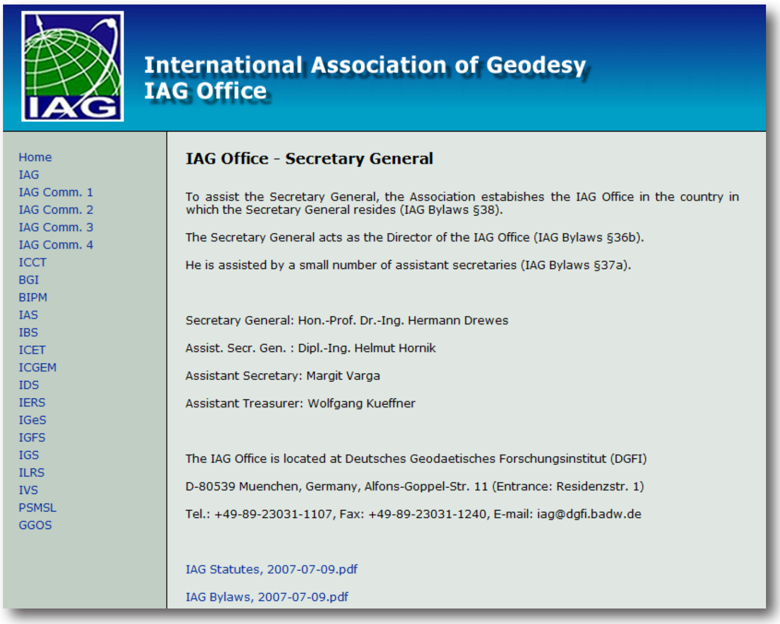

Fig. 4.1.2: Screenshot of the web site of the new IAG Office, now hosted at DGFI.

Geodesy Information System GeodIS

The geodesy information system GeodIS, located at

`http://www.dgfi.badw.de/~geodis`

is further maintained by DGFI with the objective to compile informations about the most important areas of physical geodesy. The intention of GeodIS is to help people in finding information on and data relevant to geodesy. GeodIS provides, for example, a summary about relevant scientific organizations and international services with direct links to the corresponding home pages.

Internet site for Deutsche Geodätische Kommission (DGK)

Another Internet site is maintained for the "Deutsche Geodätische Kommission" (DGK). The site is available at location

`http://dgk.badw.de`

and informs about the structure of the DGK, the membership, working groups, geodetic research institutes in Germany, and the numerous publications of DGK. The complete catalogue of DGK publications can be downloaded as pdf file or browsed by means of a comfortable search function (see Fig. 4.1.3).

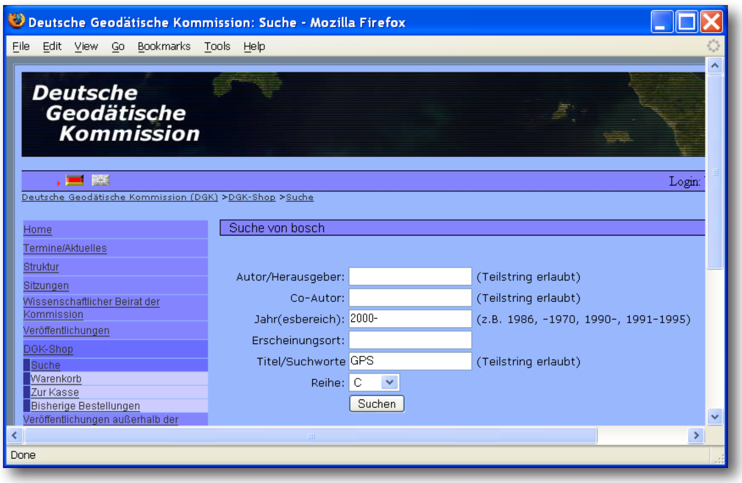

Fig.4.1.3: The search function of the DGK catalogue allows to look for author(s), year or period of years, keywords and substrings within the title of publications.

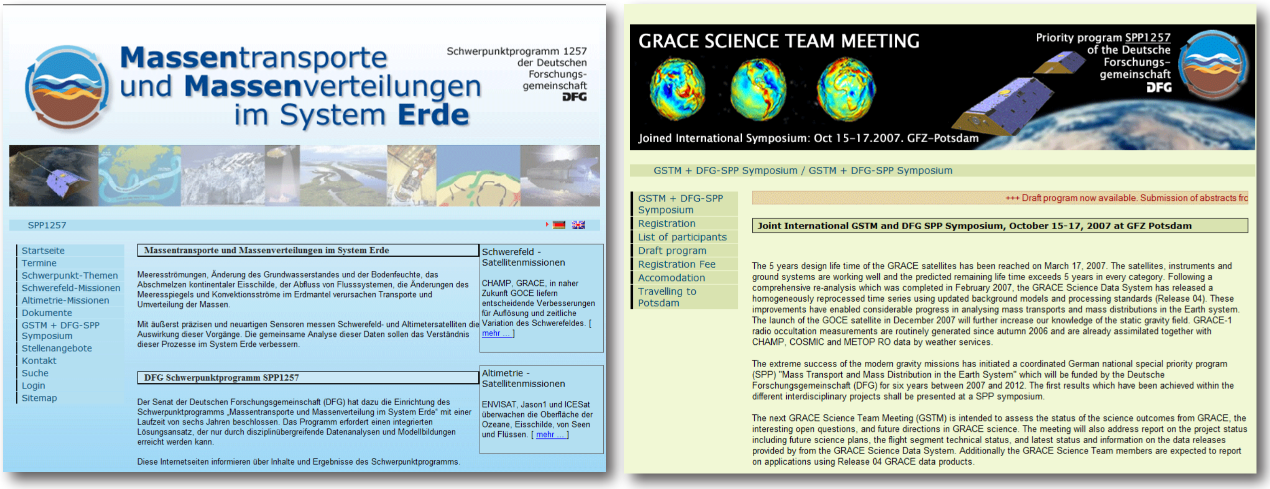

Fig 4.1.4: Screenshots of the Internet sites for the DFG priority program "Mass transport and mass distribution in the Earth system", SPP1257 (left) and the International GSTM+DFG-SPP Symposium, jointly organized by the GRACE Science Team and the DFG SPP 1257 priority program (right).

Internet site for the new DFG priority program „Mass transport and mass distribution in the Earth system"

Finally, an Internet site for the new 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 got it's own domain name

`http://www.massentransporte.de` .

The site (see Fig. 4.1.4) 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.

Mailing lists

Several mailing lists are maintained by DGFI to fulfil the requirements for information exchange within the ILRS Global Data Centre or to support discussions within the Planning Group of the International Altimeter Service. The mailing lists are partly realized by a set of 'bash'-scripts, which are automatically executed according to pre-defined schedules or 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

Finally it should be mentioned that 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.

4.2 Publications

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Bosch, W.: Information on the DFG priority research program SPP1257, "Mass transport and mass distribution in the Earth system". DGK plenary session, BAdW, München, 2006-11-23

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Bosch, W.: Multi-Mission Altimetry: joint estimation of relative range biases, radial errors and sea state biases for contemporary missions. ENVISAT Symposium 2007, Montreux, Switzerland, 2007-04-25 (Poster)

Bosch, W., C.K. Shum, Ph. Woodworth, and G. Mitchum: Towards an International Altimeter Service (IAS) – a component of the Global Earth Observing System. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09 (Poster)

Bosch, W.: Report on the work of the Inter-Commission Project ICP 1.1 Satellite Altimetry. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09

Bosch, W.: Numerical integration of ocean tides for an improved de-aliasing of GRACE gravity field models. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09

Bosch, W.: Estimating the sea surface topography – profile approach with error examination. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09

Drewes, H.: Inconsistencies in geodetic concepts, models and analyses at the 0.1 ppb Level. GGOS Workshop, München, 2006-10-08

Drewes, H.: Geodetic reference frames – opening address. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09

Drewes, H.: Aufgaben und Programm des Deutschen Geodätischen Forschungsinstituts (DGFI). INTERGEO supporting program, BAdW, München, 2006-10-10

Drewes, H.: The APKIM2005, basis for a non-rotating ITRF. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-11

Drewes, H.: A unique reference frame, basis of the Global Geodetic Observing System (GGOS) for geodynamics and global change. Joint FIG-IAG-INTERGEO plenary session "Global Change", Munich, 2006-10-12

Drewes, H.: DGFI Forschungsprogramm 2007–2008. DGK Science Advisory Board Meeting, Darmstadt, 2006-10-18

Drewes, H.: GNSS im Deutschen Geodätischen Forschungsinstitut (DGFI). DGK round table, Darmstadt, 2006-10-19

Drewes, H.: DGFI Jahresbericht 2005–2006. DGK plenary session, München, 2006-11-23

Drewes, H.: Konsequenzen aus der Stellungnahme des WR zur Überführung des DGFI in ein WGL-Institut. DGK plenary session, 2006-11-23

Drewes, H.: ITRF2005 computation at DGFI. IERS Directing Board Meeting No. 43, San Francisco, 2006-12-11

Drewes, H.: GGOS Working Group "Conventions, Models, Analysis", Status Report 2006. GGOS SC7 Meeting, San Francisco, USA, 2006-12-12

Drewes, H.: EU-Project "Alps GPS Quakenet" im Community Initiative Programme (CIP) INTERREG IIIB "Alpine Space". DGK-AK "Rezente Krustenbewegungen", Frankfurt/Main, 2007-02-02

Drewes, H.: GGOS Working Group "Conventions, Models, Analysis", Status Report February 2007. GGOS SC8 Meeting and Retreat, Oxnard, CA, USA, 2007-02-19

Drewes, H.: GEO Capacity Building Committee (CBC) − Status Report February 2007. GGOS SC8 Meeting and Retreat, Oxnard, CA, USA, 2007-02-19

Drewes, H.: IAG Commission 1 "Reference Frames" and the Global Geodetic Observing System. GGOS SC8 Meeting and Retreat, Oxnard, CA, USA, 2007-02-21

Drewes, H.: Activities and Results of Project-Partner Deutsches Geodätisches Forschungsinstitut, München, Germany. EU CIP INTERREG IIIB Alpine Space Programme, Project Alpine Integrated GPS Network, Final Meeting, Trieste, Italia, 2007-02-26

Drewes, H.: Geodetic monitoring of global change and natural hazards. EU CIP INTERREG IIIB Alpine Space Programme, Project Alpine Integrated GPS Network, Final Meeting, Trieste, Italia, 2007-02-27

DREWES, H.: Convergence of ITRF solutions realized with different strategies. IERS Directing Board Meeting No. 44. Vienna, Austria, 2007-04-15

DREWES, H.: Sistemas de referencia. Taller científico, Semana Geomática, Bogotá, Colombia, 2007-06-04

DREWES, H.: Retos futuros de la geodesia: El Sistema de Observación Geodésica Global (GGOS), Semana Geomática, Bogotá, Colombia, 2007-06-08

DREWES, H.: IAG Commission 1 "Reference Frames" − Highlights of the Period 2003 – 2007. IUGG XXIV General Assembly, IAG Opening Session, Perugia, Italy, 2007-07-02

DREWES, H.: Reference Systems, Reference Frames, and the Geodetic Datum − Introduction to the IAG Symposium GS001 and Report 2003-2007 of IAG Commission 1. IUGG XXIV General Assembly, Symposium GS001 "Reference Frames", Perugia, Italy, 2007-07-03

DREWES, H.: On the ITRS datum specifications. IERS Workshop on Conventions, Sèvres, France, 2007-09-20

DREWES, H.: Referenzsystem, Referenznetz und geodätisches Datum. INTERGEO / Geodetic Week, Leipzig, 2007-09-27

GERSTL, M.: Requirements of a user on the IERS conventions models. IERS Workshop on Conventions, Paris-Sevres, France, 2007-09-21

GERSTL, M.: Safety and portability of IERS conventions software. IERS Workshop on Conventions, Paris-Sevres, France, 2007-09-21

GÖTTL, F.: Integration of space geodetic observations and geophysical models. Geodetic Week 2006, ICM, München, 2006-10-12

GÖTTL, F.: Earth Rotation and Global Dynamic processes. Working group meeting of the DFG project "Erdsystemmodell", DGFI, München, 2007-02-16

GÖTTL, F.: "Verknüpfung von Erdrotation, Schwerefeld und Geometrie mit geodätischen Raumverfahren" Teil A: Überblick und Stand der DGFI Arbeiten. Statusseminar der DFG Forschergruppe "Erdrotation und globale dynamische Prozesse", Dresden, 2007-05-31

GÖTTL, F.: Contribution of non-tidal oceanic mass variations to Earth rotation determined from space geodesy and ocean data. IUGG XXIV General Assembly, Perugia, Italy, 2007-07-06

KELM, R.: Rigorous variance component estimation in weekly intra-technique and inter-technique combination for global terrestrial reference frames. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09

KRÜGEL, M.: Zur Berechnung des GGOS-D Referenzrahmens. Geotechnologien-Projekttreffen, Bonn, 2007-02-13

LUZ, R.T., W. BOSCH, S.R.C. FREITAS, B. HECK: Evaluating the Brazilian Vertical Reference System and Frame through Improved Coastal Satellite Altimetry Data. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09 (Poster)

MARTÍNEZ, W., L. SÁNCHEZ: Realization of the SIRGAS reference frame in Colombia. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09/14 (Poster)

MAYER-GÜRR, T., W. BOSCH, and A. EIKER: Regional high resolution geoid determination by a combination of GRACE data and in-situ altimetry observations. IUGG General Assembly 2007, Perugia, Italy, 2007-07-02/09 (Poster)

MEISEL, B.: Influence of time variable effects in station positions on the terrestrial reference frame. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-11

MEISEL B., D. ANGERMANN, H. DREWES, F. SEITZ, M. KRÜGEL: Detecting geophysical signals in station position time series of ITRF2005 data. AGU Fall Meeting 2006, San Francisco, USA, 2006-12-11/15 (Poster)

MEISEL, B.: Akkumulieren von GGOS-D Beobachtungsreihen. GGOS-D Geotechnologien 4th project meeting, IGG, Universität Bonn, 2007-02-12

MÜLLER, H.: Some Aspects Concerning the SLR Part of ITRF2005, 15th International Laser Ranging Workshop, Canberra, Australia, 2006-10-16

Müller, H.: Station Coordinates, Earth Rotation Parameters and Low Degree Harmonics from SLR within GGOS-D, 15th International Laser Ranging Workshop, Canberra, Australia, 2006-10-16

Müller, H.: Analysis of Multi-Wavelength SLR Tracking Data Using Precise Orbits, 15th International Laser Ranging Workshop, Canberra, Australia, 2006-10-18

Müller, H.: The potential of Starlette and Ajisai for station positioning. ILRS Fall Workshop, Grasse, France, 2007-09-25

Müller, H.: Cooperation between stations and analysis, status and future, ILRS Fall Workshop, Grasse, France, 2007-09-25

Noll, C., M. Torrence, W. Seemüller: Laser ranging archiving and infrastructure support at the ILRS Data Centres and WEB site. 15th International Laser Ranging Workshop, Canberra, Australia, 2006-10-17 (Poster)

Richter, B.: Various Definitions of the Ecliptic. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09/14 (Poster)

Sánchez, L.: Strategy to establish a Global Vertical Reference System. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-11

Sánchez, L.: Current status and future activities of the subcommission 1.3b (South and Central America) of the IAG Commission 1 on Reference Frames. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-13

Sánchez, L., M. Krügel, M.: The role of the TIGA project in the unification of classical height systems. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09/14 (Poster)

Sánchez, L.: A new vertical reference system for South America. American Geophysical Union, Spring Meeting. Acapulco, Mexico, 2007-05-22/25 (Poster)

Sánchez, L.: Sistemas verticales de referencia. Taller. II Semana Geomática del Instituto Geográfico Agustín Codazzi (IGAC). Bogotá, Colombia. 2007-06-05

Sánchez, L.: SIRGAS working group III: Vertical Datum. Report 2006 – 2007. SIRGAS 2007 meeting. II Semana Geomática del Instituto Geográfico Agustín Codazzi (IGAC). Bogotá, Colombia, 2007-06-07/08

Sánchez, L.: Realización del nivel de referencia vertical para SIRGAS dentro de una definición global. II Semana Geomática del Instituto Geográfico Agustín Codazzi (IGAC). Bogotá, Colombia, 2007-06-08

Sánchez L.: Vertical motion control of the tide gauges in the Atlantic as a part of the TIGA project. IUGG XXIV General Assembly, Perugia, Italy, 2007-07-02/13 (Poster)

Savcenko, R., W. Bosch: Tides in shallow water from satellite altimetry – a case study at the Patagonian shelf. Geodetic Week 2006, ICM, München, 2006-10-10/12 (Poster)

Savcenko, R.: BINs – Satellite altimeter data re-organized for time series analysis. Geodetic Week 2006, München, 2006-10-12

Savcenko, R., W. Bosch: Residual Tide Analysis in Shallow Water − Contributions of ENVISAT and ERS Altimetry. ENVISAT Symposium 2007, Montreux, Schweiz, 2007-04-25 (Poster)

Savcenko, R., W. Bosch: Empirical ocean tide analysis of cross-calibrated multi-mission altimeter data. IUGG XXIV General Assembly. Perugia, Italy, 2007-07-05 (Poster)

Savcenko, R.: Potential der Multi-Missionsaltimetrie bei der empirischen Gezeitenmodellierung, Geodätische Woche 2007, Leipzig, 2007-09-26

Schmidt, M.: Spatio-temporal multi-resolution representation of the gravity field from GRACE data. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09

Schmidt, M.: Regional multi-dimensional modelling of the ionospheric electron density. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-10

Schmidt, M.: Multi-resolution representation of the gravity field from satellite data. GRACE Science Team Meeting 2006-12-08/09, San Francisco, USA, 2006-12-09

Schmidt, M., S.-C. Han, C.K. Shum: Multi-resolution representation of gravity field changes caused by the Sumatra-Andaman earthquake from GRACE. AGU Fall Meeting 2006, San Francisco, USA, 2006-12-11 (Poster)

Schmidt, M.: Spatio-temporal multi-resolution representation of the gravity field from satellite data. GFZ, Oberpfaffenhofen, Germany, 2007-02-08

Schmidt, M., F. Seitz, C.K. Shum, L. Wang: Modeling and Validation of GRACE Regional 4-D hydrological mass variations. EGU Gen. Ass., Vienna, Austria, 2007-04-18

Schmidt, M., D. Bilitza, C.K. Shum, C. Zeilhofer: Regional multi-dimensional modeling of the ionospheric electron density from satellite data and IRI. EGU Gen. Ass., Vienna, Austria, 2007-04-19

Schmidt, M., D. Bilitza, C.K Shum, W. Bosch, C. Zeilhofer, Y. Yi, L.-C. Tsai, K. Cheng: Regional multi-dimensional modeling of the vertical total electron content from satellite data and IRI. IUGG XXIV General Assembly, Perugia, Italy, 2007-07-06

Seemüller, W.: The position and velocity solution DGF06P01 for SIRGAS. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-13

Seemüller, W.: The IGS regional network associate analysis centre for SIRGAS (IGS RNAAC SIR), Workshop on Tectonik Geodesy, German Armed Forces University, Munich, 2007-04-05

Seemüller, W., H. Drewes, A. Abolghasem: Status of the IGS Regional Network Associate Analysis Centre SIRGAS (IGS RNAAC SIR), AGU Joint Assembly, Acapulco, 2007-05-22/25 (Poster)

Seitz, F., M. Krügel: Modelling vertical site displacements due to surface loads in consideration of crustal inhomogenities. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09

Seitz, F., J. Dickey, S. Marcus: Loading effects in Siberia and Northern Canada determined from hydrological model data and GRACE gravity field observations. AGU Fall Meeting 2006, San Francisco, USA, 2006-12 -11 (Poster)

Seitz, F.: Modellergebnisse für die Polbewegung der Erde unter Verwendung eines gekoppelten Atmosphären-Ozeanmodells. Working group meeting of the DFG project "Erdsystemmodell", DGFI, München, 2007-02-15/16

Seitz, F.: Use of hydrological data for the geophysical interpretation of space geodetic observations. Co-operation Seminar, Bundesanstalt für Gewässerkunde, Koblenz, 2007-05-07

Seitz, F., M. Schmidt, C.K. Shum, Y. Chen: Signals of extreme weather conditions in Central Europe from GRACE 4-D wavelet expansions. IUGG XXIV General Assembly, Perugia, Italy, 2007-07-04 (Poster)

Shum, C.K., S.-C. Han, C. Jekeli, C.-Y. Kuo, M. Schmidt: GRACE Observed Mass Variations of the Earth. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09/14 (Poster)

Tesmer, V.: Effect of various analysis options on VLBI-determined CRF. International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-10

Tesmer, V.: Comparison of different models to estimate nutation and polar motion rates. 18th Working Meeting on European VLBI for Geodesy and Astrometry, Vienna, Austria, 2007-04-13

Tesmer, V.: Effect of various analysis options on VLBI-determined CRF. 18th Working Meeting on European VLBI for Geodesy and Astrometry, Vienna, Austria, 2007-04-13

4.4 Membership in scientific bodies

International Council for Science (ICSU)

- Committee on Space Research (COSPAR): Subcommission B2: International Coordination of Space Techniques for Geodesy and Geodynamics (President: H. Drewes) *

International Union of Geodesy and Geophysics (IUGG)

- IUGG Representative to Panamerican Institute for Geography and History, PAIGH (H. Drewes)
- IUGG Representative to United Nations Cartographic Office (H. Drewes) *

International Association of Geodesy (IAG)

- IAG Secretary General (H. Drewes) +
- IAG Assistant Secretary (H. Hornik) +
- IAG Commission 1: Reference Frames (President: H. Drewes) *
- IAG-Representative to Sistema de Referencia Geocéntrico para las Américas, SIRGAS (H. Drewes)
- Inter-Commission Project 1.1: Satellite Altimetry (Chair: W. Bosch) *
- Inter-Commission Project 1.2: Vertical Reference Frames (L. Sánchez) *
- Inter-Commission Committee on Theory (ICCT) Working Group “Inverse Theory and Global Optimization” (M. Schmidt) *
- Subcommission 1.3a: Reference Frame for Europe (Secretary: H. Hornik)
- Subcommission 1.3a: Reference Frame for Europe, Technical Working Group (H. Hornik)
- Subcommission 1.3b: Reference Frame for Central and South America (Vice President: L. Sánchez) +
- Subcommission 1.3b: SIRGAS, Working Group I “Reference Frame” (W. Seemüller)
- Subcommission 1.3b: SIRGAS, Working Group III “Vertical Datum” (L. Sánchez)
- Working Group 1.2.3 and Inter-Commission Committee on Theory (ICCT) Working Group 3: Integrated theory for crustal deformation (B. Meisel) *
- Working Group 2 “Interactions and consistency between terrestrial reference frame, Earth rotation and gravity field”, Subcommission 1.1 “Coordination of Space Techniques” (Chair: D. Angermann) *
- Study Group 1.1: Ionosphere Modelling and Analysis (Chair: M. Schmidt) *
- Study Group 1.3 and Inter-Commission Committee on Theory (ICCT) Working Group: Quality measures, quality control, and quality improvement (M. Krügel) *
- Study Group 2.3: Satellite Altimetry: data quality improvement and coastal applications (W. Bosch) *
- Global Geodetic Observing System (GGOS) Working Group “Conventions, Analysis and Modelling” (Chair: H. Drewes)
- International Earth Rotation and Reference Systems Service (IERS): IERS Working Group on Combination (D. Angermann)
- International Earth Rotation and Reference Systems Service (IERS): ITRS Combination Centre (Chair: H. Drewes)
- International Earth Rotation and Reference Systems Service (IERS): IERS Combination Research Centre (Chair: D. Angermann)
- International Earth Rotation and Reference Systems Service (IERS): Working Group Site Survey and Co-location (D. Angermann)
- International Laser Ranging Service (ILRS): Governing Board (H. Drewes, W. Seemüller)
- International Laser Ranging Service (ILRS): Analysis Working Group (D. Angermann, R. Kelm, H. Müller)
- International Laser Ranging Service (ILRS): Analysis Centre (H. Müller)
- International Laser Ranging Service (ILRS): Backup Combination Centre (R. Kelm)
- International Laser Ranging Service (ILRS): Data Formats and Procedures Working Group (Chair: W. Seemüller)
- International VLBI Service for Geodesy and Astrometry (IVS): Operational Analysis Centre (H. Drewes, M. Krügel, V. Tesmer)
- International VLBI Service for Geodesy and Astrometry (IVS)/International Earth Rotation and Reference Systems Service (IERS): Working Group on the Second Realization of the ICRF (ICRF2) (V. Tesmer)

* until July 2007, + since July 2007

Group on Earth Observation (GEO)
- Committee on Capacity Building and Outreach (IAG Substitute Delegate: H. Drewes)

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 Sciencee Team for Jason (Joint Altimetry Satellite Oceanography Network) (W. Bosch)

Consortium of European Laser Stations EUROLAS
- Member in the EUROLAS Board of Representatives (W. Seemüller)
- EUROLAS Secretary (W. Seemüller)

Deutsche Geodätische Kommission (DGK)
- "Ständiger Gast" (H. Drewes)
- Working Groups Rezente Krustenbewegungen", "Theoretische Geodäsie" (several collaborators)

Deutscher Verein für Vermessungswesen (DVW), Gesellschaft für Geodäsie, Geoinformation und Landmanagement
- Working Group 7 "Experimentelle, angewandte und theoretische Geodäsie" (H. Drewes)
- Working Group 3 "Messmethoden und Systeme" (D. Dettmering)

4.5 Participation in meetings, symposia, conferences

GGOS Workshop, IAPG TUM, Munich, 2006-10-08/09 (Drewes)

International IAG Symposium "Geodetic Reference Frames, GRF2006", LVG, München, 2006-10-09/14 (Angermann, Drewes, Gerstl, Göttl, Hornik, Kelm, Krügel, Meisel, Richter, Sánchez, Schmidt, Seemüller, Seitz, Tesmer)

Geodetic Week 2006, ICM, München, 2006-10-10/13 (Bosch, Göttl, Savcenko, Schmidt, Tesmer)

Joint Sessions of XXIII. FIG Congress, IAG Symposium GRF2006, and INTERGEO Congress, Munich, 2006-10-12 (Angermann, Bosch, Drewes, Göttl, Krügel, Meisel, Sánchez, Savcenko, Schmidt, Seitz, Tesmer)

ILRS Data Formats and Procedures Working Group, Canberra, Australia, 2006-10-16, (Seemüller)

EUROLAS Meeting, Canberra, Australia, 2006-10-16 (Seemüller)

15th International Laser Ranging Workshop, Canberra, Australia, 2006-10-16/20 (Kelm, Müller, Seemüller)

ILRS Refraction Study Group Meeting, Canberra, 2006-10-17 (Seemüller)

DGK Science Advisory Board Meeting, Darmstadt, 2006-10-18 (Angermann, Bosch, Drewes, Hornik)

DGK round table "Zukunft von GNSS-Diensten in Deutschland", Darmstadt, 2006-10-19 (Drewes, Hornik)

ILRS Governing Board, Canberra, Australia, 2006-10-19 (Seemüller)

ILRS General Assembly, Canberra, Australia, 2006-10-20 (Müller, Seemüller)

ILRS Analysis Working Group Meeting, Canberra, Australia, 2006-10-21 (Kelm, Müller)

Scientific colloquium, Technische Universität Berlin, Germany, 2006-10-27 (Angermann)

42nd Meeting of the EUREF Technical Working Group, Frankfurt a.M., 2006-11-6/7 (Hornik)

3rd International GOCE User Workshop. ESA, ESRIN, Frascati, Italy, 2006-11-06 to 08 (Bosch)

DFG priority program SPP1257 "Mass transport and mass distribution in the Earth system" – Kick-Off Meeting, Frankfurt, 2006-11-13 (Bosch)

DGK plenary session 2006, BAdW, München, 2006-11-22 /24 (Bosch, Drewes, Hornik)

GRACE Science Team Meeting 2006, San Francisco, USA, 2006-12-08/09 (Schmidt)

IERS Directing Board Meeting No. 43, San Francisco, USA, 2006-12-11 (Drewes)

AGU Fall Meeting 2006, San Francisco, USA, 2006-12-11/15 (Krügel, Schmidt, Seitz)

GGOS SC7 Meeting, San Francisco, USA, 2006-12-12 (Drewes)

GGOS Working Group "Ground Networks and Communication", San Francisco, USA, 2006-12-13 (Drewes)

GEO-TOP 1st Project Meeting, IAPG, Technical University, München, 2006-12-14/15 (Bosch, Savcenko)

GEO-TOP 2nd Project Meeting, IAPG, Technische Universität München, 2007-02-07 (Bosch, Savcenko)

GGOS-D Geotechnologien 4th project meeting, IGG, Universität Bonn, 2007-02-12/13 (Angermann, Bosch, Krügel, Meisel)

Working group meeting of the DFG project "Erdsystemmodell", DGFI, München, 2007-02-15/16 (Bosch, Drewes, Göttl, Savcenko, Schmeer, Seitz)

EUREF Technical Working Group Meeting, Lissabon, Portugal, 2007-03-05/06 (Hornik)

IAS-Planning Group Splinter Meeting, Hobart, Australia, 2007-03-12 (Bosch)

Ocean Surface Topography Science Team (OSTST) Meeting, Hobart, Australia, 2007-03-12/ 15 (Bosch)

Workshop of the DFG priority program SPP1257 "Oceanography, Hydrology, Ocean Tides and Gravity Field", Gummersbach, 2007-03-21/23 (Bosch, Göttl, Savcenko, Schmeer, Schmidt, Seitz)

GEO-TOP 3rd Project Meeting, DGFI, München, 2007-03-28 (Bosch, Savcenko)

Workshop on Tectonic Geodesy, German Armed Forces University, Munich, 2007-04-04/05 (Angermann, Seemüller)

ICSU meeting "Global Scientific Challenges: Perspectives from Young Scientists". Lindau, Germany. 2007-04-04/06 (Sánchez)

IVS/IERS ICRF2 Working Group meeting, Vienna, Austria, 2007-04-12 (Tesmer)

18th Working Meeting on European VLBI for Geodesy and Astrometry, Vienna, Austria, 2007-04-12/13 (Tesmer)

8th IVS Analysis Workshop, Vienna, Austria, 2007-04-14 (Tesmer)

ILRS AWG Meeting, Wien, Österreich, 2007-04-14 (Kelm, Müller)

IERS Directing Board Meeting No. 44. Vienna, Austria, 2007-04-15 (Drewes)

2nd VLBI 2010 Working Meeting, Vienna, Austria, 2007-04-15 (Tesmer)

EGU General Assembly, Vienna, Austria, 2007-04-15/20 (Angermann, Schmidt, Seemüller)

ILRS Analysis Working Group Meeting, Vienna, Austria, 2007-04-14 (Kelm, Müller)

IERS Workshop on Combination, Vienna, Austria, 2007-04-16 (Angermann)

IAG Executive Committee Meeting. Vienna, Austria, 2007-04-16 (Drewes)

ILRS Data Formats and Procedures Working Group, Vienna, Austria, 2007-04-16 (Seemüller)

ILRS Governing Board, Vienna, Austria, 2007-04-16 (Seemüller)

GGOS Steering Committee Meeting. Vienna, Austria, 2007-04-17 (Drewes)

GGOS Working Group "Ground Networks". Vienna, Austria, 2007-04-18 (Drewes)

GGOS Working Group on Networks Meeting (joint with IERS Working Group on Site-Colocation, Vienna, Austria, 2007-04-18 (Angermann)

ENVISAT Symposium 2007, Montreux, Schweiz, 2007-04-23/27 (Bosch, Savcenko)

GEO-TOP 4th Project Meeting, IAPG, München, 2007-05-04 (Bosch, Savcenko)

Working group meeting at Bundesamt für Gewässerkunde and Global River Runoff Data Centre, Koblenz 2007-05-07 (Bosch, Drewes, Schmidt, Seitz)

DAROTA Kick-Off Meeting, DGFI, München, 2007-05-10/11 (Bosch, Savcenko)

Arbeitstreffen mit GFZ/TU-Dresden, Dresden, 2007-05-16 to 2007-06-01 (Krügel)

Workshop "Earth Rotation and Global Geodynamic Processes", Dresden, 2007-05-30/31 (Angermann, Bosch, Drewes, Göttl, Seitz)

II Semana Geomática del Instituto Geográfico Agustín Codazzi (IGAC). Bogotá, Colombia. 2007-06-04/08 (Drewes, Sánchez)

EUREF Technical Working Group Meeting, London, United Kingdom, 2007-06-05 (Hornik)

SIRGAS Executive Committee Meeting. Bogotá, Colombia, 2007-06-07/08 (Drewes, Sánchez)

EUREF Symposium, London, United Kingdom, 2007-06-06-09 (Hornik)

GEO-TOP 5th Project Meeting, AWI, Bremerhaven, 2007-06-19/20 (Bosch, Savcenko)

IUGG XXIV General Assembly, Perugia, Italy, 2007-07-01/13 (Angermann, Bosch, Drewes, Göttl, Sánchez, Savcenko, Schmidt, Seitz)

IAG Executive Committee Meetings, Perugia, Italy, 2007-07-02/04/06/10 (Drewes)

ILRS AWG Meeting, Perugia, Italy, 2007-07-10 (Kelm, Müller)

German Kick-off Meeting of the European Territorial Cooperation "Alpine Space Programme" 2007−2013. Neu-Ulm, 2007-07-12 (Drewes)

Workshop "Earth System Model", Potsdam, 2007-08-08/09 (Drewes, Seitz)

GGOS-D Projekttreffen, Potsdam, 2007-09-11/12 (Angermann, Bosch, Drewes, Krügel, Meisel, Müller, Tesmer)

DAROTA 2nd Project Meeting, ZAMM, Hamburg, 2007-09-17/18 (Bosch, Savcenko)

IVS/IERS ICRF2 Working Group Meeting, Paris, France, 2007-09-19 (Tesmer)

IERS Workshop on Conventions, Sèvres, France, 2007-09-20/21 (Drewes, Gerstl, Meisel)

ILRS AWG Meeting, Grasse, France 2007-09-24 (Kelm, Müller, Seemüller)

INTERGEO/Geodetic Week, Leipzig, 2007-09-25/26 (Savcenko)

ILRS Fall 2007 Workshop, Grasse, France, 2007-09-25 to 2007-09-28 (Müller, Seemüller)

INTERGEO / Geodetic Week, Leipzig, Germany, 2007-09-27 (Drewes)

ILRS Fall 2007 Workshop Session 10: Technological Challenges with Data Format: Progress of the Consolidated laser ranging data (CDR) Format and Experiences with the Consolidated Prediction Format (CPF), Grasse, France, 2007-09-27 (Seemüller, co-chair)

ILRS General Assembly, Grasse, France, 2007-09-27 (Seemüller)

ILRS Governing Board, Grasse, France, 2007-09-28 (Seemüller)

4.6 Guests

2006-10-10:	A group within the frame programme of the INTERGEO Congress, Munich.
2006-10-16 to 24:	Prof. J. Báez, Universidad de Concepción, Chile.
2006-11-09 to 28:	Roberto Luz, Universidade Federal do Paraná (UFPR), Curitiba, Brazil.
2006-11-09 to 10:	Prof. Silvio Freitas, Universidade Federal do Paraná (UFPR), Curitiba, Brazil.
2007-02-23:	Dr. Zinavy Malkin, University St. Petersburg, Russia
2007-03-05 to 09:	Dipl.-Ing. Robert Heinkelmann, Technische Universität, Wien, Austria
2007-07-01 to 26:	Eng. William Martinez-Diaz, Instituto Geográfico Agustín Codazzi, Bogotá, Colombia
2007-07-30:	Johannes Boumann, Netherlands Institute for Space Research (SRON), The Netherlands

5 Personnel

5.1 Number of personnel

Total staff of DGFI during the 2006/2007 period (incl. DGK Office):

Regular budget

12 scientists
9 technical and administrative employees
1 worker
9 student helpers with an average of 214 hours/year
2 minor time employees

Project funds

7 junior scientists

5.2 Lectures at universities

Hon.-Prof. Dr. H. Drewes: Geodätische Geodynamik, Technische Universität München, WS 2006/2007

Dr. W. Bosch: Lectures on Satellite Altimetry, Technische Universität München, WS 2006/2007

PD Dr. M. Schmidt: Approximation Methods, Technische Universität München, WS 2006/2007

PD Dr. M. Schmidt: Wavelets, Technische Universität München, SS 2007

Dr. F. Seitz: Appointment as a professor for "Earth Oriented Space Research" Technische Universität München

6 Miscellaneous

DGFI organized the International IAG Symposium "Geodetic Reference Frames (GRF2006)", LVG, München, 2006-10-09/14.

DGFI with its collection of geodetic instruments participated in the "Long Night of Museums", Munich, Germany, 2006-10-21/22.

Research visit at NASA's Jet Propulsion Laboratory/California Institute of Technology, Pasadena, USA (2006-October-December) (Seitz)