Observation of the System Earth from Space

The investigation of the spatial and temporal variations of the Earth’s gravity and magnetic field using new satellite technologies has received wide international attention in the past years. Geoscientific satellites such as CHAMP (German/US), GRACE (US/German) and the planned GOCE Mission (ESA’s first Core Earth Explorer mission) allow measurements with hitherto unprecedented accuracy. They open a new segment in Earth system research.

In Germany a significant part of the data evaluation and interpretation is carried out under the umbrella of the R&D-Programme GEOTECHNOLOGIEN. Under the thematic focus »The Observation of the System Earth from space« eleven collaborative research projects are funded by the Federal Ministry for Education and Research (BMBF) and the German Research Council (DFG). They are carried out in close co-operation of various national and international partners from academia and industry and focus on the recovery and optimal use of the spatial and temporal variations of the Earth’s gravity and magnetic field for geodynamics. The ultimate aim is the establishment of mass anomalies within the solid Earth, of glacial, oceanic and hydrological mass transport, and of mass exchange and balance in Earth system.

The abstract volume contains the presentations given at a science meeting held in Munich, Germany, in June 2003. The presentations reflect the multidisciplinary approach of the programme and offer a comprehensive insight into the wide range of research opportunities and applications, including solid Earth sciences, glaciology, oceanography, hydrology, meteorology, and geodesy.
Observation of the System
Earth from Space

Status Seminar
Bavarian State Mapping Agency (BLVA),
Munich
12-13 June 2003

Programme & Abstracts

No. 3
Preface

The investigation of the Earth’s magnetic and gravity field has received wide international attention. In the frame of the R&D-Programme GEOTECHNOLOGIEN research projects have been launched in 2002 related to the satellite missions CHAMP, GRACE and ESA’s planned mission GOCE, to complementary terrestrial and airborne sensor systems and to the consistent processing of multiple satellite observing systems.

The overall scientific aim is the data exploitation for Earth system research and application. Expected results are an improved understanding of the spatial and temporal variations in the Earth’s gravity field and their use for the study of the dynamics of the Earth’s lithosphere and upper mantle, global sea level variations, ocean circulation and ocean mass and heat transport, ice mass balance, the global water cycle and the interaction of these phenomena.

In an initial 3-year-phase (2002-2004) a total sum of about 10 Million EURO is spent by the Federal Ministry of Education and Research (BMBF) and the German Research Council (DFG) on a balanced portfolio of laboratory and field studies, tool design and testing and computer model development. The projects are carried out in strong collaboration between universities, research institutes and small/medium sized enterprises on a national and international level.

The main objective of the first status seminar »The Observation of the System Earth from Space« is to bring together all participants from the different research projects to present their ongoing work and exchange their ideas. To all of the participants, this meeting will serve as a lively forum for the discussion of the status, challenges and future goals of these projects and as an encouragement of national and international collaborative efforts.

Reiner Rummel
Ludwig Stroink
# Table of Contents

Scientific Programme........................... 1 - 6

Abstracts of Oral Presentations  
and Posters (in alphabetical order)....... 8 - 195

Authors’ Index........................................ 196 - 198

Notes
Programme of the Status Seminar
»Observation of the Systems Earth from Space«, Bavarian State Mapping Agency (BLVA), Munich – 12-13 June 2003

Thursday, 12 June 2003

10:00-11:00
Registration and Poster Mounting (BLVA Munich, Alexandrastr. 4, 4th Floor)

11:00-11:30
Welcome by BLVA, TU Munich & GEOTECHNOLOGIEN

11:30-12:00
Reigber Ch.: CHAMP/GRACE Short Mission Status Review and General Impact on Science

SESSION IERS (CHAIR: N.N.) – 12:00-13:15

12:00-12:15

12:15-12:30
Schwegmann W., Richter B.: Development of an Information and Database System for the IERS, Status and Outlook

12:30-12:45
Angermann D., Drewes H.: Status and Future of ITRF Combination

12:45-13:00
Nothnagel A., Angermann D., Campbell J., Fischer D., Gerstl M., Kelm R., Krügel M., Meisel B., Rothacher M., Steinforth Ch., Thaller D., Vennebusch M.: Combination of Earth Monitoring Products by IERS Combination Research Centers

13:00-13:15

13:15-14:15
Lunch break
SESSION CHAMP (CHAIR: N.N.) – 14:15-15:30

14:15-14:30

14:30-14:45

14:45-15:00
Grafarend E.W., Marinkovic P.S., Reubelt T.: Spectral Harmonic Analysis From Semi-continuous Ephemerides of CHAMP Geodetic Quality, Blackjack Class GPS Receivers

15:00-15:15
Jakowski N., Tsybulya K., Heise S.: Detection of Ionospheric Perturbation by GPS Measurements Onboard CHAMP

15:15-15:30
Lühr H., Maus S., Rother M., Haak V., Choi S., Mai W.: Pre-processing of CHAMP Magnetic Field Telemetry Data and Their use in Scientific Investigations

SESSION GRACE I (CHAIR: N.N.) – 15:30-16:30

15:30-15:45

15:45-16:00
Frommknecht, B.: Integrated Sensor Analysis GRACE

16:00-16:15

16:15-16:30
Ritschel B., Behrends K., Braune St., Freiberg S., Kopischke R., Palm H., Schmidt A.: CHAMP/GRACE - Information System and Data Center (ISDC) – The User Interfaces for Scientific Products of the CHAMP and GRACE Mission

16:30-17:00
Coffee break

17:00-19:30
Short Poster Presentation (1-2 Transparencies each), followed by Poster Session

approx. 19:30
Dinner in the Kantine of BLVA
Friday, 13 June 2003

SESSION GRACE II & RELATED DFG-PROJECTS (CHAIR: N.N.) – 08:30-09:45

08:30-08:45
Flechtner F.: Short-term Atmosphere and Ocean Gravity De-aliasing for GRACE

08:45-09:00

09:00-09:15

09:15-09:30
Müller J., Denker H., Timmen L.: Absolute Gravimetry in the Fennoscandian Land Uplift Area: Monitoring of Temporal Gravity Changes for GRACE

09:30-09:45
Thomas M., Zahel W.: Numerical Simulations of Ocean Induced Variations of the Earth’s Gravity Field

SESSION GOCE-GRAND (CHAIR: N.N.) – 09:45-10:30

09:45-10:00
Rummel R., Flury J., Gruber Th.: GOCE-GRAND: A Detailed Gravity Model for Earth Sciences Derived from ESA’s First Earth Explorer Mission GOCE

10:00-10:15
Wermuth M., Földváry L.: Semi-Analytical Gravity Field Solution-Strategy for GOCE-Data

10:15-10:30
Schuh W.-D.: GOCE Gravity Field Determination – Simulation Studies

10:30-11:00
Coffee break

11:00-11:15

11:15-11:30

11:30-11:45
Denker H., Jarecki F., Müller J., Wolf K. I.: Calibration and Validation Strategies for the Gravity Field Mission GOCE
SESSION AIRBORNE GRAVIMETRY & GEOSENSOR (CHAIR: N.N.) – 11:45-13:00

11:45-12:00
Boedecker G., Spohnholtz T., Stürze A.: SAGS: StrapDown Airborne Gravimetry System Development

12:00-12:15
Cremer M., Stelkens T.H.: The Research Aircraft Dornier 128-6 and the Airborne Gravimeter at the Institute of Flight Guidance and Control (IFF)

12:15-12:30
Kreye Ch., Hein G.W.: GNSS Based Kinematic Acceleration Determination for Airborne Vector Gravimetry – Methods and Results –

12:30-12:45

12:45-13:00

13:00-14:00
Lunch break

14:00
Final Discussion & Further Planning

approx. 15:30
End of Meeting
POSTER SESSION (CHAIR: N.N.) – THURSDAY AFTERNOON

IERS

Rothacher M., Dill R., Thaller D.: IERS Analysis Coordination (WWW-pages)

Angermann D., Krügel M., Meisel B., Müller H., Tesmer V.: Time Series of Station Positions and Datum Parameters

Dill R., Rothacher M.: IERS Analysis Campaign to Align EOP’s to ITRF 2000 / ICRF

Drewes H., Meisel B.: An Actual Plate Motion and Deformation Model as a Kinematic Terrestrial Reference System

Kelm R.: Automated Combination of SLR Solutions within ILRS

Krügel M., Meisel B.: DGFi Results of the IERS Sinex Combination Campaign

Meisel B., Krügel M., Angermann D., Gerstl M., Kelm R.: Intra- and Inter-Technique Combination for the ITRF

Steinforth Ch., Fischer D., Nothnagel A.: Combination of Earth Orientation Parameters from VLBI

Fischer D., Vennebusch M., Nothnagel A.: Geodetic VLBI - The Only Connection Between the Celestial and Terrestrial Reference Frames

Thaller D., Rothacher M.: Comparison and Combination of GPS, VLBI and SLR Solution Series

CHAMP

Offermann P.: CHAMP Mission Overview Poster (Without Abstract)

Grafarend E.W., Marinkovic P.S., Reubelt T.: Spectral Harmonic Analysis from Semi-continuous Ephemerides of CHAMP Geodetic Quality, Blackjack Class GPS Receivers

GRACE & RELATED DFG-PROJECTS

Offermann P.: GRACE Mission Overview Poster (Without Abstract)


Niehuus K., Schmeling H.: Geodynamic Interpretation of Satellite Gravity-Field Measurements
GOCE-GRAND

Rummel R., Flury J., Gruber Th.: GOCE-GRAND: A Detailed Gravity Model for Earth Sciences Derived From ESA's First Earth Explorer Mission GOCE

Alkhatib H.: Numerical Analysis of GOCE Normal Equations With the GOCE-Analyser

Boxhammer Ch.: Tailored Parallel Least Squares Algorithms for GOCE Data Processing


Jarecki F., Müller J.: Validation of GOCE Gradients Using Cross-Overs

Kargoll B.: Implementation and Validation of the Stochastic Model of GOCE SGG Data

Svehla D., Rothacher M.: Testing Kinematic and Dynamic Orbit Determination Approaches for GOCE Mission With Data From the CHAMP and JASON-1 Satellite

Wolf K.I., Denker H., Müller J., Jarecki F.: Prediction of Gravitational Gradients From Terrestrial Data for GOCE Calibration

AIRBORNE GRAVIMETRY


Stelkens T.H., Cremer M.: The Research Aircraft Dornier 128-6 and the Airborne Gravimeter at the Institute of Flight Guidance and Control (IFF)
Numerical Analysis of GOCE Normal Equations with the GOCE-Analyser

Alkhatib H.
Institut fuer Theoretische Geodaesie, Universitaet Bonn, 53115 Bonn, Germany, E-Mail: halkhatib@geod.uni-bonn.de

1. Motivation
The GOCE mission, as one of the dedicated gravity field missions, is based on a sensor concept: satellite-to-satellite tracking (SST) using the GPS system, and satellite gravity gradiometry (SGG). These SGG and SST observations are used to estimate the parameters of the earth’s gravity field in terms of harmonic coefficients by means of a least squares adjustment in the form a Gauss-Markov model.

Before the actual solution of the normal equations is determined, the normal equation matrix is obtained, the inverse of which contains information about the accuracy and the correlation of the spherical harmonics.

The purpose of the proposed GOCE-Analyser is to analyse the behaviour of SGG-only and combined SGG/SST normal equations as well as of SGG-only observations. These analyses involve the examination of the occupation structure and of the properties of the eigenvalue decomposition of normal equations. In addition, the accuracy of the estimated spherical harmonics shall be determined.

Sec. 2 of this paper deals with the design of the GOCE-Analyser and gives an overview over the implemented modules. In sec. 3, a numerical example for the analysis procedure is presented and discussed. In sec. 4, an outlook to functions still to be implemented is given, which involves specially the regularization of the normal equations.

2. The design of the GOCE-Analyser
Fig. 1 shows the design of the main parts and modules of the GOCE-Analyser. The »Read Module« affords the reading of reference frame parameters and of an earth gravity field model. Afterwards, the a priori harmonic coefficients can be sorted and renumbered into different schemes depending on the kind of analysis to be performed.

In order to create the observation equations, the geodetic coordinates of the satellite orbit with respect to a specified sampling rate are transformed into geographical coordinates. Now the Legendre functions and their first and second derivatives are computed for these positions in order to obtain the tensor components of the second derivative of the gravity potential. This observation trend function is superposed with colored noise, which represents the error budget of the satellite gradiometer, yielding a simulated data set. The colored noise is generated by filtering a white noise series with the coefficients of an autoregressive moving average (ARMA) model derived from the spectral representation of the error budget (cf. Schuh 2000). The design matrix is set up directly as far as the Legendre functions are evaluated.

In order to make the computations faster and more efficient the computational scheme just described is completely vectorized, i.e., the Legendre functions are not evaluated position by position, but for a vector of positions. Similarly, the design matrix is not set up in row by row, but in blocks containing several rows. This vectorization reduces the total computation time by more than 90 percent. The optimal block size depends on the maximal degree of development of the spherical harmonics and on the available main memory of the computer used.
The normal equation matrix is assembled such that corresponding blocks of the design matrix are multiplied and summed up. In other words, one block with several columns of the transposed design matrix is multiplied with the corresponding block of rows of the design matrix. For each of these operations the entire normal equation matrix is filled and finally added up.

The next step is the solution of the system yielding the estimations of the spherical harmonic coefficients. However, it is also possible to add an SST normal equation matrix to the SGG normal equation matrix first in order to improve and stabilize the condition of the system.

The computation of the inverse normal equation matrix, which is the variance-covariance matrix of the estimated parameters, is numerically costly, since the matrix is fully occupied. With the current processor and memory used, the development of the parameter model is limited to 100 degrees and orders.

3. Numerical experiments

In order to demonstrate the characteristics of a simulated SGG normal equation system, of its inverse, and of an SST normal equation matrix, the following test data set was generated:

- Orbit: 30-day repeat GOCE orbit, 467 revolutions, mean inclination 96.60°;
- Observations: diagonal components of the SGG tensor, sampling rate 5s;
- Development: up to degree and order 70;
- Noise: trend was superposed with white noise.

Due to the sun-synchronous orbit, the polar gaps, and the constant sampling rate, the observations will not reflect a gridded space-domain structure. As a consequence, the orthogonality relations of the basis functions are lost, and a least squares approach will deliver a fully occupied normal equation system (Schuh 1996). However, the distribution of the data locations is approximately symmetric with respect to the equator. Therefore, the assembled normal equation system nearly reflects a block-diagonal structure. Fig. 2 shows the absolute values of the normal equation matrix.
for a block of the size 250 by 250. It can be seen that the main diagonal dominates the secondary diagonals, and that the off-diagonal elements are relatively low. However, this block-diagonal structure shows only in the case of white observation noise.

To get a deeper insight into the numerical behaviour of the normal equations, a spectral analysis was performed. Fig. 3 displays the eigenvalues of the compound normal equation matrix. A large number of eigenvalues shows a nearly linear trend, whose tilt is low. Thus, the normal equations can be characterized as very homogeneous. The largest eigenvalues influence only the numerical behaviour of the system, i.e., the condition number of the normal equation matrix and the accuracy of the solution. However, if one computes the inverse of the normal equation matrix the reciprocals of these large eigenvalues hardly contribute to the inverse while the small eigenvalues become dominant. An analysis of the eigenvectors belonging to the small eigenvalues showed that they pertain to the coefficients of the low degrees and orders.

4. Goals and outlook
The ill-conditioning of the normal equation system is caused by the downward continuation of the observations from the satellite altitude to the earth’s surface, by the colored observation noise, and by data gaps (cf. Bouman et al. 2000). All this implies that the spherical harmonic coefficients cannot be accurately determined from the data alone. In this case, the application of a suitable regularization becomes essential. Therefore, the Tikhonov regularization will be implemented into the proposed GOCE-Analyser in order to stabilise the normal equation system. This involves two problems: the choice of the best regularization matrix and the optimal choice of the regularization parameter. Both of them require the development of tailored algorithms which will be based on Monte Carlo simulation.

Furthermore, a statistical analysis, including the mean, median, minimal, and maximal values, of the variances for all degrees and orders will be performed in order to evaluate the behaviour of the accuracy and the correlations of the estimated parameters by analysing the inverse normal equation matrix.
5. Bibliography


Status and Future of ITRF Combination

Angermann D., Drewes H.
Deutsches Geodäetisches Forschungsinstitut (DGFI), Marstallplatz 8, 80539 München, Germany,
E-Mail: angerman@dgfi.badw.de

Background and overview
The International Earth Rotation Service (IERS) is in charge of the establishment and maintenance of the International Terrestrial Reference Frame (ITRF), a realization of the International Terrestrial Reference System (ITRS). The basic idea of ITRF is to combine station positions and velocities computed by various analysis centers, using space geodetic observations, such as Very Long Baseline Interferometry (VLBI), Lunar and Satellite Laser Ranging (LLR and SLR), Global Positioning System (GPS), and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS). A series of ten ITRF were compiled, the first was the ITRF88 and the latest is the ITRF2000. ITRF2000 is the most extensive and accurate terrestrial reference frame, including positions and velocities of about 800 stations located at about 500 sites, with better distribution compared to past ITRF versions (Altamimi et al., 2002). The ITRF solutions are widely used in geodetic and geophysical applications and research projects. A highly accurate and consistent realization of the terrestrial reference frame is a fundamental basis for the progress in Earth sciences and for a multitude of new satellite missions (e.g. GRACE, JASON-1, ENVISAT) as well as for future GOCE and GALILEO to achieve their scientific goals.

Within the recently re-organized IERS structure, ITRS Combination Centers (ITRS CC) were included as new components; currently three ITRS CC were established at DGFI (Germany), IGN (Institute Geographique National, France) and NRCan (National Resources Canada). The ITRS CC are responsible for the generation of highly precise and reliable ITRS products from combination of different space geodetic data (solutions) which are provided by the specific services (IVS, ILRS, IGS, and IDS) and/or by individual analysis centres. The work of the ITRS CC at DGFI is being funded by Geotechnologie-Projekt of the German BMBF (Bundesministerium für Bildung und Forschung), Verbandprojekt: FE: Vorhaben: IERS(F0336C). The activities are closely related to the jointly established IERS Combination Research Centre of DGFI, FESG (Forschungseinrichtung Satellitengeodäsie, TU München) and GIUB (Geodätisches Institut, Universität Bonn), all imbedded in the FGS (Forschungsgruppe Satellitengeodäsie), see Nothnagel et al., this issue.

1. ITRS Combination Center at DGFI
The main components of the ITRS CC at DGFI are:
- A Data Management and Information System to organize and provide all relevant ITRF data and products (e.g. station informations, local ties, ITRF input solution, ITRF products)
- The Data Analysis for ITRS Realization consisting of:
  - Validation of submitted input data (solutions);
  - Generation of unconstrained normal equations for each individual solution;
  - Combination of individual normal equations with DGFI Software DOGS-CS;
- Strategy:
  (1) Combination (comparison) of solutions of each technique (intra-technique)
  (2) Combination (comparison) of techniques combined solutions (inter-technique)
  (3) Iteration and final combined adjustment (weighting, outlier rejection, datum definition, etc.)
The ITRF Quality Control and external comparisons with independently generated ITRF solutions are of major importance to ensure ITRF products with highest possible accuracy and reliability.

A major focus was on the validation of the various components of the ITRS CC and on the analysis and verification of our combination strategy. The major data pool, which we used for combination studies and TRF computations are the input solutions submitted for ITRF2000 computation (see http://lareg.ensg.ign.fr/ITRF/ITRF2000/submissions.html). We checked all these solutions regarding various aspects (e.g. SINEX format, constraints, suitability for TRF combination) and identified »suitable« solutions to compute a first TRF realization at DGFI (ITRF2000_DGFI.P, see DGFI report of ITRS CC in IERS Annual Report 2001) and compared the results with the official ITRF2000 provided by IGN (see below). Recently we computed a second (refined) TRF computation by using in addition to the ITRF2000 data pool, some newer solutions containing more recent observations (see Meisel et al., this issue). A detailed description of the combination methodology and of the combination results will be published separately (Angermann et al., in preparation).

2. Present status of ITRF combination and deficiencies

In the last decade, the scope and accuracy of space geodetic observations, as well as the software systems, models and processing strategies improved continuously, and consequently also a remarkable progress could be achieved for the realization of the terrestrial reference frame.

The most recent official IERS realization of the terrestrial reference frame is the ITRF2000. All ITRF2000 results and related files are available at http://lareg.ensg.ign.fr/ITRF/ITRF2000. For details concerning data analysis and quality evaluation of ITRF2000, see Altamimi et al., 2002. The authors estimated the accuracy and long-term stability for the ITRF2000 scale and origin definition based on the contributing SLR and VLBI solutions. The propagated WRMS values over 10 years suggest a frame stability better than 4 mm in origin and better than 0.5 parts per billion (ppb) in scale (equivalent to a shift of approximately 3 mm in station height). Furthermore the improvement of ITRF2000 compared to ITRF97 was shown, about 50% of station positions have an error less than 1 cm, and about 100 sites with velocities being determined at (or better) than 1 mm/yr level. But on the other hand, the ITRF2000 includes also a number of stations with too few observations for a realiable estimation of station positions and velocities (e.g. mobile SLR and VLBI stations, GPS and DORIS stations with observation time spans less than one year). For about 20% of the ITRF sites the standard deviations for velocities are larger than 1 cm/yr, and for 5% of the sites the uncertainties exceed 10 cm/yr. Consequently, there are a number of ITRF sites with unreasonable velocity estimations (see Fig. 1). From our point of view these »poorly estimated« stations should not be included in the ITRF.

We performed an external quality evaluation for the realization of the terrestrial reference frame by comparing our TRF computations with ITRF2000. Fig. 1 shows a comparison of station velocities derived from ITRF2000 and the combined DGFI solution based on ITRF2000 input data (ITRF2000_DGFI.P). The site velocities show in general a good agreement. The discrepancies between both ITRF realizations are (in average) in the order of 1-3 mm/yr, but there are some sites with larger discrepancies, which need to be further investigated in cooperation with IGN. Note that in both TRF computation the datum was defined in a
similar way, i.e. the scale being defined by SLR and VLBI solutions, and the origin being defined by SLR. From our experiences regarding the analysis and combination of space geodetic observations (solutions) we identified a number of deficiencies regarding current ITRF realizations, e.g.:

- Systematic effects (biases) between solutions and/or techniques can be considered as one major limiting factor of the combined solutions. As an example for the current status we mention that the individual solutions submitted for ITRF2000 reach differences of up to 5 cm for the origin and a few ppb for the scale (see Altamimi et al. 2002, and http://lareg.ensg.ign.fr/ITRF/ITRF2000/T.gif and D.gif). Also differences up to a few centimeters for positions and up to one cm/yr for station velocities exist for some collocation sites with long time series (many years) of observations (Angermann et al., 2002). The reported differences often exceed their r.m.s. errors by a factor of 5-10 or even more, indicating that the individual solutions are significantly influenced by systematic errors.

- Another important issue is the reduction of a-priori datum constraints, which normally are included in the solutions. The input solutions submitted for ITRF2000 realization were classified to include loose, minimum, or removable constraints. We found remarkable contradictions with respect to these declarations, and for some of the ITRF2000 input solutions the constraints could not be removed. If one neglects these constraints, significant biases and systematic effects might be introduced into the combination results.

- Conventionally the ITRF is realized by the adoption of a set of positions referred to a reference epoch and constant velocities for the ITRF network stations. The observed non-linear effects in position time series (e.g. due to seismic or volcanic effects, deformations at plate boundary zones, local effects) are in conflict with the assumption of constant velocities (see Angermann et al., this issue). This may produce errors and systematic effects in the individual solutions, which would also propagate into the TRF and degrade its accuracy.

- Collocation sites are a key element for combining TRF solutions provided by different techniques. Currently, only six ITRF sites exist with collocations of VLBI, SLR, GPS and DORIS, and none of these is fully satisfactory regarding the data quality and/or the time span for the various techniques. There are a number of SLR and VLBI stations that are not even collocated with a GPS receiver. In many cases, the inera-site vectors (local ties) are not well determined or dubious. The current situation regarding collocation sites and the accuracy and availability of local ties is not satisfactory. Another important aspect concerning collocation sites is how to handle velocity estimations obtained from different techniques at one site. Normally (for previous ITRF computations) the different estimations were forced to be identical. The results obtained from our latest TRF combinations indicate, that for some collocation sites the velocity estimations for different occupations seem to differ significantly, and in those cases the velocities should not forced to be identical (e.g. systematic biases between techniques do exist, local phenomena may cause occupation- and/or station-dependent effects).

- A number of relevant aspects related to the combination methodology need to be studied in more detail, e.g. the level on which the combination should be performed (e.g. observation, normal equation or solution level), the weighting of solutions for the intra- and inter-technique combination, the handling of local tie information, the handling of non-linear site motions, and datum definition issues.

3. Recommendations for future ITRF combinations

Finally we address some important aspects that should be considered for future ITRF realizations:

- To achieve further improvements there is an urgent need to investigate the existing differences between different techniques and/or solutions regarding various aspects (e.g. modeling, parameterization, software-rela-
ted issues, analysis strategy, datum definition) and to understand their origin.
- To overcome the problems concerning the reduction of constraints we recommend for future ITRF submissions, that unconstrained normal equations in addition to/or instead of solutions with variance-covariance matrices should be provided. Then the normal equations can be combined directly without removing constraints.
- The assumption of constant site velocities is not true in reality, since various geophysical phenomena may vary as a non-linear function of time. Furthermore mass redistributions within the Earth system, including the solid Earth, oceans and the atmosphere and oceans cause variations of the geocenter, relative to the origin to a crust-fixed coordinate frame like the ITRF. Therefore, alternative – and probably more realistic – representations for the time evolution of the ITRS should be developed (e.g. time series combination of station positions); in this context the consistency between ITRS, ICRS and EOPs should be ensured to the highest possible extent.
- A re-definition and improvement of the IERS network according to various aspects is essential to achieve further improvements for the accuracy and long term stability of the ITRF. Relevant issues are improvements regarding collocation sites and the availability and accuracy of local tie information. Furthermore, we suggest to exclude »poorly« observed stations from ITRF computations and to define suitable criteria that must be fulfilled for IERS network stations.
- Further studies of the combination methodology regarding various aspects are important, such as the »optimal« level of combination (observation, normal equation, or solution level), weighting, handling of eccentricities, datum definition, etc. For the definition of the kinematic datum of the ITRF we propose to use kinematic models based on geodetic observations (e.g. APKIM) instead of geophysical models (e.g. NNR NUVEL-1A) to ensure that the no net rotation condition is more accurately fulfilled.

References
Figure 1: Comparison of site velocities derived from ITRF2000 and ITRF2000_DGFI.P.
1. Background and motivation

In its function as IERS Combination Research Centre and as ITRS Combination Centre, DGFI is strongly involved in the analysis and combination of different space geodetic observations. It is well-known that technique- and/or solution-related systematic effects (biases), which are often poorly characterised or quantified, are assumed to set the accuracy limits of the space geodetic observations in most cases. The analysis of time series is important to get further insight into the solution characteristics and to identify possible problems. One major goal is to study the existing differences of techniques and to understand their origin in order to achieve further improvements. A significant part of the work is being funded by Geotechnologien-Projekt of the German BMBF (Bundesministerium für Bildung und Forschung), Verbundprojekt: FE: Vorhaben: IERS (F0336C).

Another motivation for this study is strongly related to the tasks of the ITRS Combination Centre at DGFI.Conventionally, the terrestrial reference frame is realised by the adoption of positions referred to a specific reference epoch and constant velocities for a set of global tracking sites. In reality, the assumption of constant site velocities is in conflict with non-linear effects caused by several geophysical phenomena (e.g. seismic or volcanic effects, deformations at plate boundary zones, local effects).

In addition, mass redistributions within the Earth system, from various internal processes and from surface mass changes associated with the atmosphere, oceans, and the continental hydrological cycle, cause variations of the geocenter relative to a crust-fixed coordinate frame like the ITRF. Therefore, alternative – and probably more realistic – representations for the time evolution of the terrestrial reference frame should be developed (e.g. time series of station positions).

This presentation focuses on the analysis of site position time series obtained from VLBI, SLR, GPS and DORIS solutions. We also present time series for the origin and scale derived from these solutions and discuss their contribution to the realization of the terrestrial reference frame. We analyzed the time series with respect to non-linear effects, periodic signals and systematic differences and compared the results at collocation sites.

2. Data and processing strategy

The characteristics of the individual solutions that we used for the time series analysis are summarized in Table 1. We applied 7 parameter Helmert-transformations to align the individual VLBI, SLR, GPS and DORIS solutions into the ITRF2000 datum. A well-known problem related to these similarity transformations is the fact that the results are sensitive to the geometric station distribution and to changes in the station configuration. This is especially a problem in case of VLBI, since normally only 4-6 telescopes observe simultaneously in a daily session and furthermore the network geometry changes from one session to the next (for more details see Krügel and Meisel, this issues).
3. Results
To get further insight into the characteristics and the contribution of the different space geodetic observations to the realization of the terrestrial reference frame, we analysed the time series of scale and translation variations derived from similarity transformations between the individual space technique solutions and ITRF2000. Fig. 1 shows the time series of scale variations. Both SLR and VLBI determine the scale with a high long-term stability and the results are in good agreement with the ITRF2000 scale. The three GPS series agree within 1 ppb during the last two years, whereas before early 2000 larger discrepancies and irregularities exist. The DORIS scale differs significantly from ITRF scale by 2-3 parts per billion (ppb). The time series for the translation variations are displayed in Fig. 2. The most stable results were obtained from SLR, which are in good agreement with the ITRF2000 origin. The annual signals for the translations of SLR series seem to represent »real« motions of the geocenter with respect to the ITRF. The GPS and DORIS results show significant larger variations compared to SLR, especially for the z-component of the origin.

We analysed the position time series with respect to non-linear effects, systematic effects and compared the results at collocation sites. Fig. 3 shows the effect of instrumental changes on the time series of station positions. Both collocation sites do not show similar effects in VLBI position series, indicating that the observed jumps in the GPS series are a technique-related problem and not a »real« motion. Fig. 4 shows the effect of large earthquakes on the position time series for three stations.

4. Conclusions
The time series of the datum parameters have evidenced that SLR is the major technique to define the origin of the terrestrial reference frame. VLBI and SLR define the scale consistent with ITRF2000, and with a high long-term stability. Further improvements for GPS and DORIS seem to be necessary to use these techniques for the datum definition of the terrestrial reference frame.

The observed non-linear effects in the position time series (e.g. due to earthquakes, instrumental changes) are in conflict with the assumption of constant velocities. This may produce errors and systematic effects in the individual solutions, which would also propagate into the TRF and degrade its accuracy. Hence a better monitoring of the TRF may require non-linear components in site positions and in future also the variations of the geocenter with respect to a crust-fixed coordinate frame should be considered.

Table 1: Summary and characteristics of solutions used for the analysis of time series.

<table>
<thead>
<tr>
<th>Technique</th>
<th>AC</th>
<th>Software</th>
<th>Data Time Span</th>
<th>Stations</th>
<th>Solution Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLBI</td>
<td>DGFI</td>
<td>OCCAM</td>
<td>1984.0-2002.0</td>
<td>47</td>
<td>2227 daily session solutions</td>
</tr>
<tr>
<td>GPS</td>
<td>CODE</td>
<td>Bernese</td>
<td>1996.0-2002.2</td>
<td>171</td>
<td>weekly SINEX files</td>
</tr>
<tr>
<td>GPS</td>
<td>JPL</td>
<td>GIPSY</td>
<td>1996.0-2002.2</td>
<td>172</td>
<td>weekly SINEX files</td>
</tr>
<tr>
<td>GPS</td>
<td>SIO</td>
<td>GAMIT</td>
<td>1995.0-2002.2</td>
<td>147</td>
<td>weekly SINEX files</td>
</tr>
<tr>
<td>DORIS</td>
<td>IGN/JPL</td>
<td>GIPSY/OASIS</td>
<td>1992.8-2002.0</td>
<td>82</td>
<td>weekly SINEX files</td>
</tr>
</tbody>
</table>
Figure 1: Time series of scale variations [ppb]. Note that for SLR, GPS and DORIS the resolution is weekly, whereas for VLBI the variations for daily sessions are shown.
Figure 2: Time series of weekly translation variations (cm). Note that VLBI is not included, since these techniques do not contribute to the definition of the origin of a reference frame.

Figure 3: The effect of instrumental changes is shown in the position time series for two collocation sites (GPS and VLBI) at Onsala, Sweden and Westford, USA.
Figure 4: The effect of large earthquakes is shown for three stations located at Arequipa (Peru), Ankara (Turkey) and Cocos Island (Australia).
Within the wide spectrum of gravimetry applications in geophysics, geodesy and metrology, airborne gravimetry is the most adequate observation technique to complement satellite methods for spatial resolutions better than some 50 km and to replace terrestrial observations to a great extent. The current state of the art are platform gravimeters for the vertical gravity component with $\pm 1 \times 10^{-6}$ g at a spatial resolution of about 3...5 km; one new instrument may even go beyond. There is a strong need to significantly increase performance, add full vector capability and improve operability in order to be competitive and extend applications particularly for the study of small scale mass variations in the upper crust such as associated with oil, water or ore deposits or with phenomena such as mountain roots or plate margins.

For this reason, a group of five institutions set out to advance airborne gravimetry in Germany: Three different hardware approaches are being developed and compared; two companies establish the links to the requirements and chances not only for geoscientific research, but also for commercial exploration.

The institutions within the »Verbund Fluggravimetrie« are (affiliates):
- Bavarian Academy of Sciences, München »BEK«
- Technical University Braunschweig »IFF«
- Aerodata Systems, Braunschweig »Aerodata«
- IfEN GmbH für Satellitennavigation, Neubiberg »IfEN-GmbH«
- University FAF München, Neubiberg »EN«

IFF owns a conventional platform scalar gravimeter to be upgraded. EN starts from an INS to be diverted and BEK searches for optimal sensor component configuration, both aiming at vector gravimetry. Aerodata and IfEN-GmbH care for the link to customers.

Besides hardware and software development, a common field of interest is GNSS kinematic positioning particularly for acceleration. Joint flight tests will enable comparisons and definition of further developments necessary.

From the above it is clear that the partnership is very promising: It very luckily combines a conventional hardware which has already proven its merits with novel approaches which elsewhere have shown interesting initial results but require still significant progress to unfold their full capabilities. These activities would not have been possible without funds from the
BMBF. The union enables the institutes to benefit not only from the funds but also from mutual communication and interaction.

The common time schedule of the five partners provides a first impression of the variety of problems to be solved. The poster will show more details of the common structure and of some of the peculiarities.
1. Introduction
In view of the breathtaking progress in satellite gravity field missions their limitation in spatial resolution to about 50 km has to be recognized. Therefore supplementary terrestrial gravity observations are necessary for a wide spectrum of applications such as fine structure and exploration geophysics. »Terrestrial« includes airborne gravimetry for a spatial resolution of 50 km down to a few kilometres and accuracies of about 1 mGal. Classical airborne gravimetry systems derived from land gravimeters via marine gravimeters are operational since a number of years, but most of them are quite bulky, costly to operate and do not meet the 1 km / 1 mGal aim. For this reason, airborne gravimetry still is under development. Within the »GEOTECHNOLOGIEN-Programm« a group is established – »Verbundprojekt Fluggravimetrie« – aiming at the 1 km / 1 mGal target from three different starting points:
• classical platform gravimetry improvement,
• diverting SINS,
• composing components in optimum strapdown configuration.
This contribution reports on the latter, labelled SAGS: StrapDown Airborne Gravimetry System.

Because of the accuracy requirements, both of the acceleration quantities have to aim at a relative accuracy of $10^{-6}$.

3. Sensors and Signals

3.1. Accelerometers
The accelerometers used are QA3000/30 which are capable of the above accuracy – provided they are treated carefully. Fig. 1a shows a preliminary SAGS2.2 prototype with the accelerometers and electronics; fig. 1b is the follow-up SAGS4 prototype design to be realized within this project. Fig 1c demonstrates the very low acceleration signal noise while stationary and low drift rates as also the nice behaviour after shocks. This is accomplished by a wide range of measures for careful EMC, vibration isolation, temperature control, high performance ADC, filtering etc. For calibration and alignment of the sensors, an in-flight procedure is under work.

Figure 1a
3.2. GNSS
GPS currently provides not only position and kinematic acceleration, but also attitude information.

3.2.1. Positioning and kinematic acceleration
Standard L1 L2 carrier phase positioning procedures at 10 S/s are used for positioning. However, atmospheric – primarily ionospheric – noise deteriorating the position by – admissible – decimeters badly degrade the accelerations derived. For this reason, reference station arrays for providing correction information are tested and the accelerations results significantly improved; fig. 2a and b reflect the improvement in acceleration root error covariance over time traveled before filtering. Double differentiation is combined with filtering, thus keeping the deviation within 5mm after (double) re-integration. Nevertheless, GPS-derived accelerations are the critical part.

3.2.2. Attitude
A GPS multi antennae receiver Ashtech3DF is used to provide a longterm stable orientation reference at 2 S/s – albeit with a big epoch error of the order of 0.2 degrees. This information, however, is integrated with a high resolution and short term high accuracy FOG (fiber optical gyro [of various brands]) information to provide an integrated attitude information better than 0.01 degree at some 100 S/s.

3.3. Synchronisation
Analog acceleration sensor signals are AD converted in parallel with a GPS-controlled clock signal, thus providing high accuracy synchronisation.

3.4. Filtering
Filtering is carried out with a cascade of mechanical damping and analog filtering (for accelerometers) and subsequent numerical FIR filtering to avoid phase shifts.

4. Outlook
The new SAGS4 prototyp will maintain the observation quality of its predecessor and hopefully even improve. The in-flight calibration and alignment of SAGS has to be finalized. The GPS acceleration still is the critical problem. Therefore, the sampling rate will be increased particularly for employing light aircraft with high dynamics. Ionospheric modelling will be pursued further.
1. Introduction
This paper outlines the problems that occur in processing satellite gravity gradiometer (SGG) data for the GOCE mission. Since the catalog of requirements of the ESA contains the full accuracy information for estimated parameters a direct solution has to be computed. In the following the dimensions of the matrices will be illustrated and the problems arising from computing a direct solution will be pointed out. Strategies to solve this giant task will be presented. The text ends with an outlook on future investigation.

2. Problem Size
Within the GOCE mission the duration of a period of measurement will be six months. For every satellite position four gradiometer measurements will be made. This leads to a total of 6 months times 30 days times 24 hours times 60 minutes times 60 seconds times four measurements which are 62 millions observations.

This huge amount of observations will be used to determine the spherical harmonic coefficients of the earth’s gravity field with a resolution up to degree and order 300. The number of parameters in this problem size is about 90000.

2.1 Memory Problems
Trying to solve this overdetermined least squares problem with standard techniques like a Gauss-Markov model leads to matrices of giant sizes. For example sixty-two millions of observations and 90000 unknown parameters lead to a normal equation matrix of 60 gigabytes, a design matrix of 4000 gigabytes, and a weighting matrix of 261 terabytes. These dimensions show that it is extremely difficult to store, invert or solve this matrix of normal equations, but it is impossible to store either the design matrix or the weighting matrix. Therefore, the problem is how to assemble the normal equations with weighted observations. The classic approach to weight the observations in a least squares problem is a Cholesky decomposition of the weighting matrix and premultiplication of the factorisation matrix to (a) the design matrix (b) the vector of observations, and (c) the vector of residuals [Koch 1997 S. 167]. This is not possible in the case of GOCE observations because of two reasons. On the one hand, it is impossible to store this matrix, and on the other hand, the expected computing time for the Cholesky decomposition will be astronomical. The required number of operations for the Cholesky decomposition is of the order of 1/6 times n to the power of three plus rest. Having an n of sixty-two millions of observations the number of required operations is 3.6 times 10 to the power of nineteen operations. A pentium 4 processor with 3 gigahertz which is one of today’s fastest processors can perform about 2900 mflops per second [Dongarra 2003]. This speed leads to a computing time of 375 years.

This problem is circumvented by applying a digital filter to the rows of the design matrix and to the vector of observations [Schuh 1996]. The great challenge of computing the design matrix and assembling the normal equation matrix has to be taken. The computation will
be performed on a Linux cluster. Therefore, parallel programs have to be developed which are, on the one hand optimized with regard to memory usage, and on the other hand, optimized with respect to performance.

Figure 1 shows the orders of magnitude of the matrices in GOCE data processing in comparison to available computer memory.

2.2 Computing Time
Again, why is computing time critical? Let’s look at the major steps that have to be performed to determine the unknown parameters.

1) Calculating the design matrix has to be done with recursive formulas, which are very ineffective on modern computers.
2) Multiplication of the design matrix with its transpose takes \( n^2 \times m \) operations, with \( m = 62 \) millions observations and \( n = 90000 \) parameters. This is a total of about \( 5 \times 10^7 \) to the power of 17 operations. Taking the fast pentium 4 processor this calculation will take 2000 days.
3) The normal equation matrix is small in relation to the design matrix. It has \( 90000 \times 90000 \) elements which require 60 gigabyte of computer memory. Again the Cholesky decomposition requires \( \frac{1}{6} \) times \( n \) to the power of three operations resulting in a computing time of about 12 hours.
4) Computing the inverse of the normal equation matrix requires \( n \) to the power of three operations resulting in a computing time of 3 days.

Figure 1: Memory usage in standard problems and data streaming methods for GOCE data processing.
3. Strategies

The programs that analyse GOCE SGG data must be optimal in performance and optimal in memory use. Furthermore a parallel processing strategy is necessary because it is obvious that the speed of one processor is not enough. Optimization has to be done first on a single computer, and then parallel optimizations can be developed.

3.1 Vectorisation

The recursive formulas to compute the Legendre polynomials are poison for every modern computer architecture, because of the hierarchical memory model and the internal pipeline processing. To improve the performance of the computation of the design matrix we developed a method to vectorize the computation of the Legendre polynomials and their derivations. This method achieved a speedup of factor eight.

3.2 Parallel Computing

Since the speed of a single processor is not sufficient for this huge problem parallel programs have to be developed. For these purposes a Linux cluster of 15 PCs has been built at our institute, (15 Pentium 4 with 2.2 GHz, 1GB RAM each, 40 GB Harddisk). We use a parallel assembling strategy to build up the normal equations, where each node works on an individual part of the design matrix. This strategy is implemented in the program DPA which computes the global gravity field up to degree and order of 90 based on 1.5 millions of observations within 45 minutes on our Linux cluster. The collection of parts of the normal equation matrix is a tree based approach that is part of the LAM MPI implementation we used, [LAM-MPI] (cf. figure 2). The results achieved show, that our strategy appears to be promising to solve this huge linear least squares problem. With our parallel strategy we reach a computing speed, that is about 14 times faster than that of one pentium 4 processor. Applying this speed to the time estimations made above, the computing time of 2000 days for the assembling of the normal equations shrinks to 143 days.

4. Outlook

The assembling of normal equation matrices for resolution higher than degree and order 90 forces us to use an out-of-core strategy. Preliminary tests have shown that out-of-core strategies are very well suited for numerical computation when matrix multiplication is involved. The reason why the out-of-core method can be very effective even though harddisks are extremely slow in comparison to memory, is the complexity of multiplication. The complexity of the multiplication of two \( n \) times \( n \) matrices is \( n^3 \) to the power of three.
have 4 times n square disk to memory transfers in order to be able to make n to the power of three multiplications. The larger n grows the longer the computing time for the multiplications becomes in comparison to the disk to memory transfers. Thus having large enough matrices, the performance of the out-of-core approach is similar to the performance of in-core-methods. Future investigation will focus on out-of-core methods for two problems: (1) assembling the normal equations, and (2) the solving the normal equations. We are planning to improve our software DPA to be able so solve the gravity field very effectively on a Linux Cluster up to degree and order 300 making intensive use of out-of-core methods.

5. Bibliography


[Koch 1997] Parameterschätzung und Hypothesentests, Dümmler Verlag


[LAM-MPI] LAM-MPI Homepage, http://www.lam-mpi.org
The Research Aircraft Dornier 128-6 and the Airborne Gravimeter at the Institute of Flight Guidance and Control (IFF)

Cremer M., Stelkens T.H.
Institute of Flight Guidance and Control, Technical University of Braunschweig, Hermann-Blenk Str. 27, 38108 Braunschweig, Germany, E-Mail: m.cremer@tu-bs.de

Same abstract as

Stelkens T.H., Cremer M. – The Research Aircraft Dornier 128-6 and the Airborne Gravimeter at the Institute of Flight Guidance and Control (IFF); this volume.
Calibration and Validation Strategies for the Gravity Field Mission GOCE

Denker H., Jarecki F., Müller J., Wolf K.I.
Institut fuer Erdmessung (IfE), Universitaet Hannover, Schneiderberg 50, 30167 Hannover, Germany
E-Mail: denker@ / jarecki@ / mueller@ / wolf@ife.uni-hannover.de

Abstract
The objective of GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) is the determination of the Earth’s gravitational field with high spatial resolution and accuracy. The most challenging part is the operation of the gradiometer, which allows the derivation of gravitational gradients, i.e., the second derivatives of the gravitational potential. The diagonal components of the gravitational tensor shall be determined with an accuracy of about 4 mE/Hz$^{1/2}$ in a frequency range from 5 to 100 mHz. To meet these requirements, various calibration steps have to be performed. We show how external data may be used to support the GOCE calibration. We have applied least-squares collocation as well as the spectral combination technique by integral formulas using data from a regional test area in Europe to predict gravitational gradients at GOCE altitude, which can then be used to derive the calibration parameters, like biases and scale factors. Furthermore, internal and external validation of the observations has to be performed to detect systematic errors and to check the results for the gravity field quantities. Some ideas and procedures are under discussion. As a first internal accuracy check of the gradients, we analysed satellite cross-overs from simulated data.

1. Introduction
GOCE aims at the highly accurate determination of the static part of the Earth’s gravitational field with high spatial resolution (about 80 km at the surface of the Earth), see also ESA (1999). For the first time, satellite gravity gradiometry will be applied for the derivation of the medium and short-wavelength parts of the gravity field, combined with satellite-to-satellite tracking to the GPS satellites for the orbit determination and the retrieval of the long wavelengths of the gravity field. The gradiometer accuracy of 4 mE/Hz$^{1/2}$ in a frequency range from 5 to 100 mHz (so-called measurement bandwidth MBW) is strongly dependent on the behavior of the single sensors (e.g., accelerometers) as well as on their interaction with each other and with the control system. In this respect, many error sources affect the observations, e.g., scale factor errors, misalignments, non-orthogonality of the accelerometer axes or the non-linear behaviour of the accelerometers (Cesare, 2002). To meet the high accuracy requirements, the gradiometer measurements are calibrated on ground and in orbit by specific procedures (e.g., by shaking of the satellite) up to a certain level. To adjust the gradients with respect to the real gravity field of the Earth, a further calibration step is required, where external information, e.g., terrestrial gravity data or existing gravitational field models, are used. Besides the calibration, where the gravitational gradient observations are really changed to bring them »closer« to reality, validation is applied to check the accuracy of the resulting gravitational gradients or other derived gravity field quantities (e.g., spherical harmonics).

Here, we discuss two topics in this respect. The first is the external calibration with gravity anomalies in a regional area on the Earth using...
the standard least-squares collocation technique as well as the spectral combination technique by integral formulas to determine independently the gradients at satellite altitude. The final goal is to reduce the systematic errors in all gravitational gradients and to determine calibration parameters like biases $b_{ij}$ and scale factors $\lambda_{ij}$. A simple model is given by

$$V'_q(t) = V'_q(t) + b_q(t) + \lambda_q(t) + \frac{db_q}{dt} / dt \Delta t$$ (1)

In the calibration equation (1), $V'_q$ represents the observed gravitational gradients, which have to be adjusted with respect to the reference gradients $V'_q$, and $\frac{db_q}{dt}$ models a possible time-dependent behavior of the bias. The possible time and frequency-dependency of the calibration parameters is one of the open questions.

Concerning validation, an investigation of the gradients in satellite cross-overs is performed to verify the relative accuracy of the gravitational gradients observed in the same position, but at different epochs, and to identify systematic errors.

2. External Calibration by Terrestrial Data

For the GOCE calibration we have developed a two-step procedure. In the first step, least-squares collocation (LSC) is applied for the upward continuation of gravity anomalies, resulting in gravitational gradients and their error covariances at satellite altitude. In the second step, calibration parameters and their error covariances are derived using again LSC. The input data of the first step comprises terrestrial gravity anomalies in a regional test area. The data are used in a remove-restore procedure, where the low-frequency gravity field parts (long wavelengths) are removed using the global geopotential model EGM96 (Lemoine et al., 1998) and where also the high-frequency signals caused by the topography are removed. The accuracy of the input gravity anomalies is assumed to be 1 mGal. In the LSC approach, all signal and error covariances are computed successively following standard procedures (see Tscherning, 1976, and Moritz, 1980). The maximum prediction errors are about 1-2 mE for the gravitational gradients at satellite altitude, if ground data from a well surveyed area are used. These values are accurate enough to meet the GOCE accuracy requirements. Further details are given in Müller et al. (2003) and Wolf et al. (2003) in this volume. These results are confirmed by an independent study (Denker, 2003), where the spectral combination technique by integral formulas has been applied.

In the second calibration step (not yet performed explicitly), the calibration parameters (e.g., bias and scale factor) shall be estimated together with their covariances, again using collocation techniques. The input quantities are the predicted gravitational gradients of step I as well as the measured GOCE gradients. Here, one has to ensure that the predicted gravitational gradients are given in the same reference frame as the observed ones. Also the spectral and temporal behavior of the calibration parameters has to be considered.

3. Cross-Over Validation

In contrast to calibration, validation means the comparison of the observed gradients or derived gravity field quantities with independent data without correcting the observations. Such data may be terrestrial gravity anomalies, oceanic or altimetric observations, or any other relevant data sets. Our recent validation approach begins one level earlier, where we compare measured gradients with other measured gradients at satellite cross-overs (XO). This technique has been applied very successfully in satellite altimetry. Cross-overs do not test the measurements independently, but allow to detect possible systematic errors, to check the inherent accuracy of the gradiometer system and to give accuracy information, which may be helpful as input for collocation.

The idea is to compare observed gradients, when the satellite passes the same geographical position again. Unfortunately, reality is not that simple, just to take the measured values and compare them, but one has to reduce the gradients to make them comparable at all.
E.g., the orbit eccentricity (about $5 \cdot 10^{-3}$) leads to a height difference at the cross-overs and to a small rotation between the gradiometer axes. After having identified the cross-overs in a corresponding two-dimensional projection, the gradients and the heights are interpolated into these points using a quadratic approach. Then the gradients are reduced to the same reference height. This so-called height reduction can be applied by

$$ V_\theta(h_2) = V_\theta(h_1) + (dV_\theta/dh)_1 \Delta h_2 \quad (2) $$

The derivative of the gradients in the height direction is computed from a global geopotential model like EGM96. Thereby, commission and omission errors of the global model were investigated. Also, errors caused by the rotation of the gradients, which are observed in different frames related to the ascending resp. descending tracks, were considered. When all these reductions are carried out, the gravitational gradients at the cross-overs can be compared. The resulting differences in the radial component of the gravitational tensor are less than 0.6 mE for the noiseless simulated test data set, far below the GOCE accuracy (about 2 mE). So far, our method for the relative validation works with sufficient numerical accuracy concerning the interpolation and rotation routines. A further test assuming noisy input gradients confirmed that the XO approach can be used to detect shortcomings in the measurement process. An open question remains: What is the spectral behavior of the gradients and how does it affect the XO concept?

In the near future, we intend to use also external data for the validation as a different approach. Further details of the cross-over validation processing are given in Müller et al. (2003) and Jarecki et al. (2003) in this volume.

4. Conclusions and Outlook
Calibration and validation plays an important role for GOCE to overcome instrumental and measurement errors and to achieve the high accuracy of about 4 mE/Hz$^{1/2}$ in the MBW (5 to 100 mHz), but also to reach a maximum performance outside the MBW. In this context, we developed a possible concept for GOCE calibration using terrestrial gravity anomalies, which gave promising first results. For the internal validation, a cross-over analysis was investigated which works quite well. But the further development of our approaches is necessary to meet the final GOCE accuracy requirements in the MBW for all tensor components.

5. References


The intention of this EOP Alignment Campaign is to achieve an overall accuracy of 0.1 mas for Earth Orientation Parameters and to create EOP series with highest possible consistency with ICRF and ITRF2000. Therefore the EOP Alignment Campaign deals with the analysis and understanding of the origin of systematic errors belonging to the reference frame definition.

In September 2001 the IERS Analysis Coordinator presented the »IERS Analysis Coordination Campaign to align EOPs to ITRF2000/ICRF« as proposed by J. Ray. At the end of September 2001 the EOP Alignment Campaign was started with an initial call for participation. The final results should be recommendations for future realizations of reference frames. The Campaign is subdivided into two parts.

In a first step the Technical Centers were asked to produce EOP series with a reference frame fixed to the ITRF2000 / ICRF at the level of uncertainty. In addition they were asked to produce solutions with different constraints on ITRF2000 (ICRF). Until May 2002 21 proposals were submitted, see also the web-pages http://alpha.fesg.tu-muenchen.de/iers/eop/campaign.html. 12 of them contributed to the first step and produced more than 40 EOP series from all geodetic space techniques (VLBI, SLR, GPS, DORIS) with various constraints (fixed, significant, minimum) to realize the alignment to the ITRF2000 reference frame. Tab. 1 gives an overview of the submitted EOP series. The series are freely available on an ftp-archive, ftp://alpha.fesg.tu-muenchen.de/iers/eop/. Additional to each series a detailed description file about the constraints, the reference frame, the reference sites and the combination approach which was used is available.

In the second step 12 participants are now analysing the submitted EOP series by comparison with the official annual solutions of 2000 and by studying the consistency between the series. A first overview was presented at the EGS General Assembly in Nice 2002 by R. Dill and at the IERS Combination Workshop in Munich by

- Dill, R.: Comparison of EOP series from the IERS analysis campaign to align EOPs to the ITRF2000/ICRF

More final results are expected at the EGS-AGU-EUG Joint Assembly 2003 in Nice.

The presented results showed that the analyses have to cope with many special problems coming from the pooling of EOP series from different techniques. In order to compare the series they need to be reformatted and resampled in one common format. Problems occur with data gaps, mainly in the unevenly sampled VLBI series and with different or wrong signs of UT1-UTC in series of satellite techni-
ques. In a first comparison of the EOP series against each other, three EOP parameters (Xpol, Ypol, UT1-UTC) were studied by a simultaneous estimation of OFFSET (shift in amplitude), DRIFT and SCALE factor. Additionally, possible time lags (shift in time) were detected. The estimation was done by a nonlinear least squares fit, including the given errors as weights. Unfortunately the results depend on the applied interpolation scheme, especially for the VLBI data sets.

A comparison was made with a piece-wise cubic interpolation and the usual lagrange interpolation, both with different sampling rates from 0.5 days to 5 days. Instead of UT1-UTC we switched to UT1-TAI to avoid interpolation errors at the leap second steps.

The following comparisons are performed with piece-wise cubic interpolation for GPS and SLR series and Lagrange interpolation for VLBI series, both with 1 day sample rate. After this preprocessing steps we selected 37 series for Xpol and Ypol and 36 series for UT1-UTC adding IERS C04 as reference dataset. 

In polar motion (Xpol, Ypol) most series coincide within ±0.5 mas in OFFSET and almost no DRIFT can be identified, except for IGN 01 (≈ 1.5 mas/a). Meanwhile IGN acknowledged problems with its DORIS solution and offers a corrected series. DRIFTS result mainly between the long VLBI series (IAA, GAUS, GSFC) where the ITRF2000 velocities are used over long time intervals. Most VLBI and SLR series show also a good accordance in UT1-UTC, < ± 5 Ìs, except IAA 03. The comparison of UT1-UTC in the case of satellite techniques is a known problem. Compared to C04 all UT1-UTC series from IGS show a negative sign over the first part of the series and a large OFFSET coming from orbit systematics. From this first comparison there is no significant indication that fixed constraints are better than loose or minimum constraints to achieve the alignment to ITRF2000. Only the ASI 01 series differs from the other series, maybe due to the loose constraints conditions used. Plots from all parameters of this comparison can be found on the web-pages http://alpha.fesg.tumuenchen.de/iers/eop/results.html.

Taking the IERS C04 as a reference series, we can search for systematic patterns in OFFSET and DRIFT. The SLR and the VLBI series with minimum constraints show a slight shift (negative in Xpol, positive in Ypol) against the series realized with fixed site coordinates. Most of the series are not distributed around the C04 reference, they are focused with an OFFSET of 0.15 mas in (–Xpol,Ypol) direction. In UT1-UTC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5d</td>
<td>5d</td>
<td>0.5d</td>
<td>5d</td>
</tr>
<tr>
<td>Xpol</td>
<td>-0.045</td>
<td>-0.023</td>
<td>-0.060</td>
<td>-0.036</td>
</tr>
<tr>
<td>Ypol</td>
<td>+0.124</td>
<td>+0.087</td>
<td>+0.103</td>
<td>+0.081</td>
</tr>
<tr>
<td>UT1-UTC</td>
<td>+2.708</td>
<td>+1.326</td>
<td>+2.852</td>
<td>+2.163</td>
</tr>
<tr>
<td></td>
<td>-0.003</td>
<td>-0.004</td>
<td>-0.005</td>
<td>-0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5d</td>
<td>5d</td>
<td>0.5d</td>
<td>5d</td>
</tr>
<tr>
<td>Xpol</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Ypol</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>UT1-UTC</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>UT1-TAI</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5d</td>
<td>5d</td>
<td>0.5d</td>
<td>5d</td>
</tr>
<tr>
<td>Xpol</td>
<td>0.531</td>
<td>0.528</td>
<td>0.526</td>
<td>0.518</td>
</tr>
<tr>
<td>Ypol</td>
<td>0.368</td>
<td>0.378</td>
<td>0.380</td>
<td>0.386</td>
</tr>
<tr>
<td>UT1-UTC</td>
<td>33.542</td>
<td>31.799</td>
<td>36.925</td>
<td>37.327</td>
</tr>
<tr>
<td>UT1-TAI</td>
<td>0.252</td>
<td>0.257</td>
<td>0.231</td>
<td>0.224</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5d</td>
<td>5d</td>
<td>0.5d</td>
<td>5d</td>
</tr>
<tr>
<td>Xpol</td>
<td>0.485</td>
<td>0.473</td>
<td>0.482</td>
<td>0.465</td>
</tr>
<tr>
<td>Ypol</td>
<td>0.345</td>
<td>0.353</td>
<td>0.358</td>
<td>0.357</td>
</tr>
<tr>
<td>UT1-TAI</td>
<td>0.231</td>
<td>0.235</td>
<td>0.225</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Table 2: Estimation of OFFSET and DRIFT between DGFI 04 and C04 using wo different interpolation schemes and two different sampling rates. The given errors of the EOP series are included in the least squares adjustment.
Figure 1: OFFSET estimation for the Xpol-component. Each series against each other using error weighted least square adjustment. The series are sorted by technique and constraints used for the reference realization (2-minimum, 1-significant, 0-fixed constraints).

Figure 2: OFFSET estimation for Xpol / Ypol – component from each series against reference series IERS C04 using error weighted least squares adjustment.
the VLBI series have a negative OFFSET of about -0.4 µs against C04, while the SLR solutions have a positive OFFSET of 0.1 µs. This comparison with C04 shows a considerable inconsistency between the EOP series and the ITRF2000 realization.

More detailed comparisons can be done with special subsets of the submitted series. The results for the GPS subset, especially the 13 GPS EOP series submitted from IGS, seem to depend more on the selected stations than on the constraining method which were used to realize the ITRF2000 alignment, see tab. 3. In Xpol the solution with 132 stations fixed or constrained to ITRF2000 coordinates shows much smaller OFFSETs against C04 than the other solutions with 54 or 154 stations. In Ypol the OFFSETs are smaller for 154 stations than for 54 or 132 stations. The more constrained to the ITRF2000 coordinates the stations are the more the Xpol component of the solutions are aligned to C04. The same is true for the Ypol component of the CODE series. The Ypol component of the IGS series shows the opposite characteristics.

Further investigations can be done by analysing the remaining residuals after correcting for the fitting parameters. We can identify periodic signals and noisy time spans in the residuals. This should help to detect systematic differences in the EOP series and to give future recommendations for a more consistent generation, parameterisation and interpolation of EOP series.

Table 3: OFFSET estimation for Xpol / Ypol – component for GPS EOP series against IERS C04.

<table>
<thead>
<tr>
<th></th>
<th>xpol</th>
<th>ypol</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54 stations</td>
<td>IGS03</td>
<td>0.022</td>
</tr>
<tr>
<td>132 stations</td>
<td>IGS06</td>
<td>0.004</td>
</tr>
<tr>
<td>154 stations</td>
<td>IGS12</td>
<td>0.023</td>
</tr>
<tr>
<td>CODE</td>
<td>CODE02</td>
<td>0.080</td>
</tr>
<tr>
<td>significant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54 stations</td>
<td>IGS01</td>
<td>0.029</td>
</tr>
<tr>
<td>132 stations</td>
<td>IGS04</td>
<td>0.004</td>
</tr>
<tr>
<td>154 stations</td>
<td>IGS10</td>
<td>0.027</td>
</tr>
<tr>
<td>minimum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54 stations</td>
<td>IGS02</td>
<td>0.041</td>
</tr>
<tr>
<td>132 stations</td>
<td>IGS05</td>
<td>0.029</td>
</tr>
<tr>
<td>154 stations</td>
<td>IGS11</td>
<td>0.029</td>
</tr>
<tr>
<td>CODE</td>
<td>CODE01</td>
<td>0.092</td>
</tr>
</tbody>
</table>
1. Motivation and objectives
The International Terrestrial Reference System (ITRS), the basis for all precise positioning using geodetic space techniques, e.g., GPS, is realised by the International Terrestrial Reference Frame (ITRF) as a set of materialised points (station monuments) at the Earth’s surface. Each ITRF station has got three-dimensional position coordinates for a defined reference epoch and linear velocities (coordinates changes with time) derived from sufficiently long time series of space geodetic observations. The datum parameters for the positions are the Earth’s centre of mass (geocentre) as the origin, a mean Earth rotation axis for the orientation, and the speed of light defining the scale. The reference for the velocities shall be defined with respect to the global Earth rotation parameters (ERP), i.e., there shall remain no net rotation of the reference frame with respect to the entire rotating body of the Earth (NNR condition).

The latest ITRF realisations (including ITRF2000) use the geologic-geophysical rigid plate velocity model NNR NUVEL-1A (De Mets et al. 1994) for the kinematic reference. The r.m.s. deviation of a set of selected ITRF station velocities is minimised with respect to the corresponding NNR NUVEL-1A velocities. This procedure of kinematic datum definition for geodetic purposes suffers from two principal shortcomings:

1. The geologic-geophysical velocities used for calculating the NNR NUVEL-1A model are average values over millions of years and may not represent the present-day motions.

2. All the data is collected at plate boundaries where deformation is evident. But the entire plate surface is considered undeformable. No deformations of the Earth’s surface are included in the rigid plate model.

In particular for these two reasons we need to derive a geodetic, present-day, Actual Plate Kinematic and deformation Model (APKIM) covering the entire surface of the Earth and fulfilling the NNR condition. This model should serve as the kinematic reference for the ITRF.

2. Methodology
We may, in general for the mentioned purpose, characterise the Earth’s surface by two different physical properties, rigid plates and inter-plate deformation zones (cf. Gordon 1995). The motion of a rigid plate is uniquely described by the rotation of a spherical cap around the geocentre (effects of the ellipsoidal figure of the Earth in the order of 1:300 may be neglected in view of the maximum velocities of 15 mm/a). The surface velocity $\frac{dX_i}{dt}$ of a station $i$ with the position vector $X_i$ on a plate $k$ with the geocentric rotation vector $\Omega_k$ is then

$$\frac{dX_i}{dt} = \Omega_k \times X_i$$

The plate rotation vectors $\Omega_k$ can be estimated from the geodetically observed velocities $dX/dt$, e.g., by a least squares adjustment procedure (Drewes 1982).

Inter-plate deformations can be modelled as a viscous-elastic-plastic continuum undergoing active tectonic forces (Heidbach 2000).
Regarding only the surface deformation and considering only a short time interval (existing space geodetic observations over about 20 years) an approximation by an elastic material is sufficient to provide the required velocity field for geodetic purposes (Drewes 1993).

In the present procedure of global modelling using wide-spaced data sets we divide the deformation zones into crustal blocks with motions described by spherical rotation vectors as given in (1). This is not to model the complete deformation zones but just to include the inter-plate motions into the NNR condition.

The method of determining the motion of the entire surface of the Earth is thus the estimation of a set of rigid plate rotation vectors and the rotation vectors of crustal blocks in between the plates. The integral of velocities over all plates \( k \) and blocks \( l \) has to become zero. Replacing the integral by the sum of plate elements \( i \) or block elements \( j \), respectively, we get

\[
\sum_{i} \Omega_{i} \times X_{i} + \sum_{j} \Omega_{j} \times X_{j} = 0
\]

(2)

3. Used data sets

The data sets used for the adjustment of plate and block rotation vectors are those of the DGFI inter-techniques combination for the ITRF (Meisel et al. 2003). They include

- 199 GPS station velocities of the combined IGS solution (IGS03P01, Ferland 2002);
- 65 SLR station velocities combined from the solutions of Communications Research Laboratory (CRL), Japan, Center for Space Research (CSR), USA, Joint Center for Earth System Technology (JCET), USA, and Deutsches Geodätisches Forschungsinstitut (DGFI);
- 75 VLBI station velocities combined from the solutions of Geodetic Institute, University Bonn, (GIUB) Germany, Goddard Space Flight Center (GSFC), USA, Shanghai Astronomical Observatory, China, and Deutsches Geodätisches Forschungsinstitut (DGFI);
- 53 DORIS station velocities combined from the solutions of Groupe de Recherche de Géodésie Spatiale (GRGS) and Institut Géographique National (IGN), France.

Each of the 392 stations (occupations) was attributed to a rigid plate or a block in a deformation zone, respectively, according to the DGFI plate model. The total set was then introduced into the adjustment procedure of rotation vectors.

4. Adjustment procedure

A total of twelve rigid plates and six blocks in deformation zones were covered by the input data. These include ten rigid plates of the NUVEL-1A model (Cocos and India plates are missing due to lack of data) and, in addition, an Asia plate (East Asia) and a Somalia plate which are considered different from the Eurasian and African plates, respectively, where they are assigned to in the NUVEL model. The blocks in deformation zones include the Mediterranean (Adria, Aegea, Anatolia blocks), Japan, California, and central Andes.

In addition to the plate and block rotations, relative datum rotation vectors for the individual techniques were estimated in the adjustment procedure. For this purpose, the initial datum of the GPS solution (IGS03P01) was held fixed and each one datum rotation vector was estimated for the SLR, VLBI, and DORIS combined solutions with respect to the IGS03P01 velocities. By this means the final solution of rotation vectors refers to the IGS03P01 kinematic datum.

The adjustment was done using only the horizontal velocity components (in geographic latitude and longitude directions). Relative weights between the techniques (i.e., SLR, VLBI, DORIS w.r.t. IGS) were determined by an iterative a posteriori variance estimation after Helmert. Using the three-dimensional Cartesian velocities \( (v_x, v_y, v_z) \) instead of the horizontal components only would falsify the relative weight estimation because of the different influence of height uncertainties in the individual techniques.
From the adjusted plate and block rotation vectors a complete 1° x 1° grid of Earth surface velocities is computed by appointing each grid element to a certain plate or block, respectively. A common rotation vector is then estimated considering the weight of the grid elements according to its size (i.e., the cosine of the latitude).

5. Results
The result of the adjustment procedure are the rotation vectors of 12 plates, 6 blocks and 3 datums of observation techniques with their r.m.s. errors. The standard deviation of unit weight (= IGS03P01) is \( \sigma_0 = \pm 2.2 \text{ mm/a} \) in relation to the a priori \( s_0 = \pm 1.0 \text{ mm/a} \). The relative weights of the individual techniques are \( p_{\text{SLR}} = 0.61 \), \( p_{\text{VLBI}} = 0.25 \), and \( p_{\text{DORIS}} = 3.25 \). During the adjustment procedure we eliminated the outlier velocities, i.e., those with residuals \( |v_i| > 3 \sigma_i \). These were 30 in GPS, 5 in SLR, 5 in VLBI, and 3 in DORIS. The remaining data set consists thus of 349 station velocities. The result of the estimation of a common rotation vector from the 1° x 1° grid of derived plate and block motions is \( \omega_x = -0.12 \pm 0.03 \), \( \omega_y = 0.14 \pm 0.03 \), \( \omega_z = -0.30 \pm 0.03 \) [mrad/Ma]. This corresponds to a maximum velocity of 0.2 mm/a at the equator of the common rotation. All adjusted rotation vectors were corrected by this common rotation in order to get the »NNR« condition. The result, called APKIM 2002.0 is shown in table 1 in comparison with the NNR NUVEL-1A model. Considering the r.m.s. errors there are some significant discrepancies.

A graphic representation of selected point velocities derived from the APKIM2002.0 model is shown in figure 1 in comparison with NNR NUVEL-1A. We find in general a good agreement within the rigid plates but significant discrepancies in the plate boundary zones.

6. References


Table 1: Rotation poles and velocities of the geodetic and geologic-geophysical plate models.

<table>
<thead>
<tr>
<th>Plate</th>
<th>APKIM 2002.0</th>
<th>NNR NUVEL-1A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
</tr>
<tr>
<td>AFRC</td>
<td>51.61 ± 0.52</td>
<td>278.60 ± 1.22</td>
</tr>
<tr>
<td>ANTA</td>
<td>62.73 ± 1.23</td>
<td>237.54 ± 2.04</td>
</tr>
<tr>
<td>ARAB</td>
<td>29.38 ± 5.67</td>
<td>277.58 ± 61.1</td>
</tr>
<tr>
<td>AUST</td>
<td>33.69 ± 0.25</td>
<td>59.90 ± 0.43</td>
</tr>
<tr>
<td>CARB</td>
<td>45.21 ± 2.08</td>
<td>248.56 ± 10.5</td>
</tr>
<tr>
<td>EURA</td>
<td>56.53 ± 0.90</td>
<td>261.52 ± 0.71</td>
</tr>
<tr>
<td>NAZC</td>
<td>46.21 ± 1.67</td>
<td>269.97 ± 0.60</td>
</tr>
<tr>
<td>NOAM</td>
<td>-1.55 ± 0.77</td>
<td>77.41 ± 0.35</td>
</tr>
<tr>
<td>PCFC</td>
<td>-64.30 ± 0.18</td>
<td>105.52 ± 1.15</td>
</tr>
<tr>
<td>SCAM</td>
<td>-10.74 ± 1.59</td>
<td>239.63 ± 4.34</td>
</tr>
<tr>
<td>ASIA</td>
<td>59.61 ± 2.30</td>
<td>253.51 ± 3.81</td>
</tr>
<tr>
<td>SICIL</td>
<td>53.05 ± 3.81</td>
<td>270.34 ± 7.25</td>
</tr>
</tbody>
</table>

**Figure 1:** Comparison of station velocities derived from geodetic and geophysical plate models.
Geodetic VLBI - The Only Connection Between the Celestial and Terrestrial Reference Frames

Fischer D., Vennebusch M., Nothnagel A.
Geodaetisches Institut der Universitaet Bonn, Nussallee 17, 53115 Bonn, Germany, E-Mail: nothnagel@uni-bonn.de

Same abstract as

Nothnagel A. et al. – Combination of Earth Monitoring Products by IERS Combination Research Centers; this volume.
GRACE shall produce monthly gravity field solutions with unprecedented accuracy (i.e. the cumulative geoid height error up to degree 70 shall be less than 0.4 mm). Therefore all short-term (hourly to weekly) atmospheric, oceanic and hydrological mass variations have to be taken into account because these mass variations cause time variant forces acting on the orbiting satellites. This could be neglected by repeated observations within a short time interval using repeat orbits, but this would decrease the spatial sensitivity of GRACE to measure the global gravity field. As a consequence GRACE is using a non-repeat orbit and one has to de-alias this mass variations during product generation using appropriate correction models. Generally GRACE is sensitive to these short-term signals up to approximately degree and order 30-40 (666-500 km half wavelength).

While hydrological models with sufficient resolution and accuracy are not yet existing, GFZ as part of the joint UTCSR/JPL/GFZ Science Data System generates atmospheric and oceanic de-aliasing products based on 6-hourly, 0.5 degrees resolution ECMWF meteorological fields on a routine basis with maximum 3 days time delay in a two step procedure.

In a first step JPL’s barotropic ocean model PPHA (Pakanowski, Ponte, Hirose, Ali) which is
driven by 6-hourly, 0.5 degrees resolution ECMWF meteorological fields and an initial ocean model state delivers hourly 1.125 degrees resolution barotropic sea level grids. To calculate oceanic mass variations a mean field has to be subtracted from the time-varying field. In the current product the mean of 2001 is used.

In a second step 6-hourly, 0.5 degrees resolution residual atmospheric pressure fields provided as spherical harmonic coefficients $C_{nm}$ and $S_{nm}$ using a 3D ($t, \phi, \lambda$) surface (equation 1) or 4D ($t, \phi, \lambda, h$) vertical integrated pressure approach (equation 2) and a corresponding 2001 mean field ($\bar{P}_g$ resp. $\bar{P}_{vl}$) are calculated.

$$C_{nm} = \frac{\alpha^2 (1 + k_n)}{(2n+1) M g} \int_{\text{Earth}} \left( \bar{P}_g - \bar{P}_n \right) P_{nm}(\cos \theta) \cos(\xi) dS$$ (1)

$$S_{nm} = \frac{\alpha^2 (1 + k_n)}{(2n+1) M g} \int_{\text{Earth}} \left( \bar{P}_g - \bar{P}_n \right) P_{nm}(\cos \theta) \sin(\xi) dS$$

$$C_{nm} = -\frac{\alpha^2 (1 + k_n)}{(2n+1) M g} \int_{\text{Earth}} \left[ \frac{a}{r} \left( \frac{a}{a + \xi} \right)^{n+1} \right] dP$$

$$S_{nm} = -\frac{\alpha^2 (1 + k_n)}{(2n+1) M g} \int_{\text{Earth}} \left[ \frac{a}{r} \left( \frac{a}{a + \xi} \right)^{n+1} \right] dP$$ (2)

where
- $a$ radius of the Earth,
- $k_n$ load love numbers for degree $n$,
- $M$ Earth mass,
- $g$ mean gravity acceleration,
- $P_{nm}$ normalized associated Legendre polynomials,
- $r, \theta, \lambda$ spherical coordinates of the mass element,
- $dS$ surface element,
- $\phi$ geopotential height at different pressure levels (function of temperature and specific humidity at pressure level) and
- $\xi$ height of the mean geoid above the mean sphere $r = a$.

These atmospheric mass variations are then combined with the ocean model output, which has to be interpolated to 0.5 degrees and transformed from cm to Pa.

Three sets of spherical harmonic coefficients up to degree 100 (global atmosphere and ocean combination, global atmosphere and ocean only) are available as the ASCII GRACE Level-1B Atmosphere and Ocean De-aliasing product (AOD1B) for the GRACE Science Data System and after end of the GRACE validation phase for the users in the GRACE Information System and Data Center (GRACE ISDC).

The atmospheric and oceanic mass variations converted to geoid height differences are in the order of ± 3-4 mm but can reach values of up to 15-20 mm.

The difference between the 2D and the 3D approach is generally small, but cannot be neglected to meet the strong GRACE requirements.
Figure 2: Geoid height variations [mm] caused by 3D atmospheric and oceanic mass variations between July 1, 2000 and February 28, 2003.

Figure 3: 3D-2D geoid height variation [mm] on October 18, 2001 0h.
Development of the GRACE Science Data System

GeoForschungsZentrum Potsdam, Department 1 »Geodesy and Remote Sensing«, 14473 Potsdam, Germany.
E-Mail: flechtne@gfz-potsdam.de

GRACE science data processing, archiving and distribution is performed in a shared Science Data System (SDS) between the Jet Propulsion Laboratory (JPL), the University of Texas Center for Space Research (UTCSR), and the GeoForschungsZentrum Potsdam (GFZ). The co-operative approach includes the development of the SDS, sharing of processing tasks, harmonization of product archives and validation and comparison of products.

The GRACE Science Data System Development Plan (JPL 327 710) describes the definition of the different GRACE processing and archiving facilities, the products and the overall data flow, the responsibilities within the project and the necessary documentation. In order to compare GRACE Level-2 gravity field products CSR and GFZ shall use common processing standards (reference systems, initial models, constants as described in IERS2000). Regular meetings and reviews with the US SDS partners guarantee the progress and success of the joint development. To calibrate and validate the monthly and mean GRACE gravity fields a US and European Science Working Team has been established. For the coordination of the national partners within the »GEOTECHNOLOGIEN Program« (Geodetic Institute University Stuttgart, Institute for Theoretical Geodesy

![Diagram of GRACE ground segment operations.](image-url)
Bonn, Institute for Astronomical and Physical Geodesy University Munich), telecons and status meetings have been organized.

Figure 1 shows the overall data flow and responsibilities within the GRACE SDS. The onboard stored science instrument and housekeeping data of the GRACE twin satellites are regularly (several times a day) downloaded to DLR’s (Deutsches Zentrum für Luft- und Raumfahrt) receiving stations in Weilheim and Neustrelitz. In the Raw Data Center (RDC) in Neustrelitz these telemetry data are decommutated and provided to the SDS in an rolling archive. GFZ and JPL acquire these Level-0 data and store them in a long-term archive at GFZ’s Information System and Data Center (ISDC) respectively JPL’s Physical Oceanography Distributed Active Archive Center (PO.DAAC).

JPL has developed the Level-0 to Level-1 processing software. In a first level of processing (Level-1A) the raw binary data are converted to engineering units and all sensor calibration factors are applied. In a next step the data are correctly time-tagged and the data sample rate is reduced to a higher rate. As a result calibrated Level-1B accelerometer, star camera and K-band ranging data are available with 0.2 Hz, GPS code and phase data with 0.1 Hz sampling rate. This primary GRACE instrument data are accomplished by different products describing the onboard time scale (satellite clock relative to GPS time), thruster firing events, satellite mass changes and housekeeping data such as magnetorquer currents or tank pressure values and temperatures.

For backup reasons and to extract Level-1A GPS navigation solutions in order calculate twice per day Satellite Laser Ranging (SLR) prediction elements the Level-1 software has also been installed at GFZ. For the precise calibration of the Level-1B instrument data JPL is...
responsible for the analysis of regularly performed center of mass trim and accelerometer to star camera frame alignment maneuvers.

Additionally, based on 6-hourly atmospheric fields, which are regularly acquired from ECMWF (European Center for Medium Weather Forecast), and a barotropic ocean model (Pakanowski, Ponte, Hirose, Ali) which was provided by JPL, GFZ generates with a maximum of 3 days time delay a Level-1B product which is used in later Level-2 processing to de-alias the monthly gravity field solutions from atmospheric and oceanic short-term mass variations.

As for the Level-0 data all Level-1 products are archived in GFZ’s GRACE ISDC and JPL’s PO.DAAC. Both archives will be regularly harmonized on the basis of JPL product tables and Directory Interchange Format (DIF) meta data to guarantee common data contents. The data access rules will be defined by the GRACE PI and Co-PI. The GRACE ISDC has been developed on the basis of the successfully operated CHAMP ISDC. The products can be accessed by the GRACE users in a batch, direct and retrieval mode. It is planned to complement this data access procedures by a Graphical User Interface (GUI) in the very next future.

The Level-1 products and a set of ancillary data which are regularly generated by GFZ (GPS orbits and clocks) or acquired from international services like ILRS, IGS or IERS (GRACE SLR data, GPS ground station observations, Earth rotation parameters) are the basis for the Level-2 processing of monthly and mean gravity field solutions. Therefore a Level-1 pre-processing software has been developed, which reads the different GRACE instrument data, transforms the GRACE science reference frame to GFZ’s EPOS software (Earth Parameter and Orbit System) internally used reference frame, applies all corrections to the K-band data and coarse bias parameters to the linear accelerometer observations, interpolates star camera and accelerometer data gaps and writes a chronologically binary output file. Additionally the inter-satellite K-band ranging observation was implemented in EPOS to generate the theoretical observations and to solve for empirical K-band parameters (bias, bias drift, periodic terms). Due to the huge number of GRACE observations and unknowns EPOS was optimized to generate gravity field partials and to manipulate and solve great normal equation systems in a timely sufficient manner. To process the extreme K-band data micrometer precision different modules of EPOS have to be investigated on numerical accuracy (e.g. numerical integration). Finally, for quality control of GRACE derived gravity fields different test procedures were developed such as comparisons with independently derived gravity fields (CHAMP, CSR GRACE gravity fields), global and regional gravity anomalies on different grids, altimetric and GPS leveling derived geoids or sea surface topography calculated from oceanographic models.
Semi-Analytical Gravity Field Analysis Applied to Satellite-to-Satellite Tracking Data

Földváry L., Wermuth M.
Institute for Astronomical and Physical Geodesy, Technical University of Munich, Germany, E-Mail: foeldvary@bv.tum.de

1. Precise Orbit Determination – Kinematic Orbit

One can distinguish three different methods of orbit determination of a low orbiting satellite (LEO) using high-low GPS tracking. Kinematic orbits are derived using only geometrical relationships, dynamic orbits are derived by adjusting gravity field parameters to the orbit and reduced-dynamic orbit use a given gravity model but some additional free parameters are introduced, too, in order to improve the fit of the model to the observations. Since dynamic and reduced-dynamic orbits are derived with use of a gravity field, their positions and velocities are strongly dependent on the chosen model. Therefore gravity inversion from a dynamic or reduced dynamic orbit will necessarily reflect the input gravity field.

In order to exclude such a dependency, kinematic orbits are preferable over the dynamic orbits for gravity field analysis. In case of kinematic orbits, positions are derived epochs by epoch, almost independently of each other. This also means, that position errors are almost uncorrelated. They exhibit therefore a very irregular pattern, when compared to a dynamic or reduced-dynamic orbit. In particular the high-frequency terms (signal and noise as well) are much smoother in the latter case. An example of typical differences of kinematic and reduced-dynamic orbit is shown in Figure 1. Jumps are mainly contributed by the kinematic orbit.

Kinematic orbits exhibit jumps due to loss of phase connection between the GPS satellites and the receiver. These jumps occurs between independently derived arcs of the orbit, reflecting the uncertainty of estimation of ambiguity parameters. For longer time spans of continuous arcs the determination of the ambiguity should be more certain, therefore for longer arcs smaller jumps are expected. In general, within the continuous arcs of the kinematic orbit one finds the useful information: the purely geometrical relative positions.

2. Kinematic Velocity

For semi-analytical gravity field analysis based on Satellite-to-Satellite Tracking (SST) the pseudo-observables are either positions or velocities or both, therefore purely geometrical velocities have to be derived from the kinematic positions. A method of kinematic velocity determination has been developed. We have tested several mathematical concepts, considering different (1) interpolation methods (interpolation by fitting a higher order polynomial; interpolation by cubic splines; Newton-Gregory interpolation), and (2) smoothing methods (smoothing by a higher order polynomial; smoothing by cubic spline functions). Preliminary tests have been done for simulated GOCE orbits, and in order to test the performance with real data, for CHAMP kinematic orbits (for simulated orbits the effect of smoothing can not be properly tested). Among these solutions, we found the smoothing by cubic splines giving the most reliable velocities. Therefore a procedure has been developed based on this method.
3. Long-Wavelength Gravity Field from Semi-Analytical Gravity Inversion Using the Energy Integral

In principle, the strength of the semi-analytical method, that by transforming the time series of the observables into frequency spectrum (by Fourier-transformation) the number of the pseudo-observables is drastically reduced from a long time series into a spectrum of a defined frequency band. However, Fourier transformation requires equidistantly spaced observables and for discrete Fourier transformation (DFT) also a periodic data set. If the gravity observations are expressed as functions of longitude of the ascending node and argument of latitude such a situation almost arises. The data are almost equidistant and they are almost periodic, however in two arguments. Thus it is comparable to a two dimensional DFT, or geometrically speaking, to a mapping of the time series into a torus. However this mapping is only approximate, for the time series is not exactly periodic in both arguments. This requires an interpolation from almost to an ideal two-dimensional grid. Disturbing potential projected onto a torus is shown in Figure 2.

Different solutions of semi-analytical gravity inversion are under investigation, namely the (1) energy integral, and (2) perturbation theories based on the Newtonian equation of motion, such as Kaula linear perturbation theory, or Hill-equations. The semi-analytical solution using the energy integral has been successfully tested for simulated GOCE data and actual CHAMP data.

For the simulated GOCE orbit we tried to recover the OSU91A gravity field up to degree and order 50. Numerical errors are introduced by the projection of the pseudo-observations along the orbit onto a torus (see above). The distortions were minimised by an iterative solution; after 8 iterations we reached an accuracy of about 1.5 mm in geoid height. In general, we found the semi-analytical method conver-

![Figure 1: Differences of kinematic and reduced-dynamic positions of CHAMP (along a certain axis).](image)
ging iteration by iteration to the input gravity field, eliminating effectively the interpolation errors.

The situation is more complicated when one deals with real data. Apart from the measurement errors there are processing errors which occur when deriving orbits from raw GPS measurements (see section 1). A critical issue of similar type is the processing of the onboard accelerometer measurements, in order to account for the energy dissipation due to non-conservative forces. The energy integral is known to be sensitive for velocity errors, requiring an accuracy of about 0.1 mm/s. This requirement can be achieved by cubic spline smoothing (see section 2). The case study showed, that in general the semi-analytical solution provides results comparable to a full solution. Furthermore it could be shown, that the recovered gravity field is comparable in quality to EIGEN-S2 model, an official product of the GFZ CHAMP group.

![Figure 2: Disturbing potential from CHAMP data projected onto a torus (unit: m^2/s^2).](image)
1. Introduction
The GRACE mission is the successor the CHAMP mission in the area of Earth gravity field measurements. The anticipated increase in accuracy will be achieved by utilizing two satellites following each other on the same orbital track. These satellites are interconnected by a K-band microwave link which measures the exact separation distance and its rate of change to an accuracy of about 1 µm/s. In order to be able to take into account the satellite attitude and all non-gravitational forces both satellites are equipped with star cameras and accelerometers.

The purpose of the integrated sensor analysis is to construct a simulator of the gravity measurement system of the GRACE mission. It is based on mathematical models of the individual sensors (accelerometers, K-Band Ranging, star sensors etc.) as well as of their interaction. The simulator in its final stage is also capable of processing real GRACE data for error identification and analysis purposes.

2. Environment of the satellites
The simulation of the gravity measurement system of the GRACE mission requires as a starting point the simulation of the input parameters of the various sensor systems:
- Realistic orbits (position and velocities) of the satellites as input for the K-Band measurement system,
- Realistic time series of non-conservative forces as input for the accelerometer measurement system and the attitude control system.

In order to provide these input parameters, an orbit integration program was created at IAPG.

3. Sensor systems
The following sensor systems are currently implemented in the GRACE System Simulator:
- Accelerometer measurement system (only linear accelerations)
- K-Band measurement system
- Star Camera measurement system

Additionally, the Attitude Control System including cold gas thrusters and magnetic torque rods is modelled.

An overview of the GRACE System Simulator, the Sensor Systems and their interaction is presented in figure 1.

Shown are in the central part the two satellites with the K-Band link and their GPS antennae, the accelerometers (as a simple mass-spring system), the star sensors and the thrusters for the attitude control. The upper part displays the linear and angular forces acting on the two satellites (gravitation, non-gravitational forces and torques). Below the satellite the processing steps for producing measured accelerations, positions and relative positions are shown.

4. Application Examples
In co-operation with the GeoForschungsZentrum Potsdam (GFZ), several tests on real data were conducted during the commissioning phase:
- Noise level assessment for the Star Camera measurement system
- Noise level assessment for the K-Band Measurement system
- Noise level assessment for the Accelerometer Measurement System
- Comparison between Star Camera and Accelerometer Measurement System

Frommknecht B.
Institut fuer Astronomische und Physikalische Geodaesie, Technische Universitaet Muenchen, Arcisstrasse 21, 80290 Muenchen, Germany, E-Mail: frommknecht@bv.tum.de

Integrated Sensor Analysis GRACE
Figure 1: Overview of the GRACE System Simulator.
1. Reference frames
The major task of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite mission will be the determination of the Earth’s gravity field with an accuracy never reached before. Since for the GOCE mission analysis both Satellite-to-Satellite Tracking data in the high-low mode (SST-hl) and Satellite Gravity Gradiometry (SGG) data is aimed to serve as observation input for a least squares adjustment procedure, it is quite important to become familiar with several frames of reference being fundamental for the GOCE mission data analysis.

In general, three levels of reference frames are of special interest, namely the observational, equatorial and quasi-inertial level. It is well known, that the on-board gradiometer will be oriented with respect to a moving frame of reference all the time. One special moving 3-leg in terms of Differential Geometry is the FREN 3-leg attached to the CoM (Center of Mass) of the satellite and leading to some advantages regarding orbital rotations of the spacecraft. However, for the GOCE mission an alternative frame of reference has been chosen, shortly called »along track«, »cross track«, »out-of-plane«. Such a frame, we denote as the KEPLER 3-leg \{\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3\} \{0^*\}. Notice, that the FREN and KEPLER 3-leg differ by a rotation about the common first axis, namely the direction of velocity, that means \(\mathbf{f} = \mathbf{R}_v(\alpha t)\mathbf{k}\) hold.

Whereas the FREN and KEPLER observational frames are connected to the orbit of the spacecraft, the harmonic expansion of the Earth gravity potential as well as its functionals (for example potential gradients \(\text{grad } U\) or potential gravity gradients \(\text{grad } \otimes \text{grad } U\)) refer to a frame according to the parameterization of the gravitational potential \(U\). We aim to solve the STOKES coefficients describing the Earth’s gravity field in terms of ellipsoidal harmonics leading to the so-called local frame of reference \(\{\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z\} \{0^*\}\).

Actually, the bases \(\mathbf{e}_x\) and \(\mathbf{e}_y\) of the local frame of reference are oriented into the directions of longitude and latitude of the potential reference figure, namely an ellipsoid of revolution, parameterized in JACOBI ellipsoidal coordinates \((\lambda, \varphi, \psi)\). The equatorial frames of interest are well known as Earth-fixed \{\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3\} \{0^*\} terrestrial \{\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3\} \{0^*\} and celestial \{\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\} \{0^*\} frame of reference attached to the CoM of the Earth \(0^*\). The same holds for the quasi-inertial frame of reference \{\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3\} \{0^*\}. Figure 1 illustrates the different levels in the tower of reference frames.

Notice, that for uniformity the FREN frame \(\mathbf{f}\) is also indicated by \(\mathbf{E}^*\) as well as the KEPLER frame \(\mathbf{k}\) is indicated by \(\mathbf{F}^*\). The rotations between arbitrary introduced reference frames are known and therefore any data transformation of SST and SGG observations is possible in respect of observation equation modelling.

2. Orbital rotations
Since for the GOCE satellite mission spaceborne-gradiometry is performed with respect to a moving frame of reference, namely the KEPLER frame, the observational tensor matrix \(\Gamma_i\) is composed of the gravity gradients tensor.
matrix $U_k$ as well as rotational parts, the influence of centrifugal and EULER acceleration. Thus, the SGG observational equations reads according to eq. (1).

$$\Gamma_k = U_k + \Omega^T_k \Omega_k + D_k \Omega_k^T$$  \hspace{1cm} (1)

Solving this equation with respect to gravity gradients in terms of antisymmetrization leads to a system of differential equations, namely the EULER dynamical equations. By solving them the CARTAN matrix $\Omega_k$ can be assumed to be known.

However, we want to present an alternative possibility to estimate the gravity gradients tensor matrix $\Gamma_k$ from the observation tensor matrix $U_k$, namely by curvature measures of the moving frame of reference with respect to the quasi-inertial frame of reference. These two frames are connected by the rotation matrix $R_{1\tau}$ in case of the FRENET 3-leg. In contrast to the antisymmetrization method, no gradiometer information is used for the estimation of the CARTAN matrix but only GPS information. Therefore the alternative method can deal as an independent test. The advantage in applying curvature measures is to gain insight into the geometry of the orbit. The alternative method is based on Differential Geometry, namely the derivational equations of the second kind, which represent the CARTAN matrix $\Omega_k$ as the product of the time derivative of the rotation matrix $R_{1\tau}$ and the transposed of $R_{1\tau}$, that means $\Omega_k = \frac{D}{dt} R_{1\tau} R_{1\tau}^T$ holds. The elements $\omega_i^j$ of the anti-symmetric CARTAN matrix can be converted in curvature measures by the simple relationship $\kappa_i = \sigma_i \cdot \omega_i^1$ therefore $\sigma_i$ is to be set to the absolute value of the velocity vector. According to eq. (2), in the special case of the FRENET moving frame of reference only two curvature measures, curvature $\kappa := \kappa_i^1$ and torsion $\tau := \kappa_i^2$, appear, which is the minimal amount of curvature measures to

![Figure 1: The tower of reference frames.](image)

57
describe a curve, in particular the GOCE satellite orbit, in the 3-dimensional space. This demonstrates the fundamental importance of the FRENET moving 3-leg in Differential Geometry.

\[
\Omega = \begin{bmatrix}
0 & \omega_{12} & 0 \\
-\omega_{23} & 0 & \omega_{31} \\
0 & -\omega_{32} & 0 \\
\end{bmatrix} = \sigma \begin{bmatrix}
0 & \kappa_1' & 0 \\
-\kappa_2' & 0 & \kappa_3' \\
0 & -\kappa_3' & 0 \\
\end{bmatrix}
\]  

(2)

The CARTAN matrix of the KEPLER 3-leg, \( \Omega_4 \), is presented in eq. (3). Obviously, the element \( \Omega_{13}, \Omega_{41} \) respectively, is not zero. The two sets of curvature measures, namely FRENET curvatures \( \kappa^i \) and FRENET curvatures \( \kappa^i_k \), are linked by the theorem of MEUSNIER, which is illustrated in eq. (4). As transformation parameters, the rotation angle \( \alpha_i \) between the two frames occurs as well as its time derivative \( \dot{\alpha}_i \).

\[
\Omega_4 = \begin{bmatrix}
0 & \omega_4^{12} & \omega_4^{13} \\
-\omega_4^{23} & 0 & \omega_4^{31} \\
-\omega_4^{32} & -\omega_4^{33} & 0 \\
\end{bmatrix} = \sigma \begin{bmatrix}
0 & \kappa_1' & \kappa_2' \\
-\kappa_2' & 0 & \kappa_3' \\
-\kappa_3' & -\kappa_3' & 0 \\
\end{bmatrix}
\]  

(3)

Since curvature measures describe the course of the GOCE satellite with respect to the quasi-inertial frame of reference, FOURIER analysis, in particular amplitude spectra, can deal as a method to arrive at a conclusion about periodicities of orbital rotations. For a moving frame of reference of type FRENET, periods in the range of the time of revolution of the spacecraft as well as half the time of revolution appear, whereas even periods of a third the revolution time become visible for the KEPLER frame of reference.

In Table 1, the CARTAN matrix elements with respect to different moving reference frames are summarized. Additionally, the Local Orbit Reference Frame (LORF) is introduced, which is sometimes assumed to be the moving reference frame of the gradiometer observations. The LORF differs from the KEPLER 3-leg by a rotation about the common first base by \( \pi/2 \).

<table>
<thead>
<tr>
<th></th>
<th>( \Omega_{12} )</th>
<th>( \Omega_{13} )</th>
<th>( \Omega_{23} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frenet f</td>
<td>( 10^3 )</td>
<td>0</td>
<td>( 10^2 )</td>
</tr>
<tr>
<td>Kepler k</td>
<td>( 10^3 )</td>
<td>( 10^2 )</td>
<td>( 10^{10} )</td>
</tr>
<tr>
<td>LORF I</td>
<td>( 10^7 )</td>
<td>( 10^3 )</td>
<td>( 10^{10} )</td>
</tr>
</tbody>
</table>

Table 1: CARTAN matrix elements with respect to different moving reference frames.
The path of an Earth-orbiting satellite departs from a simple Keplerian ellipse, because of the various perturbing forces acting on the satellite. The information on the forces acting on the satellite is nowadays obtained by the efficiently use observations of the satellite’s motion and its deviation from the ideal path. This orbit deviation is caused by forces acting on the satellite, which are the gravitational attractions of the Earth, but which also include the gravitational attractions of the Sun and Moon and the effects of atmospheric drag, solar radiation pressure, etc.

A highly efficient, numerical algorithm for a spectral harmonic analysis from semi-continuous ephemeris of the CHAMP satellite is presented. The algorithm input is only geometric data, positions of CHAMP satellite in the quasi-inertial frame of reference. The algorithm output is the coefficients of the spherical/spheroidal harmonic series expansion of the Earth’s gravitational field. Furtheron, a theoretical concept for the validation of the ephemeris is developed by the means of design of the special class of correlation functions.

The starting point of the algorithm design is the identity between the physical and mathematical descriptions of the satellite motion. The physical description, the so-called left side of the algorithm, refers to the model observations which are semi-continuous ephemeris of the CHAMP satellite. Thus, the physical description, the right-hand side, is the gravitational field model. This crucial identity is achieved by means of Newton’s law of motion, which balances two sides of the algorithm.

As well known, the generalized Newton’s Law of Motion for extended bodies applies to quasi-inertial reference frames, whereas terrestrial motions are observed in a non-inertial coordinate system rotating with the Earth. If given in quasi-inertial body fixed reference frame, the first order approximation of the gravitational force that acts on the satellite is time independent. According to this, coordinates of the gravitational force have to be transformed from the quasi-body to quasi-inertial frame of reference. By introducing the frame time-dependence, e.g. by precession, nutation, polar motion and GAST, the transformation problem is trivial. Such a set-up is advantageous because any frame accelerations are avoided.

The description of the left side algorithm starts with the computation of the acceleration vector at the satellite’s mass center. The basic idea to obtain accelerations is to first apply an interpolation technique on the equidistant GPS track time series of satellite positions, in the inertial frame of reference, and then to differentiate an interpolant twice with respect to time. The rigorous numerical and analytical analysis of interpolation techniques, e.g. Newton interpolation, cubic splines, smoothing splines and polynomial regression, is
performed. Tests based on the analysis of the preliminary one-week kinematic orbit and its comparison to available GFZ-RSO dynamic orbit, showed that the 9-point interpolation scheme is efficient and sufficient for the acceleration computation. The accuracy of CHAMP acceleration vectors, computed in this way, is in the level of mGal. Furtheron, the inertial accelerations are »cleaned« from non-gravitational accelerations. The HW95 tidal potential catalogue for reduction of tidal accelerations, caused by the Sun, Moon and 3rd celestial bodies is implemented. The sub-processor for the reduction of satellite surface forces (non-conservative forces), which are caused by air drag, solar radiation pressure etc., is developed. Within this approach, accelerometer data (CHAMP ISDC – GFZ Potsdam) is transformed into the quasi-inertial frame of reference.

The right side of the algorithm can be explained as following. The gradient of the gravitational potential, the gravity acceleration vector, in Cartesian coordinates in the quasi-body fixed frame of reference is calculated. The calculation is performed in Cartesian coordinates because of the direct application of the GPS-Cartesian ephemeris. The efficient recurrence formulas in Cartesian coordinates are derived. Finally, the gradient is transformed to the quasi-inertial frame of reference.

The left and right side derive in the equation system for the conversion of satellite acceleration data to spherical / spheroidal harmonic coefficients. The resulting equation system has the advantage of being linear with respect to the unknown coefficients. The observation vector contains the corrected accelerations, while the vector of unknowns is built out of the unknown harmonic coefficients. The presented equation system is solved by means of the classical least square method of Gauss-Markov type. If potential coefficients of the higher order were included in the equation system, the system would be ill-conditioned.

Figure 1: Geoid differences (up to degree/order 30/30) [cm] per latitude [°] between different models: kinematic model - EGM96, kinematic model - EIGEN2, EIGEN2 - EGM96.
Therefore, regularization algorithms have been implemented and numerically tested. The tested algorithms are the Kaula regularization and the first order Tikhonov regularization. The determination of the geopotential coefficients up to degree and order 50/50 showed that the Kaula regularization algorithm performed slightly better. The optimal regularization parameter was found by a comparison to the EGM96 model. The result from the application of the parameter to the linear equation system is significantly similar to the GRIM5C1 model.

To further elaborate the application of the algorithm, obtained results are compared to the existing models. Figure 1 represents the geoid differences per latitude between our model and EGM96, EIGEN2S. The comparison exhibits that the differences to the existing models, which serve as independent solutions, are about 3 times larger than the differences between EGM96 and the »official« CHAMP only solution EIGEN2. Since the differences between our model and the other models illustrate the same behaviour, the errors in our model have to be further studied. These differences are again 2-3 times larger than the difference between EGM96 and EIGEN2S and result from our model. The geoid is already determined relatively accurate (20 - 30 cm) at the equatorial regions and medium latitudes, while big differences are visible in the areas of 20° around the poles. An analysis of a 6 months arc of a CHAMP kinematic orbit, as it should become available after the EGS-AGU-Meeting, should reduce the noise level in contrast to an analysis of a 8 days arc about a factor of 4-5. Thus, significantly comparable results to the existing CHAMP models are expected.

![Graphical representation of the numerical study results](image)

**Legend:**
- **estimated correlation**
- **"Taylor-Karman" correlation**
- **correlation difference**

Figure 2: Graphical representation of the numerical study results (20 minutes correlation length, 40 points for the seconds sampling rate).
A stochastic model for homogeneous and isotropic analysis of measurements is investigated for the data validation purposes. The measurements are »directly« obtained values, i.e. CHAMP satellite positions along the orbit arc. The statistical properties of the model are calculated, in particular 2nd order correlation structure function which is defined by the 2nd rank tensor, the Taylor-Karman tensor. The Taylor-Karman variance covariance tensor is computed as the ensemble average of the set of incremental differences in measured components, the distance between consecutive satellite positions. More specifically, the Taylor-Karman correlation tensor is calculated with the assumption that the analyzed random function is of a »potential type«. The special class of homogeneous and isotropic correlation functions is introduced. The data validation is performed by the means of the canonical comparison of the »real« and the modeled Taylor-Karman variance-covariance matrix. The advantage of this approach is that instead of referring to the quality of the process (the satellite orbit and/or satellite position) through one number, the whole spectrum of information about the process quality becomes available.

As well known, consecutive positions of CHAMP satellite will not be uncorrelated as the result of the time-dependent measurement process of satellite positions by GPS. A strong correlation over periods of up to hundreds of seconds exists, as shown in Figure 2. Additionally, in Figure 2 it can be also observed, that the characteristic functions of the introduced Taylor-Karman correlation, as theoretically assumed, gives an upper bound of the »real« correlation situation along CHAMP satellite orbit. For the modeling of the Taylor-Karman tensor for the application in the analysis of CHAMP data, the vector-valued stochastic process is assumed to be the gradient of a random scalar-valued potential, in particular its longitudinal and lateral correlation function or »the correlation function along-track and across-track«.
The Gravity Recovery And Climate Experiment (GRACE) is a satellite-based project devoted to the global mapping of the Earth’s gravitational potential (geopotential) and its temporal variations. The GRACE space segment consists of two identical satellites following each other along almost the same orbit since their launch on March 17, 2002. Geodetic sensors on board of the two satellites yield data (signal) that can be transformed into parameters that describe globally the unknown geopotential. Since the global behaviour of the geopotential is usually expressed in terms of the spherical or spheroidal harmonic series representation, unknown parameters are represented by spherical or spheroidal harmonic coefficients of the corresponding harmonic series. The signal used for the estimation of these coefficients in the GRACE mission is represented by data measured namely by two geodetic Global Positioning System (GPS) receivers and a very accurate intersatellite ranging system. While the GPS receivers yield accurate geocentric positions and even more accurate position differences of the two satellites, the microwave ranger provides very accurate spatial distances (ranges) and relative velocities (range-rates) between the two satellites. All these quantities represent primary GRACE observables and their numerical values GRACE observations sampled at time and space as the satellites proceed along their orbit. They are used for determination of the unknown harmonic coefficients.

A unique algorithm for determination of the spherical or spheroidal harmonic coefficients of the geopotential from the observables in the GRACE mission has been developed at Stuttgart University. In this algorithm, called the space gravity spectroscopy, the observed and unknown quantities are directly related via the well-known Newton equation of motion. This physical model links the gravitational acceleration of a mass body to the potential of the gravitational field responsible for this acceleration, i.e.

\[ D^2_t X(t) = \nabla X U \left[ X(t) \right] \]

with the position vector \( X \) of the mass body in the inertial frame of reference and the gravitational potential \( U \), both related to the instant \( t \). The gradient of the geopotential in the Cartesian coordinate system can easily be derived from the Cartesian harmonic series of the geopotential. Modelling all known non-gravitational effects (measured by an on-board accelerometer) as well as gravitational effects of other celestial bodies (namely those of the Moon and Sun) and removing them from the computed total satellite’s acceleration, the Newton equation of motion can be applied to the GPS coordinates of the GRACE satellites. Since the Newton equation of motion is strictly valid only in the inertial frame of reference and the GPS observations are related to the Earth-fixed coordinate system (currently the Geodetic Reference System 1980 is being used), the transformation between the inertial frame and the Earth-fixed frame of reference has to be applied to the GPS position vector \( x \) before its engagement in the Newton equation of motion, i.e.
This transformation is formulated using the orthonormal group of rotations $T$ that describe the physical phenomenon of the Earth's rotation, namely the polar motion, nutation and precession of the Earth's rotational axis as well as the rotation itself in terms of the Greenwich Apparent Sidereal Time (GAST). In the GRACE mission, the sum of all accelerations (both conservative and non-conservative in the origin) acting upon the satellites can be derived from the time series of the GPS-based coordinates by numerical differentiation discussed below. Moreover, the intersatellite range-rate data sampled by the microwave ranger yield after differentiation relative acceleration differences between the two GRACE satellites, i.e. differences of the gradients of the geopotential at the location of the two satellites $x_1$ and $x_2$ at the epoch $t$ projected into the intersatellite direction defined in terms of the unit vector $e$

\[ D^2_x X(t) = T^T(t) \nabla U [x(t)] \]

The indexes 1 and 2 stand for the two GRACE satellites, $\rho$ for the intersatellite range measured by the ranger, and $\Delta X$ for the intersatellite vector measured by GPS and rotated into the quasi-inertial reference frame. The equations for the single satellite acceleration and the relative satellite acceleration differences result in the solution of a large over-determined system of linear equations (for the truncated harmonic series of the geopotential) with the unknown spherical or spheroidal harmonic coefficients. While the model based on the single satellite acceleration has already been applied for the processing of Challenging Mini-satellite Payload (CHAMP) mission data, the model for the relative intersatellite acceleration has been tested only using simulated data.

Alternatively, the pair of the GRACE satellites can also be considered as a one-directional gradiometer with the two GRACE satellites representing two proof masses. Expanding the geopotential at the barycentre of the two satellites and knowing the intersatellite orientation vector $e$, a complete gradiometric tensor can theoretically be assembled at the barycentre. The observation equation of this approach has the following general form

\[ \sum_{i=1}^{n} \langle D^2_x \Delta X^{\text{ref}}(t) | \Delta X(t) \rangle = \rho(t) D^2_x \rho(t) + \rho \left[ D \rho(t) \right]^2 - \| D \Delta X(t) \|^2 \]

The model for $i=1$ involves the gravity gradients (entries of the gradiometric tensor) that must be reconstructed from the gravity gradient differences observed in one (intersatellite) direction only. This approach leads to the concept that will also be used in the Gravity Field and Steady State Ocean Circulation Explorer (GOCE). In this satellite mission (to be launched in 2006), the gradiometric concept is extended by deploying three pairs of relatively small proof masses distributed in three mutually-perpendicular directions, i.e. the gravity gradient differences in three directions are actually measured in this mission. This concept may also offer additional constraints for the determination of the unknown harmonic coefficients of the geopotential in the GRACE mission. A successful application of this approach for the GRACE mission could eventually lead to new designs of future multisatellite missions dedicated to the global gravity field exploration.

A software suite intended for processing of actual GRACE data has been developed and tested at the Stuttgart University using simulated data (relative acceleration differences) and actual data (single satellite accelerations) from the CHAMP mission. The suite consists of several modules (transformation between the quasi-inertial frame of reference and the Earth-fixed frame, numerical differentiation of data time series using the Newton interpolation formula, solution of systems of linear equations). The Newton interpolation formula is based on representing the function $f$ at the epoch $t$ by the polynomial

\[ f(t) = f(t_i) + \sum_{i=1}^{n} \left( \frac{q}{1} \right) \Delta t_i^{n/2} \]
with coefficients computed from values of the function
\[ \Delta_{i+1}^{n-1} = \sum_{j=0}^{n-1} (-1)^{n-j} \binom{n-1}{j} f(t_i) \]

The derivative of the function can then be computed by the series
\[ D_i f(t) = \sum_{j=1}^{n} D_j \left( \frac{q}{j} \right) \Delta_{i+1}^{n-1} \]

This approach was tested extensively using both the noise-free and noisy data. It proved to be very suitable especially in the case of data with a positively correlated observation noise. The research on observation noise characteristics in both the GPS and ranger data is performed as an important part of these investigations.

Concerning the solution of the large systems of linear equations, the model for the individual satellite accelerations was successfully tested using both the simulated and actual data. The observation equations can schematically be written as follows
\[ y + e_y = A\xi \]

with the vector of observations \( y \), errors \( e_y \) and the design matrix \( A \). The unknown harmonic coefficients in the vector \( \xi \) can be solved for by an ordinary linear Gauss-Markov model using the best linear uniformly unbiased estimation (BLUUE), i.e.
\[ \xi = (A^T \Sigma_y^{-1} A)^{-1} A^T \Sigma_y^{-1} y \]

with the variance-covariance matrix \( \Sigma_y \). The instability of this model for an increasing maximum degree and order of the harmonic coefficients can be encountered for by using the Tikhonov-Phillips regularization (alpha-weighted best linear estimator)
\[ \xi_{\alpha} = (A^T \Sigma_y^{-1} A + \alpha I)^{-1} A^T \Sigma_y^{-1} y \]

with the regularization parameter \( \alpha \).

The simulated GRACE data provided by the Special Commission 7 (SC7) of the International Association of Geodesy (IAG) were used for numerical testing of the developed algorithm based on the relative intersatellite acceleration differences. These data, generated by using the Earth Geopotential Model 1996 (EGM96), consist of a time series of satellites’ coordinates and velocities. The spherical harmonic coefficients of the geopotential were recovered using the relative intersatellite acceleration differences up to the maximum degree and order 70. This maximum degree and order of the recovered harmonic coefficients is due to hardware limitations (PC platform). This problem should be solved by moving the computer algorithms to a parallel platform. Once this is achieved and real GRACE data become available, routine processing of data should provide time series of the global geopotential models and thus the possibility for estimation of temporal variations of the low-degree geopotential coefficients.

Simultaneously with the investigations on the gravity field recovery from the satellite data, the research on temporal gravity field variations induced by some known geophysical phenomena has also been conducted. Namely, the effect of deglaciation on the low degree geopotential coefficients has been studied due to its dominant magnitude among secular effects. The local effect on the low-degree spherical harmonic coefficients of the geopotential caused by deglaciation of Fennoscandia was computed using a five-layer visco-elastic model of the upper mantle. The space gravity spectroscopy of actual GRACE data will lead to the time series of the spherical harmonic models of the geopotential. Temporal variations of the low-degree coefficients, investigated by their harmonic analysis, will then be compared with these (and other modelled) variations and possible correlations will be sought.

Initial results obtained using the simulated GRACE data proved that the developed approach (space gravity spectroscopy of the relative acceleration differences) can successfully be
applied for recovering of the unknown harmonic coefficients of the geopotential. Thus the space gravity spectroscopy can find its place also in the analysis of the GRACE observations. The analysis of actual GRACE data will require, however, additional research in other areas such as for example different data combination techniques, reduction of observed data for non-conservative effects, and observation noise characteristics.
Rotational Motions Induced by Earthquakes: Theory and Observations

(1) Department fuer Geo- und Umweltwissenschaften, Bereich Geophysik – Seismologie,
Ludwig-Maximilians-Universitaet Muenchen, Theresienstr. 41, 80333 Muenchen, Germany,
E-Mail: igel@geophysik.uni-muenchen.de
(2) Forschungseinrichtung Satellitengeodaesie der TU Muenchen, Fundamentalstation Wettzell,
93444 Muenchen, Germany
(* on leave from: Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand

1. Introduction
The general motion of a body is uniquely specified by three components of displacement (those determined by a classical seismometer) and three components of rotation. For a deformable body the strains are also required. While it is standard to observe translational motions the study of rotations in the context of earthquakes had little attention, partly because rotational effects generated by earthquakes are thought to be small (e.g. Bouchon and Aki, 1982) and partly because no instruments existed which directly measure absolute (or incremental) rotation.

The goal of the GEOSENSOR project is (1) to build an instrument that records rotational motions induced by earthquakes, and (2) to understand and predict the rotational effects that are to be expected in local, regional and global seismology. The theory of translational motions had much attention, however, there are no systematic theoretical studies of rotational effects in realistic media, partly because the techniques to model complete wave fields in three dimensions have only been developed recently.

Here we present preliminary results on the simulation of seismic wave fields from point sources and discuss the effects of structural heterogeneities (fault zones, near-surface low-velocity zones) and anisotropy. Further investigations will focus on the effects of finite sources and heterogeneous rupture behavior.

We also present observations of rotational motions from regional earthquakes and compare them with translational measurements.

2. Numerical simulation of rotational motions
The calculation of theoretical (synthetic) seismograms is at the heart of seismology. Only recently such calculations can be carried out for general three-dimensional models using numerical techniques such as finite differences, finite elements or others. While those techniques are providing the complete displacement (or velocity or acceleration) wave field on a 3D grid at all times it is straightforward to also extract the rotation (rate) by applying the curl operator to the wave-field using differential operators.

At present we are adopting our methodology to have as standard output of surface ground motion not only displacement but also rotation information, resulting in 6-component seismograms. This initial study focused on wave propagation in the vicinity of a source of approximate magnitude M5.0 with a seismic moment of $M_0=10^{16}$ Nm. The source was modeled as a point double couple with dip-slip characteristics ($M_{xx}=M_{yy}=M_0$, all other moment tensor components are zero). The 3D model setup is illustrated in Figure 1. A receiver ring and two profiles above the source were calculated. Here we focus on the illustration of the effects of a low-velocity fault zone, a common feature at
transform faults with high deformation rates (e.g. San-Andreas Fault, North-Anatolian Fault). When the source is inside such a low-velocity fault zone, the ground motion above the fault is considerably amplified and we investigated what amplification can be expected for rotations.

The overall results of the 3D simulations can be summarized as: (1) surface low velocity zones (e.g., sedimentary layers) may lead to amplification of horizontal rotational components exceeding the corresponding effects on ground velocities; (2) The amplification of rotational motions due to low-velocity fault zones is comparable to that observed for shear waves; (3) In some of the cases investigated, scattering induces amplification of rotations twice larger than the corresponding amplification for translations. (4) Due to P-to-S conversions rotational motions are observed immediately after the onset of the P waves; it jeopardizes the hopes that, through observations of rotational motions, shear wave arrival time picking could be more accurate; (5) The effects of typical crustal anisotropy (e.g. 8%) on rotational motions are likely to be small. Stronger effects are to be expected for finite sources with highly heterogeneous rupture patterns.

Figure 1: a) Model setup for wave calculations and receiver locations at the surface. b) Model setup for a fault zone. The source is located at the edge of the fault.

The overall results of the 3D simulations can be understood as: (1) surface low velocity zones (e.g., sedimentary layers) may lead to amplification of horizontal rotational components exceeding the corresponding effects on ground velocities; (2) The amplification of rotational motions due to low-velocity fault zones is comparable to that observed for shear waves; (3) In some of the cases investigated, scattering induces amplification of rotations twice larger than the corresponding amplification for translations. (4) Due to P-to-S conversions rotational motions are observed immediately after the onset of the P waves; it jeopardizes the hopes that, through observations of rotational motions, shear wave arrival time picking could be more accurate; (5) The effects of typical crustal anisotropy (e.g. 8%) on rotational motions are likely to be small. Stronger effects are to be expected for finite sources with highly heterogeneous rupture patterns. Understanding these effects is the goal of future studies.

A seismogram example is shown in Figure 2. Ground motion recordings for a source within a fault zone are compared with wave propagation in a homogeneous medium. The rotational components show similar amount of amplification than the displacements. As the rotations are related to the spatial derivatives of the wave field, the effects are expected to be stronger at the fault boundaries. This is currently investigated.
3. Observations

While the GEOSENSOR is being developed and built the 4m-by-4m ringlaser at Wettzell is operational and records earthquake related signals whenever the magnitude exceeds a certain threshold. Wettzell is also the location of a broadband station of the German Regional Seismic Network (GRSN) which records permanently three components of ground velocity in a wide frequency band (inertial sensor). One of the primary goals of this first year has been to apply the seismological standards of digital data recording (high time sampling rate, high timing precision) to the observations for rotational signals. This required developing and testing a different approach to processing the time signal carrying the Sagnac frequency. The rotation rate is now sampled at 10Hz which allows a direct comparison with the seismological data in a wide frequency band. An example of the recording of the M5.5 event in the western part of the Vosges, France, is shown in Figure 3. Note the excellent signal-to-noise ratio of the rotational recording.

The translational seismograms shown in Figure 3 for the French earthquake were converted to acceleration (by time differentiation). As noted in the paper by Pancha et al. (2000) it can be shown that – assuming plane elastic wave propagation – horizontal ground acceleration corresponding to SH type motion (transverse polarized shear waves) should be in phase with the rotation rate and their amplitude relation is proportional to frequency. This assumption is likely to hold only for long-period wave propagation (e.g. surface waves) but not for the case shown above where scattering is expected resulting in non-planar wave fronts. The location of the earthquake in France was such that the North-component at Wettzell should have most of the SH type motion emitted from the source. At least qualitatively there is good agreement between the signal recorded on the North component (Fig. 3, second trace from the top) and the rotation rate (Fig. 3, bottom trace). One of the goals of the coming months is to build a data base with such collocated translational and rotational signals for local, regional and global earthquakes and to relate these observations in a quantitative way.
4. Summary and Outlook

While an observational data base is being assembled with collocated recordings of translational and rotational ground motions, we adapt computational methods for wave propagation in seismology to account for rotations. The goal is to carry out an extensive systematic study of the rotational motions to be expected in seismology on all scales with a particular emphasis on local to regional scales (distances up to 100km from the source). The reason is that we expect rotational motions to be most interesting for the study of the physics of earthquake sources. Therefore, we began investigating phenomenologically the rotation effects of 3D crustal structures such as fault zones, scatterers and anisotropy. The initial results show that in some case the amplification of rotational motions due to local structures (e.g. near surface low velocity zones) exceeds that of the translational motions.

The next step will be to investigate the effects of finite sources, heterogeneous rupture behavior on rotations and to determine whether and what additional information can be deduced from rotational measurements.

We acknowledge funding through the BMBF Geotechnologien program.


Abstract
The space borne gravity field mission GRACE will improve our knowledge of the Earth's gravity field especially in the low, medium and moderate short wavelengths ranges. Subsequent solutions by using the observations collected over a period of, e.g., one months should enable to derive time dependencies of the gravity field parameters. In this paper a method of regional gravity field refinement is presented together with a validation procedure based on the total orbit energy along the satellite orbits. Because of the fact that, for the time being, real data of the GRACE mission are not available simulation results for a regional gravity field refinement are presented. The validation procedure is demonstrated by real data from the CHAMP mission which shows comparable orbit characteristics as the orbits of the two GRACE satellites.

1. Introduction
The solution strategy presented here is restricted to a regional refinement of the gravity field. The physical model is based on Newton's equation of motion applied to short arcs passing the selected geographical region and formulated as boundary value problem. This boundary value problem is formulated as integral equation where the integrand contains the reference and residual gravity fields. While the reference gravity field representing the low and medium frequency gravity field features are expressed by a series of spherical harmonics complete up to degree of 100 to 150 the regional features are modeled by space localizing base functions. Here we selected harmonic spline functions defined on a grid adapted to a pattern of spherical triangles constructed by a successive dyadic refinement of a spherical icosahedral grid pattern. The primary observation of the GRACE mission carrying the high resolution gravity field information are functionals of the relative motion of the two GRACE satellites, relative distances and range-rates. But also the precisely simultaneously determined orbits of both satellites based on precise GPS observations contribute to the gravity field refinement especially in the low and medium wavelengths part of the gravity field. The high-low observations can be used directly or by analyzing the precise orbits. Especially for a regional refinement of the gravity field it is important to validate the absolute/relative orbits together with the gravity field parameters. This can be performed in a two-step procedure. In a first step, the reference spherical harmonics representation of the gravity field is validated together with the orbits derived from a precise kinematical or reduced dynamic orbit determination procedure. In a second step, the regionally refined gravity field is validated again by using the absolute/relative orbits. The validation procedure is based on the computation of an extended expression for the total orbit energy of the satellites. The first step uncovers deficiencies in the orbits and the reference gravity field representation simultaneously. The second step controls the refinement of the regional gravity field.

Gravity Field Recovery and Validation by Analysis of Short Arcs of a Satellite-to-Satellite Tracking Experiment GRACE

Ilk K.-H., Mayer-Gürr T., Feuchtinger M.
Institute of Theoretical Geodesy, University of Bonn, Nußallee 17, 53115 Bonn, Germany,
E-Mail: ilk@theor.geod.uni-bonn.de
2. Regional Gravity Field Refinement

The mathematical model of the observations is based on an integral equation of Fredholm type of the first kind. It reads in case of analyzing the precisely determined orbits of the GRACE mission,

\[ r(\tau) = r_A + (r_A - r_B)T + T \int_{r_A}^{r_B} K(\tau, \tau') f(\tau', r, \dot{r}) d\tau' \]

with the normalized time,

\[ \tau = \left( t - t_A \right) / T, \quad T = t_B - t_A \]

and the kernel

\[ K(\tau, \tau') = \begin{cases} \tau'(1 - \tau) & \text{for } 0 \leq \tau' \leq \tau \\ \tau(1 - \tau') & \text{for } \tau \leq \tau' \leq 1 \end{cases} \]

In this equation, \( r_A \) and \( r_B \) are the position vectors at the boundaries of the short arcs. The function \( f(\tau', r, \dot{r}) \) contains the (known) reference and the (unknown) residual field. The former part is modeled by spherical harmonics series, the latter one by space localizing base functions of harmonic spline type. The relation can be transformed into the spectral domain by expressing the orbit as well as the kernel in eigen functions, leading to an equivalent formulation as the space domain formalism. The spectral domain procedure may have advantages in those cases where colored noise of the observations have to be taken into account and a filtering procedure shall be applied to reduce the stability problems of the downward continuation process.

In case of analyzing the intersatellite ranges and range-rates between the two GRACE satellites the relative range can be expressed in the spectral domain as follows,

\[ r_{12}(\tau) = r_{12}(\tau) + \sum_{v=1}^{\infty} \sqrt{2} r_v \sin(v \pi \tau) \]

The pseudo observations (observations in spectral form), \( r_v \), can be expressed by point-wise range measurements along the short arcs by the formula

\[ r_{v, obs} = \frac{2T}{v \pi} \int_0^T \cos(v \pi \tau') r_{12}(\tau') d\tau' \]

or, alternatively, by corresponding range measurements by

\[ r_{v, obs} = 2 \int_0^T \sin(v \pi \tau') (r_{12}(\tau') - (1 - \tau')(r_A - r_B)) d\tau' \]

The reference coefficients as functionals of the reference gravity field can be computed by the formula:

\[ r_v = \frac{-2}{v^2 \pi^2} \int_0^T \sin(v \pi \tau') \left( 1 - \frac{T^2}{T^2} + e_{12} \right) d\tau' \]

Based on these relations, the observation equation for an amplitude \( v \) of arc \( i \) can be formulated as

\[ l_i = r_{v, obs} - r_{v, ref} = \frac{-2}{v^2 \pi^2} \int_0^T \sin(v \pi \tau') e_{12} \nabla T d\tau' \]

where the disturbing potential \( T \) can be approximated by space localizing base functions,

\[ T(P) = \sum_{i=1}^{N} a_i K(P, Q) \]

with the spline kernel,

\[ K(P, Q) = \sum_{n=0}^{m} k_n \left( \frac{R}{r} \right)^n P_n(P, Q) \]

containing the degree variances \( k_n \) of the gravitational field and the Legendre’s polynomials \( P_n \). The observation equations for all amplitudes of all short arcs passing the area of interest build the system of observation equations which are solved by a regularized least squares adjustment procedure of Tikhonov type.

3. Validation

The validation procedure shall uncover deficiencies in the precisely determined orbits and the reference gravity field representation on the one hand, and shall control the refinement of the regional gravity field. It is important that the validation procedure has to be based on a different functional model than the gravity field recovery procedure. A proper tool to validate the consistency of orbit and gravitational field is the computation of the total orbit energy of the satellite or the energy exchange relations of the satellite’s motions with the gravitational field and all energy forms involved in the satellites’ motion. The classical energy balance
has to be extended for this task to cover also alternative energy exchange relations. Referred to an Earth fixed reference frame the total energy expression reads:

\[ E = E_{\text{kin}} + E_{\text{rot}} + E_{\text{gyro}} + E_{\text{tide}} + E_{\text{acc}} - V \]

with the kinetic energy \( E_{\text{kin}} \), the rotation energy \( E_{\text{rot}} \), the gyro energy \( E_{\text{gyro}} \), the tidal energy \( E_{\text{tide}} \), the energy considering the surface forces \( E_{\text{acc}} \), and the potential energy of the gravitational field \( V \). The rotational energy \( E_{\text{rot}} \) takes the Earth’s rotation into account, the gyro energy \( E_{\text{gyro}} \) the variations of the Earth’s rotation, the tidal energy \( E_{\text{tide}} \) consists of contributions of direct third body effects by Moon and Sun and the respective answers by the deformable Earth and its oceans. The term \( E_{\text{acc}} \) considers the surface forces as air drag and solar pressure (including Earth albedo) and can be derived either by models or by direct measurements. In case of consistent models for gravitational field, disturbing forces as well as transformations between space and Earth fixed reference frames and/or correct orbits the total energy \( E \) should be constant. Deviations from a constant uncover inconsistencies. But it is not easy to detect the sources of these inconsistencies, despite the fact that the residuals and its transformation in the spectral domain may help to analyze these sources. Nevertheless, the comparison before the regional refinement and afterwards are very helpful to judge the result.

4. Simulation Results

Unfortunately, real data from the GRACE mission are not applicable to the public yet. Therefore, a simulation scenario has been generated to investigate the regional recovery procedure, especially the influence of various error sources and mission scenarios. The nearly circular orbits of the two GRACE satellites have been computed at an altitude of 490km, following each other in a distance of approximately 230km. The pseudo real gravity field has been simulated by a spherical harmonics expansion complete up to degree 300. The range and range rate observations have been generated every 5 seconds covering a 30 days mission period and corrupted by white noise with an rms of 10 µm and 5 µm/sec, respectively, and the satellite positions of both satellites by white noise with an rms of 3cm. The recovery area is shown in figs. 1 and 2; a strip of 15° has been added around this area to prevent the recovery region from geographical truncation effects. The number of orbits passing this region within the 30 days analysis period amounts to 243. The total number of observations is the product of the orbits and

![Figure 1: Residuals using range measurements with an rms of 10 µm.](image)
the 80 pseudo observations generated from each orbit, resulting in a total of 19440 observations. The number of gravity field parameters modeling the regional gravity field refinement corresponds to the number of space localizing base functions defined on a grid adapted to a pattern of spherical triangles constructed by a successive dyadic refinement of a spherical icosahedral grid pattern, in the present case 8170 unknown parameters. The recovery result using range measurements with an rms of 10µm are shown in fig. 1. The differences to the pseudoreal gravity field shows a maximal error of 84.5cm, an average deviation of 14.4cm and an rms of 18.4cm in terms of geoid heights. The corresponding numbers for rangerates with an rms of 5µm / sec are 36.3cm, 7.4cm and 9.3cm as shown in fig2.

To demonstrate the results of the validation procedure, real data are used based on the PSO orbits from the CHAMP mission and the CHAMP gravity field model EIGEN-2. Corresponding results can be expected from the GRACE orbits which have approximately identical orbit characteristics. The validation check was applied to an orbit not used for the regional recovery. For this purpose the energy integral has been calculated using the potential of EIGEN-2 on the one hand (fig.3, top, red line) and the regional refinement (fig.3, top, black line). It shows a significant improvement, despite the fact, that still systematic deviations can be detected. This improvement can be seen as well if the predicted ephemeris of this orbit are inspected based on EIGEN-2 gravity field model (fig.3, bottom) on the one hand and based on our regional refinement (fig.3, middle) on the other hand. But we have to keep in mind that the latter validation is not an independent check because it is based on the orbit dynamics which is used also for the regional recovery procedure.

Summary
The results clearly show that a refinement of a global gravity field solution derived from a set of orbits is possible by using space localizing gravity field parameters using the same set of orbits, at least for a geographical region with very rough gravity field features. Certainly, we cannot expect similar results for alternative regions with smoother gravity field features; in global context the spherical harmonics will model sufficiently well the gravity field. The validation check by using the energy integral works very well as an independent validation tool.
Acknowledgement

The support by BMBF and DFG within the frame of the GEOTECHNOLOGIEN program is gratefully acknowledged. We also would like to thank the GeoForschungsZentrum Potsdam for providing PSO data.

Figure 3:
Top: Energy integral based on EIGEN-2 and the regional refinement;
Middle: orbit residuals based on the regional gravity field refinement;
Bottom: orbit residuals based on EIGEN-2 (green lines: x, red lines: y, blue lines: z).
Detection of Ionospheric Perturbations by GPS Measurements Onboard CHAMP

Jakowski N. (1), Tsybulya K. (1), Heise S. (2)
(1) Deutsches Zentrum fuer Luft- und Raumfahrt (DLR), Institut fuer Kommunikation und Navigation, Aussenstelle Neustrelitz, 17230 Neustrelitz, Germany, E-Mail: norbert.jakowski@dlr.de
(2) GeoForschungsZentrum Potsdam (GFZ), Telegrafenberg, 14473 Potsdam, Germany

1. Introduction
The ionospheric plasma is subjected to a number of quite different forces from above and from below. Major impact is due to solar forcing. Electromagnetic as well as particle radiation is extremely variable and modifies the ionospheric plasma directly via ionisation processes and indirectly via interactions with the magnetosphere and thermosphere by generating electric fields, composition changes and neutral winds. Forcing from below, e.g. from the troposphere or lithosphere, is extremely weak compared with the solar control. Nevertheless, ionospheric response to earthquakes has been reported in the literature since many years (e.g. Row, 1967; Wolcott et al., 1982; Calais und Minster, 1995). Earthquakes may cause pressure waves that propagate upward and may generate so-called »Travelling Ionospheric Disturbances« (TID’s) in the ionosphere. Thus, Calais and Minster (1995) detected such TID’s by means of differential phase analysis of dual frequency GPS measurements during the Northridge Earthquake in California in January 1994. Within the DACH project we use both ground and space based GPS measurements to detect wavelike structures or stronger long term perturbations (e.g. Oraevsky et al., 1995) of the ionospheric plasma that might occur in relation to strong earthquakes. Basic principles and some preliminary tests are discussed in the subsequent sections.

2. Methodology
The basic principle of our measurements within the project DACH is illustrated in Figure 1. The GPS measurements take advantage of the dispersive nature of the ionosphere i.e. of the frequency dependent refractivity. In the first order approximation the differential phase of L1 and L2 carrier frequencies of GPS satellites is directly proportional to the integrated electron density along the ray path. Hence, the computation of differential phases along all available satellite tracks provides a sensitive tool to get information about the ionospheric ionisation.
To analyse ground based measurements we use the globally distributed GPS stations of the International GPS Service (IGS) in a routine manner (e.g. Jakowski, 1996). Space based GPS measurements onboard CHAMP are very effective to derive vertical electron density profiles by Ionospheric Radio Occultation (IRO) measurements (Jakowski et al., 2002) and to reconstruct the 3D electron density distribution of the topside ionosphere/plasmasphere (Heise et al., 2002).

3. Observations
Figure 2 illustrates the potential of IRO measurements onboard CHAMP that are used in the analysis. It shows the number and geographical distribution of IRO measurements on CHAMP in the Chile/Bolivia border region where an earthquake of 6.5 magnitude was recorded on 28 March 2002. In addition to the IRO measurements selected in time and space around earthquakes of mag-
nitude greater than 6, we started also to collect and to analyse corresponding ground based GPS measurements related to earthquake events.

4. Discussion and conclusions
Since the project still continues, the results obtained so far have a preliminary status. Due to the expected principally small amplitudes of potential earthquake signatures, the analysis software is currently being improved and corresponding filter techniques refined.

The IRO analysis provided significant TID signals at high latitudes, in particular at the winter hemisphere. Following current knowledge, most of these TID’s are obviously generated in the troposphere. A correlation with geomagnetic activity is also possible.

In case of observed large scale effects the analysis has to remove space weather induced perturbations in particular.

To enhance the earthquake signal strength, it is useful to superimpose analysis results including all available earthquakes. The result of such a preliminary epoch analysis of signal variations that might be related to earthquakes is shown in Figure 3.

As Figure 3 shows, there is not yet a clear answer to the question whether earthquake signals are visible in IRO measurements on CHAMP. Enhanced TID activity caused by earthquakes should be characterised by a significant peak around the earthquake onset time in Figure 3. It is concluded that more detailed studies including more data and further improvements of the analysis techniques are needed to give a final answer.

Subsequent studies shall include in particular also the analysis of ground based measurements at the South-East European region. Comprehensive case studies including various types of measurements can effectively contribute to explore the mechanism of earthquake signatures in the ionosphere.

Acknowledgements
The study was carried out under grant number 03F0333B of the Federal Ministry of Education and Research (BMBF).

References


Figure 1: Schematic view on ground and space based GPS measurements to detect earthquake signatures in the ionosphere.

Figure 2: Locations of 11 IRO measurements from CHAMP in the region of the earthquake near the Chile/Bolivia border that was recorded on 28 March 2002 at 04:56:22 UT. Time window for IRO measurements is +/- 24 hours.

Figure 3: Epoch analysis of ionospheric variability signals in IRO measurements related to a total number of 77 earthquakes in a time window of +/- 24 hours showing the percentage of observations with enhanced variability in the ionisation.
Validation of GOCE Gradients Using Cross-Overs

Jarecki F., Müller J.
Institut fuer Erdmessung, University of Hannover, Schneiderberg 50, 30167 Hannover, Germany,
E-Mail: jarecki@ife.uni-hannover.de

Abstract
The ESA mission GOCE (Gravity Field and Steady State Ocean Circulation Explorer) has been planned to determine the gravitational field of the Earth with unprecedented accuracy, especially at the high frequencies, by satellite gravity gradiometry. To ensure the high accuracies, to assess the quality of the intermediate and final GOCE data, and to check the final results, several calibration and validation steps are necessary (see e.g. Denker et. al., 2003). At the moment, the data handling and processing algorithms are further developed and optimised. This study deals with one aspect of this scheme, the validation of the gradiometric data using cross-overs, which enables an internal check of the gradients observed at different tracks, but at the same geographical position.

1. Idea and Capabilities of Cross-Over Validation
In the validation concept with cross-overs (XOs), the measurements can be validated internally, without any external information. This validation is able to provide the random noise of the measurements and to detect outliers, but constant biases and (constant) scale factors as well as location-dependent systematic errors cannot be detected. Furthermore the irregular distribution of the XOs and the time differences between the reoccupation of certain positions may restrict this method. Nevertheless it offers some benefits for GOCE validation and shall be described in more detail now.
Assuming a purely static gravity field, GOCE should observe the same measurements, i.e. gravitational gradients, whenever the satellite passes the same geographical position. This could either occur in repeat orbits or in XOs as shown in figure 1. Unfortunately it is not possible to compare the raw measurements directly, but one has to consider the effects caused by the typical orbit characteristics. As the three-axes gradiometer is mounted on the spacecraft, the orientation of the satellite (one axis points along-track, one cross-track and the third completes the triad) has to be taken into account, but also offers further internal validation possibilities. If the orbit eccentricity is not very large, the radial gradients can be compared after some simple reductions (see below). In XOs where the descending and ascending tracks are intersecting orthogonally, the along-track gradient of the one can be compared with the cross-track gradient of the other. When the full gravity tensor (i.e. the nine second derivatives of the gravitational potential) is provided, it would even be possible to rotate the measurements to an arbitrary reference frame. But then one has to take care that the less accurate off-diagonal elements of the GOCE tensor and the restricted knowledge of the rotation angles do not propagate into the resulting new gradients (for more details see e.g. Müller, 2003).

XOs from real or simulated GOCE orbits show special characteristics, which require some modifications of the simple concept mentioned above. Due to the orbit eccentricity (about $5 \cdot 10^{-3}$) the satellite passes the same geographical position at different altitudes (up to 15 km).
This causes differences in the observed gradients (e.g. $V_{zz}$ up to 12 E), which has to be considered in the validation procedure (Müller et al., 2003). The choice of XOs in orthogonal trajectories would lead to a further restriction of this method because those XOs occur – due to geometrical reasons – in certain latitudes (a narrow band at about 80° latitude) only. And even there the orthogonality is not reached perfectly, but differs by about 1°. The latter effect could be reduced by rotating the measurements itself (encountering again the full problem of less-accurate off-diagonals aso.). The corresponding reductions needed for this validation concept are described in the following section.

2. Concept of Height and Orientation Reduction

The basic idea for the height and orientation reduction is to use a known gravity field in some parts of the calculation scheme for the XOs without changing the measurements characteristics. This concept avoids the rotation of the measurements itself, for which the less accurate off-diagonal gravity tensor elements would be needed. The reduction can be calculated from an actual geopotential model (GPM), e.g. the EGM96. For a first test, this concept was applied to the IAG – SC VII GOCE test data set (IAG – SC VII, 2001), which consists of a simulated 30-days orbit with 0.2 Hz sampling rate as well as corresponding gradiometer measurements, calculated from the EGM96 up to degree and order 300 in the local orbit reference frame (LORF), which will be used in the mission. The extracted test data contain 17134 XOs between 80.3° and 81.5° North and South, suitable for the computations of (orthogonal) XOs. To check the numerical consistency of the method, the reductions (for $V_{xx}$, $V_{yy}$, and $V_{zz}$) were calculated from the EGM96, up to degree and order 300, as well as the gradients from the test data set, which had been interpolated into the XOs itself. Due to the use of same gravity field in both parts, no differences between the measurements in the XOs should show up. The results of the comparison (see figure 2), however, show small inconsistencies up to 0.6 mE, especially in $V_{xx}$ and $V_{zz}$. The main error sources are interpolation errors, especially for the rotation of the gradients into the LORF of each XO. But the magnitude of these errors is much below
the sensitivity of the GOCE mission to be validated (about 2 mE in the measurement bandwidth (MBW)), and it should become even smaller when working with data, which provide the planned sampling rate of 1 Hz. This consistency check shows sufficient numerical accuracies for the reduction part of the validation concept.

3. Error Estimation for Height and Orientation Reduction

The aforementioned reductions depend strongly on the errors introduced by the global geopotential model which have not been considered in section 2. The errors from the GPM can be divided in the omission error, i.e. those high frequency parts of the gravity field which are not covered by the GPM, the commission error reflecting the uncertainties of the GPM coefficients itself, and the errors caused by the input values, i.e. the XO coordinates. To get an impression of the order of magnitude of the reductions and their errors for the XO validation processing, some numerical investigations were performed. The omission error was calculated from the Tscherning-Rapp degree variance model (Tscherning and Rapp, 1974), considering degrees above l=300, which is the upper limit of the GPM used for the reduction and of the GOCE MBW. Then, the coefficient errors of the EGM96 were propagated into reduction errors. Finally the effect of different orbit accuracies with respect to the height determination was tested by assuming radial orbit errors of 1 cm to 1 m. The omission error was found to be below 0.02 mE for the diagonal tensor elements $V_{xx}$, $V_{yy}$ and $V_{zz}$.

Considering the planned gradiometer accuracy of 2 mE in the MBW, the omission error plays no important role for GOCE. The commission error from the EGM96 coefficients (degrees 0

Figure 2: Comparison of diagonal tensor elements $V_{xx}$, $V_{yy}$ and $V_{zz}$ in XOs where reductions were computed from the EGM96 up to degree and order 300.
to 300) is shown in figure 3 together with a radial orbit error of 0.1 m. The commission error was calculated from EGM96 coefficient variances, neglecting correlations between the coefficients. Therefore they may be too optimistic. The most critical factor for the height accuracy and orientation reduction seems to be the height difference in the XOs. The diagram in figure 3 can be used to choose those XOs with sufficient reduction accuracy for the validation process: this would be those with height differences below 5 km, providing reduction errors better than 1 mE even for the worst gradient, $V_{zz}$. Fortunately over 50% of the investigated XOs can be kept, that means, even with this restriction a huge number of validation points is available. The tight limit of 1 mE was taken to counteract the neglect of the GPM coefficient correlation. As mentioned above, also the influence of the height determination accuracy was tested. The propagation of assumed orbit errors of 1 m, 0.1 m and 0.01 m led to results similar to those of figure 3. The biggest contribution of this error source shows up in XOs with small height differences. But for a realistic value of 0.1 m, they do not exceed an acceptable limit (see figure 3). Even with the pessimistic orbit accuracy of 1 m, an almost sufficient accuracy for the reduction is obtained.

4. XO Validation with Noisy Gradients

The validation concept has also been applied to noisy GOCE data. The characteristics of the noise model are indicated in table 1 (middle column). The processing steps are the same as before: identification of the cross-overs, interpolation of the noisy gradients into the XOs, height and orientation reduction, and compa-
rison of the various gradients. The result (differences in the XOs) in the time domain is shown in figure 4, the corresponding statistics are given in table 1 (right column). The standard deviation of the resulting difference is about 5 to 8 mE, where Vyy is a little bit better, because it is affected less by the rotation. Constant errors, e.g. the bias of the noise data, and location-dependent systematics remain undiscovered. For the latter reason the standard deviation may be underestimated. But obviously, random noise can be detected.

5. Conclusions and Outlook
A concept for the internal validation of GOCE gradients has been developed using crossovers. It could be shown, that errors from the global model needed for the height and orientation reduction have no big effect and can be kept small enough for GOCE validation. The concept has also been applied successfully to noisy input data. The main results can be summarised as follows: the method works, but it is not possible to detect biases and location-dependent systematics; possible orientation errors increase the gradient errors (esp. for Vxx and Vzz); time-dependent errors and outliers are well detectable.

As one of the next steps, the filtering of the input data (before entering the validation procedure) shall be investigated. Also, the spectral distribution of the errors and their possible detection during the XO validation processing shall be considered.

6. References


<table>
<thead>
<tr>
<th></th>
<th>Simulated gradiometer noise</th>
<th>XO comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vxx</td>
<td>- mean</td>
<td>-1490.0</td>
</tr>
<tr>
<td></td>
<td>- std</td>
<td>11.2</td>
</tr>
<tr>
<td>Vyy</td>
<td>- mean</td>
<td>-818.8</td>
</tr>
<tr>
<td></td>
<td>- std</td>
<td>4.4</td>
</tr>
<tr>
<td>Vzz</td>
<td>- mean</td>
<td>2308.8</td>
</tr>
<tr>
<td></td>
<td>- std</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Tscherning, C.C. and Rapp, R.H.: Closed covariance expressions for gravity anomalies, geoid undulations, and deflections of the vertical implied by anomaly degree variance models, Reports of the Department of Geodetic Science, Report No.208, The Ohio State University, Columbus, 1974.

Figure 4: Comparison of noisy diagonal tensor elements $V_{xx}$, $V_{yy}$, and $V_{zz}$ in XOs, all reductions from section 3 applied.
Implementation and Validation of the Stochastic Model of GOCE SGG Data

Kargoll B.
Institut fuer Theoretische Geodaesie, Universitaet Bonn, 53115 Bonn, Germany,
E-Mail: bkargoll@mail.geod.uni-bonn.de

1. Motivation
The main goal of the GOCE mission is to determine the harmonic coefficients representing the earth’s gravity field by analyzing satellite gradiometry observations. To obtain optimal parameter estimations (i.e., estimations that are unbiased and of minimal variance), the standard approach is to use a weighted least squares adjustment of the observations, wherein the correlations are accounted for by the stochastic model in the form of a covariance matrix. However, this approach is limited: given the sheer volume of observations that will accumulate during the proposed satellite mission, producing a covariance matrix would not be possible in view of such massive storage and processing requirements.

Alternatively, a transformation may be applied to the model such that the observations become uncorrelated – in this case an unweighted least squares adjustment also produces the desired optimal estimations. Schuh (1996) showed that observations can be decorrelated efficiently by means of an autoregressive moving average (ARMA) model, the coefficients of which are derived from a spectral representation of the gradiometer error budget; see ESA (1999). This paper includes a proposal of a process whereby such an ARMA filter can be produced (see Sec. 2).

The covariance matrix of the observations, the ARMA model, and the gradiometer error spectrum may be considered as representations of the stochastic model from different perspectives. If the stochastic model assumed a priori is not valid, the estimations will not in general be optimal. It is therefore essential to have the right diagnostic tools at hand in order to check the validity of the model assumptions.

In light of this need, the current investigation also undertakes a comparative study of established and emerging tools in an effort to determine the constellation of tests that would best serve the requirements of the GOCE mission. In particular, the selection will be made from a field of tests which are focused on the analysis of residuals. Sec. 3 of this paper is dedicated to a discussion of statistical tests capable of checking two major assumptions regarding identical distribution and independence of the residuals.

2. Building the ARMA filter
Estimating optimal ARMA coefficients from a given empirical spectral density function is not a light task. Klees et al. (2003) provide an automatic model selection strategy based on the inverse Fourier transformation of the spectral density function into the corresponding autocorrelation function. Thereby, the model with the lowest pre-defined selection criteria is identified.

The current proposal suggests another approach to model selection, this time working from within the spectral domain. This methodology involves synthesizing a digital filter by adapting the poles and zeros of an ARMA model. The idea is to specify the frequency response of the gradiometer (see ESA (1999)).
and to construct a filter whose frequency response best matches that of the instrument. The desired filter coefficients are those that minimize the difference between the filtered output and the specifications in terms of magnitude gain in a minimum mean square error sense (see Widrow and Stearns (1985), who also consider specified phase characteristics).

Advantages of the current approach are (a) a comparatively low numerical effort, and (b) the possibility of fitting critical frequencies closer than others to the desired specifications. This is done by giving these frequencies higher weights within the minimization of the weighted sum of the squared errors.

It should be noted that this method differs from that of a brute force selection process in that both the selection of the model order and the adjustment of the frequency-selective weights have been to this point performed manually. Using this method, it becomes clear that a low order model provides a sufficiently accurate representation of the error budget specifications. Fig. 1 illustrates the magnitude response of an estimated third-order ARMA filter for the zz-gradiometer tensor component in comparison to the design specifications.

The inverse filter was used to decorrelate the observation equations. The residuals resulting from the estimation of the spherical harmonics were consequently used to pursue the validation of the stochastic model.

3. Model validation
Tests which are used to validate the assumption of independent residuals (cf. Stuart et al. (1999) for examples) can be broadly categorized into four groups:

1. Autocorrelation tests
2. Periodogram tests
3. Rank tests
4. Tests based on the empirical distribution function

While none of the existing tests alone has sufficient power against all of the possible alternative hypotheses, each features certain strengths and weaknesses (a test may have much power against a particular alternative, but may be 'blind' to others). At present, the current study has investigated tests from the first two groups, and is currently undertaking the analysis of representatives from the remaining two categories.

The first test that was implemented was the Portmanteau test by Box and Pierce (1970), which serves as an example of an autocorrelation test that has become a standard tool in time series analysis. The test evaluates the significance of the empirical autocorrelation function up to a specified lag. This test in particular was considered by the current investigation due to its reliability and low numerical cost.
A second type of test that was implemented in the current study utilizes the Fourier transform of the autocorrelation function, namely the normalized periodogram. Its normalized integral has the same properties as a probability distribution function. This allows the derivation of a test based on the well known Kolmogorov-Smirnov statistic (cf., for example, Priestley (1981)), by comparing the accumulated normalized periodogram of the residuals with that of white noise. Testing whether the empirical spectral density function of a series is constant (as in the case of white noise) is equivalent to testing, in the time domain, whether the empirical autocorrelation function vanishes.

The residuals analyzed in the current study were taken from estimations resulting from a closed-loop simulation; see Schuh (2002). These residuals were then processed by the filter that was originally used to decorrelate the observation equations. The resulting filtered residuals were then further subject to testing to detect significant departure from the null hypothesis, i.e. from randomness.

Another assumption that remained to be validated was that of identical distribution of the residuals, also denoted as homogeneity or stationarity. To check this assumption, two standard tests, the Kruskal-Wallis test and a variance analysis, were applied to the residuals (Schuh and Kargoll 2002). The focus of this testing was to see whether the individual means and variances of equally-sized groups of data belong to the same basic population.

4. Outlook
Both the autocorrelation and the periodogram tests imply normal distribution of the residuals, as the data could otherwise be dependent in spite of zero correlations. At present, both tests have been implemented in the development of an software package designed to »inspect« the GOCE data. However, the normality assumption may not be appropriate in the context of the GOCE mission, and if normality cannot be assumed with confidence, both tests may prove to be blind to some non-linear time series models.

For this reason we believe it is necessary to also consider tests that disregard the normality assumption, for example rank tests (cf. Hallin and Puri (1992) for a survey) and other tests which are based on the empirical distribution function; see Hong (1998) for some examples. The latter measure serial dependence by expressing the empirical multi-dimensional distribution function as a product of its marginal distribution functions. Tests belonging to these groups are being currently analyzed with regard to their power and numerical costs.

5. Bibliography


Automated Combination of SLR Solutions Within ILRS

Kelm R.
Deutsches Geodaetisches Forschungsinstitut (DGFI), Marstallplatz 8, 80539 Muenchen, Germany, E-Mail: kelm@dgfi.badw.de

1. Motivation and introduction
Within the activities of the IERS Combination Research Center at DGFI one topic concerns the automation of combination processes for space techniques. The motivation for this investigation is given by the Call for Participation «Positioning and Earth Orientation» of the International Laser Ranging Service (ILRS). Therein, the ILRS officially solicits the daily operational production of Earth orientation parameters (EOPs) and 28-day global station coordinates, based on satellite laser ranging (SLR) measurements. Concerning the time interval, a daily or weekly production is being in discussion.

For each time interval, individual analysis centers generate solutions for EOPs and station coordinates using the same set of SLR observations – here called input solutions. The combination center merges the input solutions into official ILRS products being a combined solution for EOPs and station positions (SINEX format), a combined solution for EOPs only (SINEX format), and a summary file containing the results of the quality control. DGFI has applied for being a candidate of an ILRS combination center the concept of which is presented here.

2. Permanent process
A shell script written in Perl language is permanently running. For defined time intervals it automatically gets via FTP the SINEX input solutions from an ILRS data base (CDDIS at NASA, EDC at DGFI), performs the quality control and combination of the solutions and finally puts the combined solutions in SINEX format back to the data base (s.fig. 1).

Figure 1: Permanent process flow.
### 3. Quality control of input solutions and combination

The Perl script for quality control of input solutions and combination uses methods in a pre-described sequence (s. fig. 2).

<table>
<thead>
<tr>
<th>Data:</th>
<th>Input solutions in SINEX format</th>
<th>ILRS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method:</td>
<td>Deconstraining normals</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* recomputing solution ok?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* loose constraints ok?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* 4 smallest eigenvalues ok?</td>
</tr>
<tr>
<td>Method:</td>
<td>Reducing bias parameters</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* reducing successful?</td>
</tr>
<tr>
<td>Method:</td>
<td>Minimal constraint solutions with relative weighting</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* solving with minimal constraints ok?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* outliers for relative weights?</td>
</tr>
<tr>
<td>Method:</td>
<td>RMS differences analysis before combination</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* RMS differences of estimated parameters ≤ empirical tolerance value</td>
</tr>
<tr>
<td>Method:</td>
<td>Combination with rescaling</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* 4 smallest eigenvalues ok?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* solving with minimal constraints ok?</td>
</tr>
<tr>
<td>Method:</td>
<td>RMS differences analysis after combination</td>
<td>Pass/fail criteria:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* RMS differences of estimated parameters ≤ empirical tolerance value</td>
</tr>
<tr>
<td>Data:</td>
<td>Combined solution in SINEX format</td>
<td>ILRS:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Combined solution for position and EOP (SINEX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Combined solution for EOP (SINEX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Summary file</td>
</tr>
</tbody>
</table>

Figure 2: Quality control and combination processing flow.

Each method contains pass/fail criteria: If an input solution fails the criteria, it is excluded from the further processing. The principal processing philosophy is straightforward: After having transformed the input solution systems to unconstrained normal equation systems (Method: Deconstraining normals) minimal constraint solutions are computed on the basis of an identical set of minimal constraints for quality control and combination. In theory, the normal equation matrices of SLR measurements should contain 3 rotational rank deficiencies for the rotation of station coordinates w.r.t. the reference frame, and one offset deficiency for UT1. Hence, four conditions referring to the rank types must be inserted to the systems in order to obtain minimal constraints solutions. The conditions are defined so that they lead to an optimal alignment to the underlying reference system which is realised by the a priori values of the parameters to be estimated.

One tool of the quality control is the comparison of RMS differences before and after the combination. Before, the comparison is performed for the input solutions w.r.t. to each other (Method: RMS differences analysis before...
combination). Afterwards, the combined solution is compared to each input solution (Method: RMS differences analysis after combination). The empirical tolerance values for the pass/fail criteria depend on the actual situation of the input solutions. Another tool of the quality control deals with the analysis of the normal equation matrices: In theory, the first four smallest eigenvalues must be zero, but in practice, the numerical results only lead to near zero values because of some numerical and modelling smearing effects. Many experiences in SLR pilot projects and in first test runs of this program prove the importance of that analysis tool.

The relative weighting of the input solutions (Method: Minimal constraint solution with relative weighting) and the rescaling of the combined solution (Method: Combination with rescaling) base on the assumption that the standard deviations of coordinates for stations which are well-covered by SLR measurements should have the same accuracy level, because the huge amount of observations over these stations may align potential systematic disturbances created by different modeling and editing of the analysis centers. Hence, the relative weighting and scaling produce this same accuracy level.

Potential range and/or time bias parameters within the input solutions are reduced in the normal equations (Method: Reducing bias parameters). There are two reasons for it: The bias parameters are not aimed at, so they are useless in the combined solution. Experiences show that the epochs of the bias parameters scatter in the input solutions so that the combined solution unnessarily blows up.

Input solutions w.r.t. the Call of Participation have not yet been computed. For testing the quality control and combination processing input solutions of ILRS pilot projects and of the IERS Sinex Combination Campaign have been used so far. The pass/fail criteria are developed w.r.t. to known quality control measures (eigenvalues, RMS differences), but also developed from a practical point of view. In case that the process run is interrupted by run time errors, a pass/fail criteria is being defined in order to handle the exception. Hence, a fine-tuning and an exception handling is assumed to be necessary, when the official input solutions are being tested.

4. Status and outlook
The first step to the development of a script for the automated combination of input solutions is finished. The shell script for handling the permanent process from getting the input data files up to putting back the output data files is validated for test files. The script for quality control and combination of input solutions has been iteratively developed by applying several test sets of input solutions. This iterative development will continue with further tests until the official ILRS input solutions are available.

As soon as results of other candidates for the ILRS Combination Center will have been sent to the ILRS data bases, an intensive comparison and evaluation process will be starting. The script for this processing is in development and will perform an automated process as far as useful. Finally, after having gained an deeper insight in the automated processing of this SLR intra-technique combination, the automated procedure is planned to be applied to intra-technique combination of other space techniques and to the inter-technique combination.
The detailed structure of the earth’s gravity field and its temporal variations are important for many scientific and economic applications (e.g. exploration purposes, geophysics, geoid determination). In order to guarantee this wide field of use a measurement system for the determination of this gravity data should be on the one hand accurate, reliable and with a high resolution on the other hand also efficient and independent of the area of operation. In comparison and in extension to satellite based and terrestrial methods the principle of airborne (vector-) gravimetry seems to be an optimal solution to determine the significant regional gravity changes.

The observation of gravity anomalies using the airborne gravimetry principle is already offered by some companies. These operational systems mostly use modified Sea-Gravimeters mounted on a stabilized platform to detect the specific forces. In order to derive the required gravity value the kinematic accelerations of the airplane, especially in height, must be additionally determined. This is currently done using the GPS system in some cases combined with other sensors, e.g. barometric sensors. So far, operational airborne gravimetry is able to achieve resolutions of about 5 km with an accuracy of 2 mGal. Thereby the computation of kinematic accelerations out of GNSS phase observations and the stabilisation of the gravity sensors are the most important limitations. But in order to fulfil the requirements for the most exploration applications, that are very important especially in regard to the economical point of view, the accuracy and spatial resolution of such systems has to be increased. Another disadvantage of the current systems are the dimensions, the weight and the acquisition costs. Furthermore they are limited to observe only the absolute gravity value. Information about its direction is only available if the vector gravimetry principle is implemented.

Against this background an airborne vector gravimetry system is in development based upon the use of a commercial high precision strapdown inertial navigation System (INS) and a combination of a geodetic GNSS receiver with a multi-antenna system. During the project the performance of such a sensor configuration should be evaluated. Especially by improvements in data processing methods an accuracy of 1 mGal over 1 km is intended.

Like it is presented in figure 1 the inertial data in the instrument frame is measured by a SAGEM Sigma 30 INS. In order to derive the kinematic acceleration on the one hand a ASHTECH L1/L2 receiver is used. Additionally the L1-observations of four other GNSS antennas with fixed baselines are generated by an ADU 3 multi-antenna system. The integration of the L1/L2 observations with this data at first should provide better performance of the phase ambiguity determination. At the same time this redundant
estimation of the airplane dynamics should increase the accuracy of acceleration computation. GNSS reference stations on the ground guarantee differential observations. In opposite to the navigation application as the typical use of GNSS/INS integrations in the case of airborne gravimetry the primarily long term INS errors and the short term acceleration errors caused by the white noise of the GNSS observations are combined in the error behaviour of the gravity signal. Consequently there is only a small frequency window within which an accurate gravity determination is possible. Therefore the goal of the data processing is to increase this spectral window in order to fulfil the user requirements. In figure 1 the most important steps of this procedure are demonstrated. Against traditional approaches in airborne gravimetry the input data for the designed integration filter are not on position but an acceleration level. Therefore first the sensor data must be processed separately. In case of INS data that mainly means transformation in a common inertial system and correction of systematic errors estimated at the beginning or during the flight. As it is mentioned before, the derivation of kinematic acceleration out of GNSS observations is an important limiting factor of airborne gravimetry. So this topic is a central point of the presentation. It will be mentioned in more detail later in the next paragraph. The central Kalman Filter should divide gravity signal and sensor errors as good as possible. Using special filter models integrating additional gravity field information into the data processing the separation process can be supported. Postprocessing algorithms like waveform correlation filters are able to improve the system performance using redundant gravity information derived by end point conditions, crossing points in the flight path or forward and backward processing.

The determination of absolute or relative position of an object is the standard application of the GNSS systems. The influences of systems errors are well known. As the GNSS raw data is also on the position level no integration or differentiation process is required. Also the derivation of precise velocities using mostly a combination of phase and Doppler measurements can be characterised as a general and often used processing technique. The airborne gravimetry is nearly the only
application GNSS measurements should provide accurate mGal-level acceleration data. In this case the error influences must be evaluated in a completely different way. It has to be taken into account, that the process of differentiating amplifies these errors as function of increasing frequency, causing them to be larger as the upper edge of the bandwidth is increased. E.g. long term errors like ionospheric influences has only small direct effects on the acceleration solution, whereas the receiver noise is the most dominant influence, and already a small cycle slip leads to immense errors. The spectral analysis of double differenced GNSS phase data using different observation conditions (e.g. zero-baseline-test, multipath environment, geometry changes) demonstrates the particular influence of GNSS errors on the acceleration determination. As an example the left side of figure 3 demonstrate a typical frequency spectrum for double differenced phase accelerations using a baseline length of 300 m. Note that typical cut-off frequencies for airborne gravimetry are up to 0.05 Hz. The acceleration accuracy level of airborne gravimetry is only achievable if low-pass filters are applied. But in order to guarantee a sufficient spatial resolution their cut-off region must be restricted. Beside of various methods of data differentiation (polynomial approximation, Taylor-approximation, differentiating numerical filters) in regard to the low-pass filtering only Finite-Impuls-Response(FIR) filters are suitable for this application. Their important property of constant group delay is necessary for time synchronisation of both sensor data streams.

Concerning the complete calculation of kinematic acceleration out of GNSS measurements essentially three algorithms are possible (see figure 2).

The traditional approach is presented in the upper part of figure 2. First of all standard software packages are used to calculate the DPGS phase solution including the ambiguity fixing and the navigation processing itself. Then the position is filtered according to the required spatial resolution of the data set. The process of double differentiating finally leads to the kinematic acceleration. An other technique is the Kalman filtering of the position data. Using a simple second order dynamic model the
GNSS positions can be used to derive the actual acceleration state. Thereby the definition of the acceleration noise affects the spectral properties and the time delay of this filtering process. An advantage of this method is, that additional information like the fixed baseline between two antennas can be easily integrated. But also in this case the ambiguity terms have to be fixed. In opposite to that in the last processing algorithm based on a least squares approach on the one hand only the low-pass filtered phase accelerations of rover and reference and the GNSS code solutions are the required input values. Using the reference coordinates and approximate rover position a functional model can be designed to allow a direct estimation of airplane accelerations. The satellite geometry is considered in the stochastical model. This method is very interesting for the discussed application because the integer phase ambiguities are not required. Therefore it should be possible to substitute the normally used ionospheric free linear combination by the L1-phase measurement with a lower noise level.

As an example for the data processing using the least squares approach the calculated acceleration of a static antenna (0.02 Hz Cut-Off frequency of the low-pass filter, 300 m baseline) is shown on the right sight of figure 3. As you see the accuracy level of airborne gravimetry is nearly achieved.

Some more results that also allow a comparison between the three processing techniques of acceleration determination are demonstrated in the presentation. However, a final decision about the calculation performance in regard to the airborne gravimetry application cannot be reached before the first practical flight test data are not analysed.

Figure 3: Spectral Analysis of phase accelerations/Calculated acceleration using least squares approach.
1. Background and motivation

In its function as IERS Combination Research Centre (CRC), DGFI participates in the IERS SINEX Combination Campaign in both parts of this project: (1) providing solutions and normal equations with station positions and earth orientation parameters (EOP’s) for different techniques (VLBI, SLR, and (regional GPS), and (2) combination of the solutions of the SINEX data pool (see below). The work is being funded by Geotechnologien-Projekt of the German BMBF (Bundesministerium für Bildung und Forschung), Verbundprojekt: FE: Vorhaben: IERS(F0336C). The work is done in close cooperation with GIUB and FESG within the joint CRC (see Nothnagel et al., this issue) and with the ITRS Combination Centre at DGFI.

Major goals of the SINEX Combination Campaign are to analyse solutions of the different space techniques concerning various aspects (e.g. SINEX format, parameter definiton, rank defects, suitability for combination), to combine station coordinates and EOP’s and to develop and investigate strategies for a rigorous combination of these parameters. The final goal is to ensure a high consistency and long term stability of IERS products. This presentation focusses on investigations related to the datum definition (e.g. contribution of different techniques to define the origin and scale of the TRF, influence of VLBI network geometry on the stability of the results) and on various aspects related to inter-technique combination, such as the selection and handling of local ties, the relative weighting, and the datum definition of the weekly combined solutions.

2. Input data (solutions)

A complete summary and description of all solutions and normal equations available in the data pool of the IERS SINEX Combination Campaign is visible at http://alpha.fesg.tumuenchen.de/iers/sinex/data_pool.html. Table 1 gives an overview of the solutions that we used for the investigations related to the datum definition. For the weekly combination of station positions and EOP’s stemming from different space techniques especially the following solutions were used: weekly GPS solutions of CODE (Center for Orbit Determination in Europe), SLR solutions of ASI (Agencia Spaziale Italiano) and VLBI solutions (NEOS-A sessions) generated at DGFI.

3. Investigations concerning datum definition

For the combination of station positions and EOP’s it is essential to define the terrestrial datum in a consistent way over time and for different space techniques (GPS, VLBI, SLR and DORIS). We investigated the datum definition of data sets available for the IERS SINEX Combination Campaign (see Table 1). In a first step we aligned each individual solution to ITRF2000 by a 7 parameter similarity transformation and we analysed the obtained time series of datum parameters to detect systematic differences between techniques and/or solutions. The translation parameters agree within 1-2 cm between the different solutions (except for DORIS), whereas the discrepancies for the z-component are significantly larger. Except for some outliers in the monthly ASI
solution, the SLR solutions show a good agreement for the scale estimation. The VLBI scale variations of the daily session solutions have a higher noise level compared to the weekly solutions of the other techniques mainly due to the poor network geometry of single VLBI sessions (see below) and due to the fact that the solutions span only one day. For the DORIS scale we obtain an offset of about 4 parts per billion (ppb) to ITRF 2000.

In case of VLBI normally only 4-6 telescopes observe simultaneously within a daily session. As furthermore the network geometry varies from one session to the next it is important to use all information available, including the time dependency of station coordinates to stabilize the terrestrial datum definition. We computed monthly combined solutions (about 15 well distributed stations) to stabilize the VLBI datum, and compared the results with single session solutions (see below). For this purpose we used the DGFI combination software DOGS-CS to compute solutions for each session, by applying no net rotation/translation conditions. Then the monthly solutions were generated by adding the normal equations of each session and by applying the same datum conditions.

The advantage of this approach is demonstrated for the VLBI scale and EOP estimations. Fig. 1 shows that the large scale variations of the session solutions are smoothed significantly due to the monthly accumulation. Furthermore the wrms for the EOP estimations on the basis of the monthly datum definition improves by 10 to 40% compared to the sessionwise definition (see Fig. 2).

4. Inter-technique combination of weekly solutions

According to our combination strategy on the level of free normal equations we have to remove the a-priori datum constraints which normally are applied in the solutions. The inter-technique combination of the weekly VLBI, SLR and GPS solutions with the DGFI combination software DOGS-CS is based on the following major steps (see Fig. 3):

- Reconstruction of the unconstrained (free) normal equations: For this purpose we used the information provided in the SINEX files of the individual solution to generate free normal equations. In case of GPS we were not able to reduce the datum information completely; therefore we set up 7 Helmert-transformation parameters to ensure that GPS do not contribute to the datum definition of the weekly combined solutions (see below).

- Addition of normal equations and relative weighting: To make sure that one observation technique should not dominate the inter-technique combined solution it is essential to calibrate all of them against each other. This is done by estimating scaling factors. In a first step mean standard deviations for station positions (only of »good« stations) were estimated for each technique. In a second step »real« differences in the variance levels are considered by using rms residuals of 7 parameter Helmert-transformations of the weekly solutions to ITRF2000. The resulting scaling factors were then applied for adding the individual normal equations.

- Selection of local ties: Collocation sites and local tie information are a key element for the inter-technique combination. In a first approach we computed weekly solutions by applying datum conditions (no net translation and no net rotation) w.r.t. ITRF2000. Based on these results we computed weekly local ties (for collocations sites) and compared them with the values given in the IERS database (ftp://large.ensg.ign.fr/pub/itrf/itrf2000/tiesnx/...SNX). The resulting time series of local tie differences show a relative high noise level (in the order of 2 cm) because of uncertainties of the weekly solutions and effects resulting from the datum definition. Therefore we used in addition information from DGFI multi-years TRF computations to select »suitable« local ties for the combination.

- Datum definition: Based on the results of the analysis of datum parameters obtained from the individual techniques we define the origin by SLR and the scale by a weigh-
ted average of SLR and VLBI solutions. The orientation was defined by no net rotation conditions using subsets of »good« stations of each technique.

- Weekly combined solutions: Based on the strategy described above we computed weekly combined solutions for station positions and EOPs and compared the results w.r.t. ITRF2000 by 7 parameter Helmert-transformations. As an example the time series of weekly transformation parameters (separately for VLBI, SLR and GPS) are shown in Fig. 4. The discrepancies w.r.t. ITRF2000 are in the order of 1 cm for the x- and y-component (in the average) and larger for the z-component. Furthermore it could be shown that the weekly combination of the space techniques has a positive effect on the time series of station coordinates at collocation sites; especially for some SLR stations (e.g. Potsdam, Wettzell and Washington) a significant smoothing of the weekly station coordinate estimations could be achieved.

5. Conclusions

Based on the investigations related to the datum definition we recommend to use SLR to define the origin; GPS could be used for the x- and y-component. SLR and VLBI solutions show the highest consistency (except for some outliers) for the scale. In case of GPS the influences of constraints on the datum parameters have to be further investigated. The relative high variations in the VLBI scale time series due to the poor network geometry can be significantly reduced by taking into account the time dependency of the individual VLBI session solutions. As a first approach we computed accumulated monthly solutions. The achieved results for VLBI scale and EOP estimations demonstrate the advantage of this approach.

The inter-technique combination results proof, that the applied strategy is suitable for weekly combination. Especially the smoothing of station coordinate time series at collocation sites demonstrates the advantage of the combination. In future DGFI will concentrate on issues related to a rigorous combination of coordinates and EOP’s and on the analysis of strategies to accumulate weekly solutions.

Table 1: Summary of solutions used for this studies; all these solutions cover the year 1999.
Figure 1: VLBI scale variations obtained from daily session and accumulated monthly solutions.

Figure 2: EOP estimations obtained from VLBI solutions (daily sessions / monthly).
Figure 3: Inter-technique combination with the DGFI combination software DOGS.

Figure 4: Weekly translation parameters of combined solution w.r.t. ITRF2000.
Pre-processing of CHAMP Magnetic Field Telemetry Data and Their use in Scientific Investigations

Lühr H., Maus S., Rother M., Haak V., Choi S., Mai W.
GeoForschungsZentrum Potsdam (GFZ), Section 2.3 “Magnetic Fields”, 14473 Potsdam, Germany,
E-Mail: hluehr@gfz-potsdam.de

An important part of the CHAMP mission is devoted to the investigation of the geomagnetic field. The advanced instrumentation on board of this satellite makes it particularly suitable for a recovery of the magnetic field with an unprecedented resolution. Very sensitive scalar and vector magnetometers are accommodated on an instrument boom, to keep them away from the noise sources on the spacecraft. To provide the orientation of the vector instrument with arc-second precision, for the first time a dual-head star tracker system is employed. In order to determine the dynamics of the ionised environment and to estimate the magnetic fields caused by the currents a Digital Ion Drift-Meter (DIDM), provided by the US Air Force Research Laboratory, Hanscom, Mass., is for the first time part of a full-scale magnetic field mission.

Another feature in favour with the scientific aim is the circular and near-polar orbit. The long mission life-time of 5 years at a low altitude of 450 km, decaying to 300 km towards mission end, is achieved by the special satellite design. This allows for an improved resolution at shorter wave lengths.

To guarantee the high quality of the magnetic field data throughout the multi-year mission, an in-flight calibration capability has been installed. The readings of the absolute scalar magnetometer are used to calibrate the measurements of the vector instrument. This procedure has been used successfully on earlier missions like Magsat and Ørsted. The pre-processed magnetic field and attitude data are made available with little delay to the science community via the CHAMP Information System and Data Center (ISDC).

The data set acquired up to date provides an excellent base for advanced studies of the geomagnetic field and related phenomena. A few of such studies will be briefly described here. A major challenge for deriving highly accurate magnetic field models from satellite measurements is the proper separation of magnetic fields originating from the Earth's interior from those caused by electric currents in the ionosphere and magnetosphere. With the help of the DIDM instrument on board of CHAMP we have additional means to identify periods when ionospheric currents are negligibly small. In a dedicated study (Lühr et al., 2002) we identified the regions and the local time sectors in which significant ionospheric currents are present, even on the night-side. These currents can be regarded as noise for magnetic field modelling efforts. Equivalently, the influence of magnetospheric currents such as the ring current, the magnetopause and tail currents have to be removed. Since the standard procedure provides unsatisfying results, we have developed a technique, which is based on a track-by-track removal of external and externally induced fields (Maus et al., 2002). Thanks to this new approach the spatial resolution of internal field models was improved significantly.
A new class of satellite-derived magnetic field models called IDEMM (International Decade Earth Magnetic Model) are compiled in close cooperation between GFZ Potsdam and the Danish Space Research Institute (DSRI) in Copenhagen. Combining the Ørsted and CHAMP data allowed us to generate accurate global geomagnetic field models up to degree and order 80. Particular progress has been achieved in determining the temporal changes of the magnetic field. The secular variation can now reliably be quantified up to degree 12.

Due to its low orbit CHAMP data are crucial for the short wavelength part. The IDEMM-high part of the spectrum (red curve in Fig. 1) is entirely based on CHAMP measurements (Maus et al., 2002). The signal power of this curve is well below the results of previous models. This result provides strong evidence that the lithospheric magnetisation is significantly weaker than expected due to earlier estimates, which were probably contaminated by noise and ionospheric signals. The latest lithospheric field model shows numerous prominent features, such as the clear contrast between continents and oceans, oceanic plateaus and the structure of the lower continental crust. The model is presently used in a number of ongoing geological studies.

Figure 1: Spherical harmonic spectrum of the geomagnetic field and its secular variation.

This tremendous gain in measurement accuracy and improved modelling allowed us to search for signals from secondary sources of magnetic field. In a concerted effort together with the University of Washington, Seattle we have managed to identify the weak magnetic signal of ocean flows. As a test case we have focused on the M2 tidal motion of the

Figure 2: Global map of the vertical component of the lithospheric magnetisation.
sea water. We at GFZ separated the 50000 times smaller ocean signal from the background field, while the U. of Washington group predicted independently the magnetic signal from an ocean tidal model. Both results are in astonishing agreement, thus confirming the high precision of our measurements (Tyler et al., 2003).

The ability to monitor ocean currents by magnetic measurements from space has a tremendous potential of application. The ocean circulation has an impact on many processes in our geosystem. Having an independent method of remotely sensing the flows is of great value. During the later part of the mission when CHAMP is on a lower orbit, the conditions for these measurements will be even better.

References


Regional Gravity Field Recovery from GOCE Gradiometer Measurements and SST-High-Low Observations – A Simulation Study

Mayer-Gürr T., Ilk K.-H., Eicker A.
Institute of Theoretical Geodesy, University of Bonn, Nußallee 17, 53115 Bonn, Germany,
E-Mail: tmg@mail.geod.uni-bonn.de

1. Introduction
GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) is a dedicated gravity field mission envisaged for the years 2006 to 2007 which has the potential of deriving the static part of the gravity field with unprecedented accuracy in the high resolution spectral part. In addition, the high-low links to the GPS satellites can be used to supply the long period spectral part of the gravity field. The technique presented uses the SST and SGG observations along short arcs of GOCE. It can be used for global gravity field recovery in terms of spherical harmonics as well as for gravity field refinements in selected regions. In case of a regional application the residual gravity field is modeled by space localizing base functions of spline type. Simulation results are presented for a combination of both observation types.

2. Regional Gravity Field Determination
Global gravity field determination is a challenging task. The aim of the GOCE mission is to calculate a gravity field with a resolution of about 70 km. This is equivalent to a representation by 90,000 - 100,000 parameters, to be determined from millions of observations.

Therefore it is reasonable to restrict high resolution gravity field recovery to scientifically interesting areas. This leads to relatively small systems of equations having to be solved. This can also be of relevance to later users who need a complete covariance matrix to appropriately make use of the data. When using spherical harmonics even for the analysis of only a small region all parameters have to be used for calculation and consequently the correlations between all parameters have to be known. In global models this can be several GByte of data and handling such an amount of data will even for the following generations of processors not be a trivial problem.

Furthermore the regional approach bears the advantage of being able to deal with regions without data (e.g. the polar gap) more easily. The easiest possibility is to exclude those regions completely, alternatively they can be calculated with less resolution. Using spherical harmonics the resolution can only be defined globally and data gaps are reflected in the accuracy of all spherical harmonic coefficients. This again emphasizes on the importance of the covariance matrix. In addition to that the combination with very heterogenous terrestrial data is a lot easier to realize having a localizing representation.

3. Analysis Method
Parameterizing the gravity field by means of spherical harmonics is not suitable for regional gravity field determination because of their global support. Therefore we make use of space localizing base functions. As these should be able to approximate the gravity field’s amplitude spectrum we employ splines having a covariance function as a kernel.
Due to the characteristics of the on-board gradiometer the long-periodic parts of the gravity field can only be determined inaccurately by mere gradiometry. For this reason SST data derived from the on-board GPS receiver are processed as well. Whereas the gradiometer observations as second derivatives of the gravitational potential are directly connected to the gravity field, evaluating the SST observations is more complicated. For the analysis short arcs of the satellite’s orbit over a certain region are taken into account. The orbit data are linked to the gravity field by means of the solution of a boundary value problem. When the starting position and the end position of a short arc are given, the satellite’s trajectory is unambiguously determined by the affecting accelerations. By inverting the boundary value problem a method for gravity field recovery is acquired. We are still examining whether it is more favorable to set up the observation equations in the space or in the spectral domain.

While for the analysis of SGG data only simulated data have been used so far, we were able to gain experience in analyzing real SST orbit data from the CHAMP mission. The promising results obtained thereby show the method’s applicability.

The gravity field determination from satellite data is an ill posed problem. In satellite altitude the gravity field is a lot smoother compared to the geoid which results in attenuation of the higher frequencies. By downward continuation the measurement noise then becomes amplified. The problem is also expressed in ill conditioned systems of equations. To stabilize the systems of equations and to eliminate the ill-posedness of the problem the Tikhonov regularization is applied. In doing so, the choice of the regularization parameter is of great importance for the quality of the solution.

The combination of the two groups of observations, SGG observations on the one hand and SST observations on the other hand, as well as the Tikhonov regularization take place on the level of the normal equations. Applying appropriate weighting to the different observations is essential in this matter. This weighting depends on the accuracy of the particular observations. As the magnitude of the observation noise is only roughly known a priori, an iterative method is reasonable. Starting from preliminary weights a solution is calculated. Its measurement noise is then analyzed and an improved weighting is determined. This procedure is repeated until it converges. Taking the regularization parameter as the variance of the solution
offers the possibility of determining it by this method as well.

4. Numerical Experiments
As area of examination the Himalaya region was used, as it is characterized by featuring a strong signal in all different wavelengths. The simulated data were generated on the basis of the EGM96 up to degree 300. The gradiometer observations as well as the satellite positions for SST where simulated for a period of 30 days with a sampling rate of 5 sec. The gradiometer observations here corrupted by colored noise having a standard deviation of 1.2 mE, and for the satellite positions an accuracy of 3 cm was assumed.

The gravity fields having been calculated from these observations are displayed in the two diagrams. Shown are the differences in geoid undulations compared to the EGM96 which has been used a pseudo real field of the simulation scenario. The solution using the SGG observations exclusively is illustrated in the first diagram. It provides an RMS of 14.6 cm and an obvious long periodic error can be detected. It originates from the gradiometer observations not being able to recover the long periodic parts of the gravity field with adequate accuracy. Therefore the combination with the SST observations has been performed. This reduces the RMS to 14.0 cm and as presented in the second diagram the trend has been eliminated. This indicates that the long periodic parts of the spectrum can be determined by SST observations.

Acknowledgement
The support by BMBF and DFG within the frame of the GEOTECHNOLOGIEN program is gratefully acknowledged.
Figure 3: Differences to EGM96 in Geoidheights [cm] (SGG + SST solution).
1. Background and motivation
Within the recently re-organized IERS, DGFI serves as an ITRS Combination Centre (ITRS CC). The main task of the ITRS CC is the combination of space technique solutions provided by individual Analysis Centers and/or Technique Centers (e.g. IGS, ILRS, IVS, IDS) to derive the ITRF products (positions and velocities of IERS network stations). The current space techniques contributing to the ITRF are VLBI, SLR/LLR, GPS and DORIS. The work of the ITRS CC at DGFI is being funded by Geotechnologien-Projekt of the German BMBF (Bundesministerium für Bildung und Forschung), Verbundprojekt: FE: Vorhaben: IERS(F0336C). The ITRS CC at DGFI works in close cooperation with the joint IERS Combination Research Centre of DGFI, FESG and GIUB, see Nothnagel et al., this issue. This ensures that the state-of-the-art combination strategies, algorithms, software packages, etc. will be applied for the generation of our ITRS products.

A major focus was on the validation of the various components of the ITRS CC and on the analysis and verification of our combination strategy for the computation of a TRF realization. For this purpose we used the most recent multi-years solutions with station coordinates and velocities of the different observation techniques. We analysed the combination results concerning various aspects (e.g. datum definition, weighting for the intra- and inter-technique combination, handling of local ties) and compared our results with ITRF2000 (Altamimi et al., 2002; Angermann and Drewes, this issue).

2. Data and combination methodology
For the TRF computations we used input solutions submitted for ITRF2000 computation, see http://lareg.ensg.ign.fr/ITRF/ITRF2000/submissions.html. In addition we included some newer solutions containing more recent observations (see Table 1).
The combination methodology of the ITRS CC at DGFI is based on the following major steps (see Fig. 1):
- Validation and analysis of individual solutions: The available solutions are checked concerning various aspects, such as format and the suitability for a rigorous combination.
- Reconstruction of unconstrained (free) normal equations: According to our combination strategy on the level of free normal equations we have to remove the a-priori datum constraints which normally are applied in the solutions.
- Intra-technique comparisons/combination: Input for the intra-technique comparisons and combinations are individual (unconstrained) free normal equations of the same observation technique. Before combining them, a dedicated comparison is essential to identify possible problems, which could cause systematic effects (biases) in the combined results. In order to generate comparable individual and intra-technique combined solutions we define the datum for each of them in a consistent way by applying minimum constraints. Other important tasks are the computation of relative weighting factors for the individual solutions and the identification and rejection of outliers. The individual normal equations are then added
by applying the previously estimated relative weighting factors.

- Inter-technique comparison / combination: Input for the inter-technique combination are the combined intra-technique normal equations (unconstrained) resulting from the previous processing step. Similar to the intra-technique case, a dedicated comparison of the solutions of the different techniques (especially at collocation sites) is necessary to identify possible problems. Other important issues include the estimation of scaling factors (e.g. variance component estimation), handling of local ties, equating velocities of different occupations and/or techniques on the same site, and the datum definition. The combined intra-technique normal equations are added by applying scaling factors between the different techniques. To the resulting inter-technique combined (free) normal equations, we then add condition equations in the form of pseudo-observations with appropriate weights for local ties and for those velocities on one site, which should be forced to be identical. To generate the final combined solution we add datum conditions in the form of minimum constraints (see below) and invert the resulting normal equation system.

3. Intra-technique combination
The intra-technique combination was applied for the different space techniques:
- In case of GPS this intra-technique combination was done by the IGS, and we used the cumulative combined IGS solution (IGSO3P01) provided by Natural Resources Canada (NRCan), instead of individual GPS solutions (Ferland, 2002).
- The SLR intra-technique combination is based on four individual solutions provided by CRL (Communications Research Laboratory, Japan), CSR (Center for Space Research, USA), JCET (Joint Center for Earth System Technology, USA) and DGFI. Table 3 shows the Helmert-transformations results for the SLR intra-technique combination. The results proof the high quality of SLR to define the TRF scale and to estimate precise station positions and velocities.
- The DORIS solutions of GRGS (Groupe de Recherche de Geodesie Spatiale, France) and IGN (Institute Geographique National, France) agree within about 7-8 mm and 2 mm/yr for station positions and velocities, resp. Both solutions were transformed to ITRF2000 before combining them, hence the Helmert-transformations between these DORIS solutions are close to zero.

4. Combined inter-technique solution and comparison with ITRF2000
The intra-technique normal equations of the different techniques obtained from the previous processing step were combined according to the strategy described above. Within these inter-technique combination collocation sites and the intra-site vectors (local ties) are essential. For some of the collocation sites we identified discrepancies between our TRF combination results and the local ties information of the IERS data base (ftp://lareg.ensg.ign.fr/pub/itrf/itrf2000/tiesnx/...SNX, see also Altamimi et al., 2002). To avoid systematic biases resulting from dubious local ties we excluded those from the final combination. Another important aspect is how to handle velocity estimations obtained from different techniques at one site. The results indicate that for some collocation sites, the velocity estimates differ significantly between techniques (e.g. due to biases between techniques solutions and/or local site-dependent effects), and shown in Table 2. The results demonstrate the high stability of the SLR solutions concerning the definition of TRF origin and scale (and their rates). The positions and velocities of the individual solutions agree within 5 mm and 1-2 mm/yr, respectively.

- In case of VLBI we used four solutions provided by GIUB (Geodetic Institute of University Bonn, Germany), GSFC (Goddard Space Flight Center, USA), SHA (Shanghai Astronomical Observatory, China) and DGFI. Table 3 shows the Helmert-transformations results for the VLBI intra-technique combination. The results proof the high quality of VLBI to define the TRF scale and to estimate precise station positions and velocities.
we did not force them to be identical. To generate the final combined TRF solution we defined the geodetic datum by applying no net rotation conditions for the orientation and its rate with respect to ITRF2000 station positions and velocities. The origin (translation and their rates) is defined by SLR, and the scale and its rate by SLR and VLBI. We did not use GPS and DORIS solutions to define the datum of the combined solution. A detailed description of the combination methodology and the combination results will be published separately (Angermann et al., in preparation).

Finally, we compared the DGFI solution with ITRF2000 by means of a 14 parameter Helmert-transformation. Table 4 shows the translation and scale parameters and their rates, separately for the different techniques. Both TRF realizations agree within a few mm concerning the realization of the origin; their rates differ by less than 1 mm/yr. The scale of both TRF realizations show especially a good agreement for VLBI and SLR, whereas in case of GPS the differences are in the order of 1 ppb.

References:


Figure 1: Data flow and processing scheme for ITRF computation at DGFI (simplified).
Table 1: Summary of solutions used for TRF combination. Stations with observations of less than 1 year were excluded.

<table>
<thead>
<tr>
<th>Technique</th>
<th>AC/Solution</th>
<th>Data Span</th>
<th># Stations original</th>
<th># Stations included</th>
<th>Constraints</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLM</td>
<td>(DGFI)02R02</td>
<td>1984-2002</td>
<td>49</td>
<td>49</td>
<td>free NEQ</td>
<td>DGFI</td>
</tr>
<tr>
<td></td>
<td>(GIUB)00R01</td>
<td>1984-1999</td>
<td>53</td>
<td>53</td>
<td>loose sol. ITRF2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(GSFC)00R01</td>
<td>1979-1999</td>
<td>123</td>
<td>88</td>
<td>loose sol. ITRF2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(SHA)00R01</td>
<td>1979-1999</td>
<td>129</td>
<td>88</td>
<td>loose sol. ITRF2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(CSR)01L01</td>
<td>1975-2000</td>
<td>141</td>
<td>106</td>
<td>loose sol. ITRF2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(DGFI)01L01</td>
<td>1981-2001</td>
<td>123</td>
<td>96</td>
<td>free NEQ DGFI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(JCET)00L06</td>
<td>1993-2000</td>
<td>63</td>
<td>55</td>
<td>loose sol. ITRF2000</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>(IGS)03P01</td>
<td>1996-2002</td>
<td>216</td>
<td>207</td>
<td>min. sol. NRCan</td>
<td></td>
</tr>
<tr>
<td>DORIS</td>
<td>(IGN)10D01</td>
<td>1993-2002</td>
<td>111</td>
<td>109</td>
<td>loose sol. IGN/CDDIS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(IRIG)00D01</td>
<td>1993-1998</td>
<td>70</td>
<td>69</td>
<td>min. dat. ITRF2000</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Helmert-transformation results of individual SLR solutions w.r.t. combined intra-technique solution.

<table>
<thead>
<tr>
<th>H.-T. Results</th>
<th>CRL</th>
<th>CSR</th>
<th>DGFI</th>
<th>JCET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx [mm]</td>
<td>-0.1</td>
<td>1.4</td>
<td>0.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Ty [mm]</td>
<td>1.5</td>
<td>-0.6</td>
<td>-1.3</td>
<td>-5.0</td>
</tr>
<tr>
<td>Tz [mm]</td>
<td>0.3</td>
<td>1.0</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Scale [ppb]</td>
<td>0.03</td>
<td>0.09</td>
<td>-0.26</td>
<td>-0.10</td>
</tr>
<tr>
<td>Tx rate [mm/yr]</td>
<td>0.8</td>
<td>0.1</td>
<td>-0.2</td>
<td>-0.4</td>
</tr>
<tr>
<td>Ty rate [mm/yr]</td>
<td>-1.4</td>
<td>-0.1</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Tz rate [mm/yr]</td>
<td>-1.6</td>
<td>-0.3</td>
<td>1.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Scale rate [ppb/yr]</td>
<td>-0.09</td>
<td>0.04</td>
<td>-0.08</td>
<td>0.18</td>
</tr>
<tr>
<td>Pos RMS [mm]</td>
<td>4.1</td>
<td>4.9</td>
<td>2.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Vel RMS [mm/yr]</td>
<td>1.6</td>
<td>1.4</td>
<td>0.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3: Helmert-transformation results of individual VLBI solutions w.r.t. combined intra-technique solution.

<table>
<thead>
<tr>
<th>H.-T. Results</th>
<th>DGFI</th>
<th>GIUB</th>
<th>GSFC</th>
<th>SHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale [ppb]</td>
<td>0.17</td>
<td>-0.15</td>
<td>-0.34</td>
<td>-0.06</td>
</tr>
<tr>
<td>Scale rate [ppb/yr]</td>
<td>0.03</td>
<td>-0.08</td>
<td>-0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td>Pos RMS [mm]</td>
<td>3.4</td>
<td>2.7</td>
<td>2.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Vel RMS [mm/yr]</td>
<td>0.43</td>
<td>0.72</td>
<td>0.22</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 4: Helmert-transformation results between DGFI combined TRF solution and ITRF2000.

<table>
<thead>
<tr>
<th>H.-T. Results</th>
<th>VLBI</th>
<th>SLR</th>
<th>GPS</th>
<th>DORIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx [mm]</td>
<td>-0.0</td>
<td>1.3</td>
<td>3.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Ty [mm]</td>
<td>-3.7</td>
<td>-0.9</td>
<td>-3.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Tz [mm]</td>
<td>1.7</td>
<td>-3.0</td>
<td>5.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Scale [ppb]</td>
<td>0.01</td>
<td>-0.23</td>
<td>-0.85</td>
<td>0.62</td>
</tr>
<tr>
<td>Tx rate [mm/yr]</td>
<td>0.0</td>
<td>-0.2</td>
<td>-0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Ty rate [mm/yr]</td>
<td>0.1</td>
<td>-0.6</td>
<td>-0.1</td>
<td>-0.7</td>
</tr>
<tr>
<td>Tz rate [mm/yr]</td>
<td>-0.6</td>
<td>-0.1</td>
<td>-0.7</td>
<td>-0.0</td>
</tr>
<tr>
<td>Scale rate [ppb/yr]</td>
<td>-0.01</td>
<td>-0.05</td>
<td>0.11</td>
<td>-0.01</td>
</tr>
</tbody>
</table>
Abstract

During the five year lasting GRACE mission, a temporal geoid variation of 3.0 mm is expected in the centre of the Fennoscandian land uplift area, corresponding to a gravity change of about 100 nm/s^2. This gravity change over five years (linear trend) can be observed with an accuracy of ±10 nm/s^2 by absolute gravimetry. As the geoid derived from GRACE data can be determined with an accuracy of ±0.1 mm (at spherical harmonic degrees between 2 and 50), the land uplift causes a measurable signal. Therefore absolute gravimetry can be used very well to validate GRACE results, i.e., it can provide ground-truth for the satellite measurements, but it contributes also to the separation of the various time-variable parts in the GRACE data. It is planned to perform absolute gravity measurements yearly to improve the knowledge about the Fennoscandian uplift with respect to accuracy and reliability, where also tide gauges will be connected, and the combina-
tion with GPS data is needed. The main result of the project will be an improved model of the land uplift (gravity and geoid changes), which can be used for the validation of the GRACE measurements.

1. Geodetic Determination of the Fennoscandian Land Uplift

In Fennoscandia the Earth’s crust has been rising continuously since the deloading of the ice at the end of the last ice age. The region is dominated by the Precambrian basement rocks of the Baltic Shield and comprises mainland Norway, Sweden, Finland, the Kola Peninsula, and Russian Karelia. The spatial extension is about 2000 km in diameter. To monitor and investigate the postglacial rebound, various geodetic measurements have been collected since 1892 (mareographs, levellings, relative gravity measurements since 1966), cf. Ekman and Mäkinen (1996), see Fig. 1 (left). These observations reveal a maximum orthometric height change of 10.2 mm/a over the Bothnian Bay and show symmetry around the maximum, closely correlated to the former Late Pleistocene Fennoscandian Ice Sheet. A eustatic sea-level rise of 1.0 mm/a has been deduced from the tide gauge observations. The height change in the centre is associated with a maximum gravity variation of -20 nm/s² per year. Based on these numbers, a geoid change of 0.6 mm/a has been derived for the central area.

Since 1993 permanent GPS stations have been established in Scandinavia to implement a further geodetic method with several advantages compared to the classical techniques (permanent data acquisition, homogeneous point distribution, large extension of the measurement area, low cost). In this respect, the project BIFROST (Baseline Inferences for Rebound Observations, Sea Level, and Tectonics) was based on GPS technique and geophysical modelling and has delivered a maximum height variation (with respect to an ellipsoid) of more than 11 mm/a (see Fig. 1 (right), cf. Milne et al. 2001, Johansson et al. 2002). The location of the centre and the geometrical structure of the uplift process differ from the previous model, with no clear zero line and more regional structures being visible.

During the mission duration of GRACE (about five years), a temporal geoid change of 3.0 mm can be expected in the centre of the Fennoscandian land uplift area, corresponding to a gravity change of about 100 nm/s² (≈ 10 µGal). As the geoid derived from GRACE data can be determined monthly with an accuracy of 0.1 mm (at spherical harmonic degrees between 2 and 50), the land uplift causes a measurable signal in the observations. Therefore, Fennoscandia is a suitable application region for GRACE. Vice versa, the temporal gravity field change can be used for the validation of the GRACE measurements. For obvious reasons, Scandinavia is one of the preferable areas to apply terrestrial geodetic methods (absolute gravimetry, GPS) with the objective to obtain reliable accurate ground-truth information. Due to the excellent infrastructure the measurement stations are easily accessible. Scandinavian research institutes are investigating the rebound effect since many decades. They proved the capability of terrestrial point measurement techniques (levelling, relative gravimetry) to determine the land uplift along east-west profiles. With the availability of faster and more precise geodetic methods (absolute gravimetry combined with GPS), the geophysical phenomena can be observed more accurately now than in the past.

2. Absolute Gravimetry

Besides the geometrical methods, absolute gravimetry is a further terrestrial geodetic technique to study the land uplift. In addition and complementary to the other geodetic measurements, absolute gravimetry has the following positive characteristics:

- accuracy ±20 to 30 nm/s² (10 nm/s² =1 µGal) for one station determination,
- absolute monitoring of mass movements and vertical displacements,
- accuracy of absolute gravity net is independent of geographical extension,
- north-south profiles are possible (no calibration problems due to large gravity differences),
- independent validation method for direct comparison with GPS, VLBI, SLR, and superconducting gravimetry,
- combined with geometrical methods, vertical surface deformations and subterranean mass movements can be separated.

The benefit of absolute gravimetry has already been reaped in different research projects covering areas of global or regional extensions and monitoring variations caused by mass movements. The International Absolute Gravity Basestation Network (IAGBN) serves, among others, to determine large scale tectonic plate movements (Boedecker and Fritzer 1986). The recommendations of the Interunion Commission of the Lithosphere on Mean Sea Level and Tides propose the regular implementation of absolute gravity measurements at points 1 to 10 km away from tide gauges (Carter et al. 1989). The height differences between gravity points and tide gauges have to be controlled by levelling or GPS. In Great Britain, the main tide gauges are controlled by repeated absolute gravity determinations in combination with episodic or continuous GPS measurements (Williams et al. 2001).

Applying absolute gravimetry to the determination of crustal deformations, secular gravity changes should be measured with a precision of about ±5 nm/s² per year. This can be achieved for GRACE by annual measurements over five years. Therefore absolute gravimetry can be used to validate GRACE results, i.e., it can provide point-wise ground-truth for the satellite measurements (gravity anomaly changes with time), but it contributes also to the separation of the various time-variable parts in the GRACE data (e.g., oceanic and continental temporal variations).

3. Project Realisation and Strategy

In 2002 the Institut für Erdmessung (IFE) of the University of Hannover has received a new FG5 absolute gravity meter from Micro-g Solutions, Inc (Erie, Colorado), which is a «state-of-the-art» instrument. This version replaces the older JILAG3 system, which was successfully employed by IFE in South America, Europe and China since 1986. In the meantime, a joint project for the survey of the land uplift in Fennoscandia has been established. The Working Group for Geodynamics of the Nordic Geodetic Commission (NKG) serves as a platform to organize the project. The kick-off meeting was held in Göteborg in February 2003. The representatives of five European countries participated. Besides the IFE from Hannover, following institutions are joining the project: National Survey and Cadastre (KMS, Copenhagen/Denmark), Finnish Geodetic Institute (FGI, Masala/Finnland), Bundesamt für Kartographie und Geodäsie (BKG/Germany), Institute of Mapping Sciences, Agricultural University of Norway (Ås), Statens Kartverk (SK, Hønefoss/Norway), Onsala Space Observatory, Chalmers University of Technology (Onsala/Sweden), National Land Survey of Sweden (Gävle). The project strategy and objectives may be summarized as follows:
- absolute gravity determinations at more than 20 stations (up to 30) in 2003 (with 3 FG5 gravimeters: IFE, BKG, FGI),
- repetition measurements in the years 2004, 2005, 2006 and 2007,
- simultaneous GPS measurements (gravity stations normally located close to permanent GPS stations),
- ensuring geometrical connections between gravity stations and to tide gauges (mainly by GPS),
- auxiliary levelling measurements to excentres (control of local variations, ties between gravity and GPS stations),
- elaboration of reduction models (air mass movements, ocean tides, etc.),
- integration of other geodetic data sources (e.g., already existing FG5 measurements),
- providing the products of the project (gravity anomaly changes, two-dimensional model describing the geoid change),
- validation of GRACE results.

4. Project Goals

The main result of the project will be an improved model of the land uplift, which can be used for the validation of the GRACE measurements. Terrestrial gravimetry determines temporal changes of gravity point-wise and allows
a direct comparison with gravity changes as derived from GRACE. In this connection, the spatial resolution of the satellite results has to be considered. In addition, the terrestrial results will be used to calculate a model of the temporal geoid changes in Fennoscandia. This calculation is based upon Stokes’ formula and its first time derivation, which allows the conversion from temporal gravity and height changes into geoid changes (e.g., Strang v. Hees 1977). This result can also be used for the validation of the GRACE models. Because the final GRACE results represent additionally two-dimensional information for the geophysical modelling of the whole area of the postglacial rebound, a combination of the satellite data and the terrestrial point results should be conducted (synergy effect).

References

Figure 2: Integration of different geodetic techniques to survey gravity and geoid variations with time in the Fennoscandian land uplift area.
1. Summary
Density distributions derived from highly resolved seismic tomography and viscosity models of Earth’s mantle are investigated in analytical and numerical flow models and fitted to the GRACE satellite-mission’s gravity and geoid measurements and the field’s variation with time, with special focus on lateral variations of the viscosity in the region of the lithosphere and asthenosphere.

Advection of a given density field yields temporal variations in the geoid and dynamic topography.

In order to investigate whether identifiers of such mantledynamic processes may be discerned from other signals contained in GRACE-data, these quantities are analyzed in the spatial and spectral domain and, considering plate tectonics, they are separated into drifting and non-drifting contributions. This permits predictions for regional mantledynamic contributions and renders variations of the harmonic coefficients with time, thus providing corrective fields to apply to GRACE-data.

2. Modelling of global mantle flows
The Earth’s mantle may be treated as a high-viscosity fluid, with flow driven by a distribution of density anomalies that is assumed constant or depth-dependent, with flow driven by a distribution of density anomalies that is assumed constant or depth-dependent. Literature provides a constant or depth-dependent linear relationship \( \delta \rho = \frac{\delta \rho}{\delta \nu} \) between density and seismic velocity anomalies from tomography. The ratio \( \frac{\delta \rho}{\delta \nu} \) is based on estimates as part of the modeling procedure, inverted for from gravity [Kaban & Schwintzer, 2001] or non-hydrostatic geoid [Forte et al., 1993] or derived from mineral physics data. Advection of this density distribution drives a flow.

The governing equations are the continuity equation, the equations of motion, Poisson’s equation and the constitutive law for a Newtonian viscous fluid with zero bulk viscosity. Variables are expressed in terms of products of radial functions and scalar spherical harmonics, yielding a set of coupled first order differential equations.

Spheroidal and toroidal terms decouple, the initial solutions for a set of boundary conditions are propagated through a series of shells of constant values for the sought variables by the propagator matrix [Panasyuk & Hager, 1996]. This in turn yields solutions in the form of boundary vectors that give the fluid velocities, stresses, gravitational potential and its radial derivative at any radial level in the earth.

We plan to implement lateral viscosity variations into our analytical code (method described by [Zhang & Christensen, 1993]). While they report no significant improvement of the geoid fit, allowing for lateral viscosity variations within the lithosphere and asthenosphere yielded best fits according to most recent publishings [Cadek & Fleitout, 2003].

3. Dynamic observables
Lateral density contrasts (related to thermal and/or compositional variations) and deflections of external and internal boundaries cause...
the Earth’s gravitational potential to deviate from its hydrostatic reference position. Buoyancy of density heterogeneities in a viscous mantle induces stresses on compositional or phase-change interfaces, deflecting most importantly the surface and core-mantle boundary (dynamic topography). An interpretation of the geoid requires a careful consideration of the net effect of contributions from the internal load itself and the resulting boundary deformations associated with flow induced by the anomaly [Richards & Hager, 1984].

3.1 Dynamic topography
The actual contribution of the dynamic topography to the observed topography is difficult to discern [Stunff & Ricard, 1995; Forte et al., 1993]. The signal may be reduced by isostatically compensated crustal and lithospheric contributions. Uncertainties, however, remain large. Equally, the relation between density distributions and observables of the induced flow field, dynamic topography and geoid, is complicated. While figure 1 shows geoid [Marquardt, pers. comm.] and dynamic topography (supplement to [Steinberger et al., 2001]) highs in the West Pacific subduction zones (blue regions in tomography [Ritsema & van Heijst, 2000]), other areas exhibit no such obvious correlation. Furthermore, models are very sensitive to the choice of viscosity distribution.

3.2 Geoid kernels
Geoid kernels represent the geoid produced by a unit mass anomaly of a given wavelength at a given depth, including the effects of dynamic topography. The geoid anomaly \( \delta N_{lm} \) caused by an assumed density distribution in the mantle is obtained by a convolution of these kernels with the density field

\[
\delta N_{lm} = \frac{4\pi G r_l}{(2l+1)g} \int G_i(r) \delta \rho_i \delta r
\]

[Turcotte et al., 2001].

The temporal geoid variation is then (substituting \( \delta \rho \) with the equation of state for incompressible fluids)

\[
\frac{\partial \delta N_{lm}}{\partial t} = \frac{4\pi G r_l}{(2l+1)g} \frac{\partial G_i(r)}{\partial r} \alpha \rho_i \delta T_m \delta r
\]

[117]

Figure 1: Observables related by mantle dynamics. **Left** Seismic velocity anomalies from tomography located at a depth of 600 km [Ritsema & van Heijst, 2000]. **Middle** Dynamic topography and plate motions calculated with density distribution derived from this tomography (supplement to [Steinberger et al., 2001]). **Right** Geoid anomalies [Marquardt, pers. comm.]. For geophysical purposes, geoid heights are preferably referred to with respect to the hydrostatic reference ellipsoid, i.e., the ellipsoid which has the hydrostatic flattening of a fluid rotating Earth.
3.3 Temporal geoid variations
Mantle-dynamic processes produce time-dependent geoid signals which, according to preliminary results, reach or exceed the resolution limits of the 5-year GRACE mission (Tab. 1, Fig. 2).

<table>
<thead>
<tr>
<th>$\delta T_{slab}$ [km]</th>
<th>$v_2$ [cm/yr$^{-1}$]</th>
<th>$\delta r$ [km]</th>
<th>$l$</th>
<th>geoid variation [m/yr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>10</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>10</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>100</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>10</td>
<td>300</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>10</td>
<td>100</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 1: Estimated temporal geoid variations for subducting slabs. Equation 2 is divided by degree $l$ in order to simulate a single slab. The actual geoid variation may be higher than the values calculated since a single structure contains spectral contributions also from higher degrees which are not considered here.

3.4 Acknowledgement
We thank G. Marquart for initiating this project and providing us with her preliminary results.

References


In the frame of the BMBF Geotechnologien-Projekt, the Deutsches Geodätisches Forschungsinstitut (DGFI), the Forschungseinrichtung Satellitengeodäsie der TU München (FESG) and the Geodätisches Institut der Universität Bonn (GIUB), all imbedded in the Forschungsgruppe Satellitengeodäsie of the International Earth Rotation Service (IERS), have jointly established a set of technique oriented Combination Research Centers of the International Earth Rotation Service (IERS). Presently, the three institutions are members of the Forschungsvorhaben 03F0336, Verbundprojekt: FE: IERS (see companion paper by Rothacher et al., this issue).

The IERS is responsible for gathering data of Earth system monitoring observations related to the kinematics of the Earth in space and observatories on the Earth’s surface. From this input combined (and official) IERS products are generated for a wide range of applications such as positioning, navigation and research. The IERS Combination Research Centers have been established to support the IERS Product Centers which are responsible for the routine processing of input data and dissemination of results.

Consistent monitoring of the kinematics of »System Earth« can only be achieved if a quasi-inertial celestial reference frame is established in which the observations are correctly aligned in space and time. The Earth as such has to be represented by observatories defining a terrestrial reference frame (Fig. 1).

A celestial reference frame (CRF) consists of solar system barycentric positions of a large number of radio sources such as quasars or radio galaxies. Due to the extreme distances of these objects from the Earth, the reference frame of radio source positions is considered to be very near to a true inertial system. The terrestrial reference frame (TRF) is realized by a number of observing sites with well defined reference points together with their geocentric cartesian coordinates and velocities. The latter are required to take into account the motion of
The observatories due to crustal motion. Earth orientation parameters are needed to establish the link between the two reference frames at any given epoch. For conceptual reasons Earth orientation parameters (EOP) are divided in two groups: Precession and nutation with longitude and obliquity components describe the motion of the Earth's rotation axis in space while polar motion with its X and Y components represents the motion of the rotation axis with respect to the Earth's crust. The spin angle of the Earth is defined as the phase of the rotation in the celestial reference frame at a given epoch (UT1-UTC). Concurrently the length of day (LOD), i.e. the partial derivative of UT1-UTC with respect to time, describes the length of one solar day in SI seconds or its variation as excess length of day (∆LOD).

The IERS Combination Research Centers of the FGS concentrate on research in methods to correctly combine multiple input pertaining to any of the individual observing techniques or input from several different space geodetic techniques such as GPS, SLR (Satellite Laser Ranging) or VLBI (Very Long Baseline Interferometry). Solutions of data analysis are normally carried out with redundant observations and a high number of degrees of freedom requiring adjustment techniques like least squares, collocation or Kalman filtering. Solutions, or rather technique outputs, can be generated in various forms:
- regular solutions with fixed datum,
- regular solutions with tight or loose constraints or
- datum-free normal equations.

Depending on the level of constraints, the results of the individual observing techniques are carried over to the Combination Research Centers in several different data formats containing different levels of information:
- listings of TRF, EOP and/or CRF with standard deviations,
- TRF, EOP and/or CRF results in Solution Independent Exchange Format (SINEX) containing the full variance-covariance matrix together with information on the constraints or
- TRF, EOP and/or CRF results in the form of datum-free normal equations in SINEX format.

Deutsches Geodätisches Forschungsinstitut
The work within the DGFI CRC is closely related to the ITRS (International Terrestrial Reference System) Combination Center at DGFI. Since the beginning of the project the activities were mainly concentrated on investigations and developments related to ITRS relevant issues. They may be divided into combination methodology, analysis of provided solutions and software developments.

In principle, the combination of heterogeneous geodetic observations can be performed at different levels (e.g. observations, normal equations, solutions). From DGFI's experience within the ITRS Combination Center the reconstruction of unconstrained normal equations from the individual SINEX solutions is in many cases difficult or even impossible. Therefore, it is recommended that unconstrained normal equations in addition to / or instead of solutions with variance-covariance matrices should be provided. Then the combination could be performed directly on the normal equation level without removing constraints.

Investigations in several aspects of the combination method have been carried out:
- Regarding the parameter definition it was investigated whether the current ITRS products (positions and linear station velocities) are appropriate also for the future. Site position time series were analyzed with regard to non-linear effects, periodic signals, etc.
- Investigations and software developments concerning the weighting of solutions for intra- and intertechnique combination were performed.
- The eccentricities (local ties) are important to combine different space techniques into a common reference frame. Therefore, we concentrated on the validation of local ties and on their handling in the combination.
Concerning the datum definition we analysed the contribution of individual space techniques. For the definition of the kinematic datum we propose to use kinematic models based on geodetic observations (e.g. APKIM 2000) instead of geophysical models (e.g. NNR NUVEL-1A) to ensure that the no net rotation condition is more accurately fulfilled.

DGFI has developed and/or employs various software packages for processing different space geodetic observations, e.g. DOGS (SLR), OCCAM (VLBI), Bernese GPS Software (GPS) and the combination software DOGS-CS. Further improvements of these software packages, including documentation and detailed description have been performed to fulfill the tasks of a CRC properly. Furthermore software for validation and analysis of input solutions (e.g. SINEX format, constraints, rank defects) and for the quality control and the visualisation of the combination results has been developed.

In connection with investigations of the quality of the ITRF2000 (International Terrestrial Reference Frame) a number of input solutions were analyzed with regard to constraints, reconstruction of unconstraint normal equations, rank defects, etc.. The differences between individual technique specific solutions which reach up to 5 cm for the origin and a few ppb for the global scale (see »http://lareg.ensg.ign.fr/ITRF/ITRF2000/T.gif« and »D.gif«) were intensively studied. Further improvements of the ITRF require the analysis of these differences with respect to systematic effects, model differences, constraints, solution strategies, etc.

The last item to mention here is the participation of DGFI in the IERS SINEX Combination Campaign. The aim of this campaign is to combine station positions and EOP of weekly solutions from different space techniques and to develop new combination strategies to improve the consistency of the IERS products. DGFI has provided SLR, VLBI and GPS solutions and/or free normal equations and concentrates on the analysis of combination strategies with respect to datum definition, local ties and weighting of solutions. DGFI also participated in the ILRS pilot project with the goal to compare and combine station positions of global SLR networks and daily EOP.

**Forschungseinrichtung Satellitengeodäsie**

The FESG as IERS Combination Research Center participates in the second step of the IERS SINEX Combination Campaign. The following series were selected for combination:

- session (= daily) VLBI files from DGFI,
- weekly GPS files from CODE (Center for Orbit Determination in Europe),
- weekly SLR files from ASI (Agenzia Spaziale Italiana).

All three series contain station coordinates and Earth orientation parameters (EOP).

After recovering the free normal equations for the GPS and SLR solutions – the SINEX files of the VLBI solutions already include the free normal equation – some tests were carried out:

1. The EOP from the VLBI solutions with fixing the station coordinates on ITRF2000 values were computed and the results compared with the EOP series from the »IERS Campaign to align EOPs to ITRF2000/ICRF« to see if this solution could be reproduced independently. The differences were smaller than 0.01mas and, thus, the normal equations were correctly retrieved.

2. For the GPS and SLR solutions it was tested whether the three degrees of freedom for the rotations were given. Therefore solutions with coordinates fixed on a rotated ITRF2000 coordinate set were computed and, as expected for free solutions, the applied rotations can be seen in the EOP.

As a next step one-year combinations with different realisations of the reference frame were computed for each solution series to check the quality of each series and to derive weighting factors for the intertechnique combination later on. The repeatabilities for the station coordinates were derived from 7-parameter Helmert-Transformations of all stations between the single solutions and the one-year...
combination, all of them with minimum constraints. Some iterations were necessary in this step because of several bad stations, that were either eliminated or not used for the datum definition. Clear differences in the size of the repeatabilities and for the relation between the three components can be seen between the three series (see table 1).

Table 1: Repeatabilities for station coordinates.

<table>
<thead>
<tr>
<th></th>
<th>ASI (SLR)</th>
<th>CODE (GPS)</th>
<th>DGFI (VLBI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North [mm]</td>
<td>20.39</td>
<td>2.60</td>
<td>3.80</td>
</tr>
<tr>
<td>East [mm]</td>
<td>19.84</td>
<td>3.41</td>
<td>3.87</td>
</tr>
<tr>
<td>Up [mm]</td>
<td>21.09</td>
<td>8.48</td>
<td>8.33</td>
</tr>
</tbody>
</table>

Figure 2: Differences to C04 for minimum constraints solutions.
The Earth orientation parameters derived from the single solutions were compared with official IERS EOP series (like C04 or Bulletin A) and interesting differences can be seen. All three solution series show similar offsets in the pole coordinates with respect to C04 (see figure 2) and from the GPS and SLR series it is clearly visible that satellite techniques are not able to estimate ?UT1. In addition, it seems that the estimated EOP depend on how the datum definition is realised, especially for the GPS solutions, because there are differences between the solutions with fixed coordinates and other methods for reference frame realisation (e.g. minimum constraints).

After all these tests with the solution series themselves, an inter-technique combination is done for each week (the appropriate VLBI sessions are selected). At the moment, this combination is done only with the EOP whereas the local ties at stations with more than one technique are not yet used. For the combination we change to an EOP parametrization with offsets only (piece-wise linear, but without rates).

Geodätisches Institut der Universität Bonn

The Geodetic Institute of the University of Bonn maintains one of the few global centers for the operation, correlation and analysis of geodetic Very Long Baseline Interferometry (VLBI) observations. In addition, the office of the global Analysis Coordinator of the International VLBI Service for Geodesy and Astrometry (IVS) is hosted by the Geodetic Institute. One of the tasks of the IVS Analysis Coordinator is the combination of the results of individual IVS Analysis Centers into a unified product. Using its experience in VLBI the group at Bonn concentrates on combination aspects of the VLBI technique and its particular aspects. The final result of this research and development project will be a method for rigorous combination of the three elements, CRF, EOP and TRF, in one common adjustment. In order to achieve this goal a number of fields have been identified which have to be investigated individually before a complete combination can be tackled.

As each IVS Analysis Center produces its own representation of a celestial reference frame through individual ways of analyzing the observations the combination of these results to a unified system has to be one of the main goals of this sub-project. Comparisons between existing radio source reference frames have been carried out as a first step towards combination. It has become obvious that the use of atmospheric gradients in VLBI tropospheric path delay modeling plays an important role in these investigations. Simple rotations through Eulerian or cardanic angles will probably not suffice to perform the necessary transformation between individual realizations. The investigations in this field currently concentrate on using input series with their formal errors, neglecting correlations between parameters. At a later stage covariances will be introduced to take into account correlations between the position components (Right Ascension and Declination) and between different radio sources employing SINEX files as output of the individual analysis centers. However, this is deemed necessary only when systematic errors are eliminated and the dominating errors are reduced.

The combination of Earth orientation parameters from VLBI analyses and the research and development activities are being carried out in the framework of the responsibilities of the IVS Analysis Coordinator. The official IVS Earth orientation parameter products are generated from a rigorous combination of input series produced by the IVS Analysis Centers. The results of the current combinations and more information are also available at the IVS home page http://ivsc.gsfc.nasa.gov with a link to the IVS Analysis Coordinator’s page.

Realizations of terrestrial reference frames from VLBI analyses are being generated in two different ways: Either as simple ASCII files of coordinates and velocities with their standard deviations or as SINEX files containing the full variance-covariance matrix of the solution from which the coordinates and velocities were estimated. In order to combine individual
solutions the input systems should ideally be datum-free and the datum should only be introduced after the combination process. In this context the validation of datum-free (singular) normal equations from VLBI analysis centers plays an important role when starting research and development of terrestrial reference frame combinations.

Recently, several IVS Analysis Centers started to generate datum-free normal equations of individual VLBI observing sessions containing coefficients for the coordinates of all stations participating in the session and the EOP of this epoch consisting of nutation offsets in longitude and obliquity, UT1-UTC, and the polar motion components in X and Y. Using the process of adding normal equations, a rigorous combination is achieved. The combined normal equation system is inverted after applying a minimum datum, so that EOP can be estimated in the inversion process. Thus, the initial steps on the way to develop a rigorous combination procedure have been successfully completed.
The launch of CHAMP right at the outset of the new millennium and the launch of GRACE almost two years later into low, almost polar orbits were major steps in addressing a more than 30 years quest for high accuracy, high resolution and globally homogeneous gravity and magnetic field data.

The CHAllenging Minisatellite Payload (CHAMP) mission is the first dedicated geopotential mission, mapping simultaneously the magnetic field with unprecedented accuracy down to spatial features of 500 km and resolving the gravity field details from high-low satellite-to-satellite tracking (SST) data over a spectral range of 600 to 40,000 km with a factor of 10 improved accuracy when comparing with pre-CHAMP gravity field models. An additional outcome from the mission is precise information about the vertical temperature, humidity and electron density distribution in the atmosphere.

The CHAMP mission is a joint project of the GFZ Potsdam and the German Aerospace Center DLR. The GeoForschungsZentrum Potsdam (PI: Ch. Reigber) is fully responsible for the successful implementation and execution of the mission. Strong technical and scientific links were established with science instruments providing agencies, such as NASA and CNES.

After a 9 months commissioning and validation phase and more than two years in full operation it can be stated that the CHAMP
satellite and all seven science instruments are performing extremely well. Exceptions with reduced performance are the Z-component of the accelerometer and the ion drift meter readings of the DIDM instrument. Fortunately both data sources are not critical for the generation of high quality scientific products.

An almost continuous flow of data from the instruments aboard the spacecraft into the Science Data System processing facilities has supported the fast generation of a large variety of high quality science data products by the GFZ project team since May 2001. Presently 3 terabyte of data and 2.5 million data products are archived in the CHAMP data base for access by the science and application users. And this wealth of data products is steadily growing. A number of outstanding models for the main magnetic field and the crustal magnetization, steadily improving EIGEN models for the static part of the Earth's gravity field and a huge number of vertical profiles for temperature, humidity and electron density distribution in the atmosphere are provided for the community.

The Gravity Recovery And Climate Experiment (GRACE) is a dedicated twin satellite gravity mission whose objective is to map the global gravity field with unprecedented accuracy over a spectral range of 400 to 40,000 km and once every thirty days. This should allow to follow the temporal variability of the field, being closely associated with mass redistributions in the solid Earth, the hydrological, ocean and atmospheric components of the Earth system. In addition limb sounding observations through the atmosphere will be carried out from both spacecrafts for global vertical profiling of atmospheric state parameters.

The GRACE mission is a joint partnership between NASA and DLR. The University of Texas’ Center for Space Research CSR (PI: B. Tapley) has overall mission responsibility. The GeoForschungsZentrum Potsdam (Co-PI: Ch. Reigber) is responsible for the German mission elements. The Jet Propulsion Laboratory (JPL) manages the U.S. portion of the project for NASA's Office of Earth Science. Science data processing, product verification, archiving and distribution are managed under a cooperative arrangement between CSR, JPL and GFZ Potsdam.

During the last 14 months of the commissioning phase the two GRACE satellites have undergone an extensive set of on orbit tests to demonstrate primarily the High Accuracy Intersatellite Ranging System's (HAIRS) ranging capability. Along with the extended on-orbit activities, the satellites have gathered over 120 days of science level data during this period. Concluding from what has been achieved so far, it can be stated that the satellites and instruments are performing remarkably well, given the ambitious goals. They are utilizing cutting edge technology to develop micron-level ranging accuracy and high-precision accelerometer measurements. These measurements involve all elements of the dual satellite configuration. In December 2002 the GRACE team released its first image that graphically illustrated its sensitivity to changes in the Earth's gravity and confirming the satellites measurements sensitivity.

As a part of the instrument and system accuracy assessments, data sets of 50 to 110 days have been used by CSR and GFZ to determine preliminary GRACE gravity models. These initial models show a significant improvement over previous models (including those from CHAMP) for wavelengths of 500 to 15,000 km and, in this region, it has exceeded, by a factor of 10 to 50, the accuracy achieved using the gravity measurements collected over the past 30 years. The mission is well on its way to reach baseline mission requirements. The initial GRACE gravity models have already shown to enable a dramatic improvement in
the altimetric determination of ocean currents.

The GRACE commissioning will come to an end mid of May 2003. This phase will be followed by a 6 to 9 months validation period, after which calibrated and validated GRACE data products will be made available to the science community for further use.

The first series of CHAMP mission gravity, magnetic field and atmospheric sensing results, their intensive use in the community and the initial very promising gravity field results from the GRACE mission demonstrate the high potential these mission will have on discipline specific investigations, such as in meteorology and climatology, in oceanography, hydrology, glaciology and solid Earth sciences, and on some application fields in geodesy, navigation and oceanography. In addition to these discipline specific studies, we have come to realize that the complex interactions of the Earth’s atmosphere, solid Earth and ocean involve mass transport – which is mostly water- and this water exchange has a discernable gravity signal. This realization has led to a paradigm shift in gravity studies. We know now that it is not sufficient to measure gravity only once, but that we must monitor it through repeated measurements. The fact that with CHAMP an ocean current flow related magnetic signal has been extracted from the space magnetic field observations has also led to a similar shift in magnetic field studies. With the exiting results obtained from the CHAMP radio occultation data a new field of GNSS climatology is likely to develop.

The many CHAMP and GRACE related presentations and posters at the last EGS-AGU meeting in Nice are indicating that both missions are on the way of opening new scientific and application fields which in some cases may change the way we presently view the Earth.
Almost 3 years ago, on July 15, 2000 the geo-
research mission CHAMP was launched into a
near polar, circular, low altitude orbit from the
cosmodrome Plesetsk / Russia. Since then the
satellite is in a free-drifting orbit and is passing
through different resonant regimes when
decaying. Due to high solar activity in the last
year and corresponding high atmospheric
drag, CHAMP’s orbital altitude was decreasing
faster than predicted for a 5 year mission
profile. Therefore 2 thrusters controlled orbit
lift manoeuvres were carried out in 2002
raising the orbit each time by about 15 km.
With these orbit altitude changes the mission
could last until 2008, if the satellite subsystems
and science instruments function properly over
such a long operation period.

The CHAMP overall system, composed of a
space- and ground-segment was commissio-
ned and validated by the project teams of GFZ
Potsdam and the German Aerospace Center
DLR during the first 9 months of the mission
and was proven to function as planned and
specified – with the exception of one electrode
of the accelerometer.

Since this time the operation of the spacecraft,
handled be DLR’s German Space Operation
Center in Oberpfaffenhofen, is running very
smoothly and effectively and CHAMP’s multi-
fuctional and complementary instrumenta-
tion, controlled by the GFZ project team, is in
full operation. This instrumentation is com-
posed of sensors for the observation of:

**Earth Gravity Field:**
a new generation GPS flight receiver for
continuous tracking of CHAMP by the satelli-
tes of the GPS constellation for accurately and
continuously monitoring of the orbit perturba-
tions, a high-precision three-axes accelerom-
eter for measuring the surface force accele-
ратions and a star camera pair for precise
attitude determination of the spacecraft body.

**Earth Magnetic Field:**
a high performance Fluxgate magnetometer
set measuring the three components of the
ambient magnetic field in the instrument
frame combined with a star camera pair deter-
mining the attitude of the assembly with
respect to the stellar frame and a Overhauser
scalar magnetometer serving as precise mag-
netic reference.

**Atmosphere / Ionosphere:**
the instrumentation used for the recovery of
the magnetic and gravity fields constitutes at
the same time a powerful assembly of sensors
for observing many parameters relevant for the
characterisation of the state and dynamics of
the neutral atmosphere and ionosphere:
GPS/CHAMP radio occultation measurements
for the derivation of temperature and water
vapour distribution in the atmosphere, digital
ion drifimeter measurements for sensing the
electric field, GPS/CHAMP soundings to deter-
mine the electron density distribution in the
ionosphere and the high resolution accelerom-
teter to sense the air density variations in
CHAMP’s orbital environment.
This instrumentation provides for the first time in space geodesy's history an almost continuous tracking of the spacecraft motion at a low altitude, a high precision in-situ measurement of the forces acting on the satellite surface and simultaneously a global mapping of the magnetic field with a precision and spatial resolution never achieved before.

CHAMP's ground segment comprises all ground-based components which perform the operational control of the spacecraft and instruments, the data flow from the on-board memory and supporting ground networks to the processors and users. Figure 1 shows the general scheme of the overall data and product flow and the responsibilities within the CHAMP Mission Operation System (MOS - DLR responsibility) and the CHAMP Science Data System (SDS – GFZ responsibility).

The CHAMP SDS, consisting of
- an S-band station in Spitsbergen for fast monitoring of the scientific equipment and fast science data reception,
- a global network of 1 Hz GPS ground stations with rapid data transmission capability,
- a science data control and data decoding facility,
- processor systems for data pre-processing and processors for orbit and gravitational field modeling, magnetic field determination and determination of atmospheric and ionospheric parameters,

is being operated by the GFZ CHAMP team almost 'round the clock' now, after a number of optimisations and automation procedures were introduced. National and international users have easy and quick access to all data, products and meta-information desired via the CHAMP ISDC data management system. The SDS is connected via its communication links and data systems with the CHAMP mission control facility at the German Space Operation Center of DLR.

CHAMP's standard science products are labelled from level-1 to level-4 according to the number of processing steps applied to the

---

![CHAMP Mission Space & Ground System](image_url)

Figure 1: CHAMP ground segment.
original data. Decommutation and decoding of level-0 data results in level-1 products. These are daily files, associated with each individual instrument and source aboard CHAMP, and the data content is transformed from the telemetry format and units into an application software readable format and physical units. Level-1 products also include the ground station GPS and laser data. Level-2 products are necessary spacecraft housekeeping data and arranged in daily files. Level-3 products comprise the operational rapid products and fine processed, edited and definitely calibrated experiment data. Finally, level-4 leads to the geoscientific models derived from the analysis of CHAMP experiment data, supported and value-added by external models and observations.

The excellent operational performance of the CHAMP mission operation and science data system, reflected in an almost continuous flow of high quality CHAMP sensor and GPS ground network data into the system with low latency, has resulted up to now in the generation of about 2.5 million data products for a total of 114 different product types. These level-0 to level-4 data products are archived for internal and external user access in the CHAMP Information and Data Center (ISDC). More than 200 external user groups, including those from the Geotechnology Programme, access presently CHAMP products via the ISDC. Accesses are almost equally distributed over the application areas gravity field, magnetic field, atmosphere/ ionosphere sounding.

In 2002 science and application users from 22 different countries retrieved data products of different level from the CHAMP-ISDC, most intensively groups from Germany (37 %, GFZ excluded), USA (24 %), Japan (21 %), China (10 %), Taiwan (3 %), Denmark (2 %) and the Netherlands (1 %).
The CHAMP-ISDC and the GRACE-ISDC are responsible for the management of all scientific CHAMP and GRACE satellite products. In addition to more than one hundred different satellite products of the scopes gravity field, magnetic field and atmosphere all necessary data for the processing and validation of the final products are also managed by the appropriate ISDC. The operation period of the ISDCs is designed to cover the whole mission period and beyond. The complex ISDC system consists of six main components (Fig. 1. Schematic Structure of the CHAMP/GRACE-ISDC).

The Operational System (OPS) is responsible for the product input, caused by the appropriated processing groups and the product output relating to all types of user requests. The product input and product output directories are located on a dedicated FTP server. According to the ISDC product philosophy (Fig. 2. ISDC Product Philosophy) every product consists of a data file in a product type depending format and a metadata file in the format of the extended DIF standard (http://gcmd.gsfc.nasa.gov/User/difguide/whatisadif.html). The product check-in process of the OPS includes the metadata parsing and the transformation of the data into a relational data structure of the Clearinghouse (CLH). The Product Archive System (PAS) transfers the complete and metadata validated products into the online product archive consisting of TByte-Raid systems as well as into the backup archive, the HSM (Hierarchical Storage Management) system of the GFZ. The Clearinghouse (CLH), the Datawarehouse (DWH) and the Product Ordering System (POS) are the main system components for product retrieval, product download and value added services. Internal and external ISDC users generally interact with the WWW based Graphical User Interface (GUI) of the system (Fig. 3. Graphical User Interface of the CHAMP-ISDC).

Using a standard Internet browser, the GUI guides registrated users according to theirs requests to the ISDC home page or the product description section as well as to the product retrieval section of the CLH or to the product download batch mode section of the POS. Additionally, the DWH offers product mapping and visualization services for dedicated atmosphere products. In order to keep the ISDC systems permanently operating, to avoid faulty operations and to protect it against hacker attacks, the system does not grant users...
direct access to the stored products within the archives, which are installed in the GFZ intranet only. Instead, users have to use the GUI or a batch mode interface of the POS for the processing of their product requests. All products provided by the PAS are stored into user own FTP directories. Extra time critical product requests are handled by the direct delivery mode of the POS via a product direct transfer from the input directories to the appropriate output directories of the FTP server.

References


WWW-pages for the IERS Analysis Coordination: According to the proposed procedure, presented at the IERS Directing Board Meeting No. 34 in September 2001 in Brussels, a new web site was planned and installed in November 2001.

The WWW-pages for the IERS Analysis Coordination are linked from the IERS homepage: http://www.iers.org/iers/about/ac/ or can be accessed at the local server under http://alpha.fesg.tu-muenchen.de/iers/.

These sites should provide a communication and data exchange platform to the Combination Research Community. It should also stimulate and support their activities. The web site presents the current activities and research intentions of the Combination Research Centres (CRCs), provides a communication platform with mail-forum and email-exploder and builds the main coordination of the IERS SINEX-Combination Campaign and the IERS Analysis Campaign to align EOPs to ITRF2000/ICRF. A more detailed description of the objectives and the planned activities can be found in the minutes of the IERS Directing Board Meeting No. 34, see also the keywords at http://alpha.fesg.tu-muenchen.de/iers/annexIII.html. The following summary presents the main topics of the WWW-site:

Communication:
The IERS Central Bureau has installed a platform for a CRC discussion group in order to support email discussions and the scientific transfer between the CRCs and interested persons.
The email support is subdivided into the email exploder with restricted access and an email forum, which is public to all interested persons. Any one, who is interested in CRC activities and wants to participate in the discussions can contact to the IERS Central Bureau (associate: A. Lothhammer, lothhammer@iers.org).

**CRC-Activities:**
The link [http://alpha.fesg.tu-muenchen.de/iers/crc/crc%20activities.html](http://alpha.fesg.tu-muenchen.de/iers/crc/crc%20activities.html) is leading to the CRC project list. This list should present an overview as up-to-date as possible of the current CRC activities. In addition to the institutions, names and contacts, it includes their objectives, combination and research strategies, their future plans and links to further publications.

**IERS Analysis Coordination Campaign to align EOPs to ITRF2000/ICRF:**
In September 2001 the IERS Analysis Coordinator presented the »IERS Analysis Coordination Campaign to align EOPs to ITRF2000/ICRF« as proposed by J. Ray. The intention of the IERS Alignment Campaign is to create Earth Orientation Parameters (EOP) series with highest possible consistency with the International Celestrial Reference Frame (ICRF) and ITRF2000. The aim of this project is to achieve an overall accuracy of 0.1 mas. This will lead to an intermediate solution until a rigorous combination of the EOP together with ITRF / ICRF is possible. Therefore it is necessary to analyse and understand the origin of systematic errors belonging to the reference frames. The IERS Alignment Campaign was started at the end of September 2001 with an initial call for participation. The Campaign is subdivided into two parts. In a first step the Technical Centres were asked to produce EOP series with the reference frame fixed to the ITRF2000 / ICRF at the level of uncertainty. In addition, they were asked to produce solutions with different constraints on ITRF2000 (ICRF). The second step consists of the analysis of the submitted EOP series by comparison with the official annual solutions 2000 and by studying the consistency against each other. The final results should be recommendations for future realizations of reference frames. The ongoing project is linked under [http://alpha.fesg.tu-muenchen.de/iers/eop/campaign.html](http://alpha.fesg.tu-muenchen.de/iers/eop/campaign.html). The sublinks »Call for Participation«, »Proposals«, »Submission of EOP series«, »List of available EOP series« and »Results« show the whole history and the processing of the Alignment Campaign.

**SINEX-Format:**
The web-pages and the communication platform was used to start a discussion about a new Solution Independent Exchange (SINEX) format. The objective was to create a single, shareable and uniform format for the exchange of solutions. This will be a basic requirement for the combination of SINEX files from all different Technique Centres. The most common SINEX format descriptions were analysed and a new uniform consistent version was proposed. The new format (Version 2.00) was announced in May 2002 with IERS message No. 26.
The final version of the SINEX 2.00 format description is available under http://alpha.fesg.tu-muenchen.de/iers/sinex/sinex_v2.pdf (see as well IERS Message No.26).

**IERS SINEX Combination Campaign:**

It is the intention of this campaign to combine »weekly« solutions from SINEX files of different techniques with station coordinates and EOPs (and ICRF) and to assess systematic biases between the individual space geodetic techniques. The web pages were prepared and the campaign was initiated at the beginning of the year 2002. Now the goals, the procedure and the participants can be found under http://alpha.fesg.tu-muenchen.de/iers/sinex/sinex_campaign.html.

**SINEX Data Pool:**

Parallel to the SINEX Combination Campaign a SINEX data pool was created and is continuously kept up-to-date. Various SINEX data files are collected and archived to provide the CRC community an easy to use data base for their research activities. An up-to-date list and links to a selected subset of SINEX files, suitable for combination research and software testing, is available in the SINEX file archive, http://alpha.fesg.tu-muenchen.de/iers/sinex/datapool.html.

Complete and up-to-date list of IERS products: Together with feedback from all components of the IERS, especially the Product Centers (PCs) a complete list of all IERS products was compiled and is now officially available at http://www.iers.org/iers/products/. The list contains all the relevant product information like accuracy, availability, update frequency, documentation etc.

For a more detailed overview concerning the IERS Analysis Coordination WWW-pages see also our poster presentation and feel free to visit our internet site.

The web-pages for the IERS Analysis Coordinator and connecting activities are supported by the scientific associates Dr. R. Dill and D. Thaller at the Technical University in Munich as part of the german project »GEO-TECHNOLOGIEN«.
Integration of Space Geodetic Techniques and Establishment of a User Center in the Framework of the International Earth Rotation and Reference Systems Service (IERS)


1) Forschungseinrichtung Satellitengeodäsie, TU München, Arcisstrasse 21, 80290 München, Germany. E-Mail: markus.rothacher@bv.tum.de
(2) Geodaetisches Institut, Universität Bonn, Germany
(3) Deutsches Geodaetisches Forschungsinstitut, München, Germany
(4) Bundesamt für Kartographie und Geodäsie, Frankfurt, Germany
(5) GeoForschungsZentrum Potsdam, Germany

1. Introduction

Over the last years the availability of and the easy access to highly accurate and consistent products of the International Earth rotation and Reference systems Service (IERS; mind the new name) has become of vital importance for geodetic, geodynamic and geophysical projects. Future research and in particular the new satellite missions (CHAMP, GRACE, GOCE, JASON-1 etc.) will require an accurate global reference frame as a crucial basis to accomplish their scientific goals, be it for precise orbit determination, gravity field estimation, monitoring of sea level change or other geodynamic and geophysical purposes.

The accuracy achieved today by the individual space geodetic observing techniques (VLBI, GPS, SLR, LLR, DORIS) is mainly limited by systematic errors of the individual techniques. Therefore, the thorough integration and combination of the techniques into a consistent global geodetic observing system is mandatory to achieve major improvements in the quality of the IERS products.

As a result of a joint proposal of the Forschungsgruppe Satellitengeodäsie (FGS), Munich, Germany, consisting of
- Deutsches Geodätisches Forschungsinstitut (DGFI), München
- Deutsches Geodätisches Institut der Universität Bonn (GIUB)
- Institut für Astronomische und Physikalische Geodäsie, TU München (IAPG)
- Forschungseinrichtung Satellitengeodäsie, TU München (FESG)
- Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt

and the GeoForschungsZentrum Potsdam (GFZ) to the new IERS (see Figure 1), these six organizations were selected by the IERS Directing Board to establish a user center for the International Earth rotation and Reference systems Service (IERS) consisting of the following components:

- IERS Central Bureau,
- Combination Center for the IERS Terrestrial Reference System,
- IERS Combination Research Centers,
- IERS Analysis Coordinator.

With the cooperation of the six institutions involved in these four areas and with the finan-
cial support of the BMBF with its GEOTECHNOLOGIEN-Programm, Germany now plays a very prominent role in the IERS in general (see, e.g., the persons involved in Figure 1) and in the integration of the space geodetic techniques in particular.

2. Objectives of the Project
The project presented here fits perfectly into the theme »Beobachtung des Systems Erde aus dem Weltraum« and the issues of a rigorous integration of space geodetic techniques as well as the establishment of user centers and data services in the area of »Global Reference Systems, Geokinematics, Earth Rotation and Potential Fields«.

Table 1 shows that the individual space geodetic techniques are contributing to different aspects of the parameter space of global space geodetic solutions. The integration of all parameters of the shaded part in Table 1 is essential for the consistency and quality of the IERS products and is the main topic of this proposal. In addition, studies will be performed to also integrate the atmospheric parameters and the gravity field into one common system.

In this way this project gives an important contribution to the combination aspects at the left-hand side of the scheme in Figure 2. A rigorous combination of the space geodetic techniques will lead to more consistent and more accurate products for the three major pillars of geodesy, namely, Earth surface geometry, Earth rotation, and the Earth’s gravity field (in the middle of Figure 2). Improvements in these fields, again, are essential for a better understanding of the Earth’s system and its interactions as shown on the right-hand side of Figure 2, and vice versa.

Figure 1: New Structure of the IERS.
With these goals and activities, the project will also contribute to the Integrated Global Geodetic Observing System (IGGOS) that will be established by the International Association of Geodesy (IAG) as its principle future project at the upcoming IUGG General Assembly 2003 in Sapporo.

The main goals of the IERS user center to be established in the frame of this project are:
- the development of strategies and algorithms for a rigorous integration and combination of the space geodetic techniques in order to improve the consistency and accuracy of the IERS products in the future (Combination Research Centers),
- quality control of the IERS products and coordination of the steps towards a full integration of the techniques (Analysis Coordination),
- the generation of consistent and accurate products for the ITRS component (ITRS Combination Center),
- and making the IERS data and products and the documentation thereof available to the broad user community in a timely, modern, user-friendly fashion (Central Bureau).

3. Present Status and Results
In the first half of the project duration, considerable progress could already be made in all the four areas mentioned above. Let us just point out the most important of these achievements here. More details may be found in several other extended abstracts concerning this joint project.

3.1 IERS Central Bureau
It is an achievement in itself, that the IERS Central Bureau (CB), located at the Observatoire de Paris for at least two decades, is now run in Germany by the BKG, but it also means a big international responsibility and obligation. The IERS Central Bureau successfully supports all the major activities of the IERS Analysis Coordinator, organises workshops

<table>
<thead>
<tr>
<th>Parameter Type</th>
<th>VLBI</th>
<th>GPS GLON.</th>
<th>DORIS PRARE</th>
<th>SLR</th>
<th>LLR</th>
<th>Altimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasar Coord. (ICRF)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nutation</td>
<td>X</td>
<td>(X)</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pole X, Y</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>UT1</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of day (LOD)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subdaily ERPs&lt;sup&gt;1&lt;/sup&gt;</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERP Ocean Tide Amplitudes</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coord.+Veloc.(ITRF)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>(X)</td>
</tr>
<tr>
<td>Geocenter</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Gravity field</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Orbits</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>LEO Orbit Determ.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Troposphere</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Time Transfer</td>
<td>(X)</td>
<td>X</td>
<td>(X)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup>ERPs: Earth Rotation Parameters
3.2 Combination Center for the IERS Terrestrial Reference System

In the course of the last 1.5 years the DGFI succeeded to generate its own combined solution for the ITRF making use of the multi-year input solutions for site coordinates and velocities from all major space geodetic techniques. The detailed comparisons with the official ITRF solution (ITRF2000) already revealed some clear deficiencies in the official solution that can be improved. The friendly competition with the other combination centers under the umbrella of the ITRS Product Center considerably speeds up the progress made in this field. A first ITRF solution of DGFI was presented in 2002.

3.3 IERS Analysis Coordination

With the »IERS EOP Alignment Campaign« and the »IERS SINEX Combination Campaign« (see internet pages of the AC for more information) two campaigns were launched by the IERS Analysis Coordinator (AC), that led to a considerable increase in research activities concerning systematic errors between techniques and combination strategies. Impressive results from many different groups were presented at the most recent EGS General Assembly 2003 in Nice in a session organized by the IERS AC. At the IERS retreat in Paris this spring (organized by the Central Bureau, the IERS AC and the IERS chairman), much progress was achieved: the IERS was renamed (see title) to better reflect its major products, it was decided that a
combination pilot project will start January 1, 2004, routinely generating weekly combinations of all space geodetic techniques, and two working groups – one on combination issues and one on site co-location – were set up.

3.4 Combination Research Centers
The CRC at the DGFI is making good progress with its work on the generation of weekly intra-technique (solutions from analysis centers of the same technique) as well as inter-technique (solutions from different space geodetic techniques) combination solutions including station coordinates and Earth Orientation Parameters (EOP). Detailed studies were performed on the quality of the local ties between the techniques and the transformation parameters between the site coordinate solutions of the different techniques giving insight in systematic errors present as well as the strengths and weaknesses of the individual techniques.

The CRC at the FESG was studying all the EOP data available for the IERS EOP Alignment Campaign, where the analysis centers of all techniques used the ITRF2000 site coordinates to realize – although with different strategies – the terrestrial reference frame for the EOP estimation. Large systematic biases between the official IERS EOP product (C04) and the results of this test campaign could be detected (e.g., an offset of 0.2 milliarcsec in the y-pole coordinate).

In addition, first combinations of weekly solutions from VLBI, GPS and SLR analysis centers were performed with station coordinates and EOPs as common parameters. The results are very encouraging and confirm the systematic biases detected in the official IERS EOP products mentioned above.

The CRC at the GIUB developed software to combine VLBI EOP series from various VLBI analysis centers. GIUB now produces the official EOP products of the International VLBI Service (IVS) and soon, a rigorous combination of EOPs and station coordinates will be routinely performed, leading to products, that will be considerably more consistent than those available today.

The CRC at GFZ already now successfully combines GPS and SLR ground station data with the tracking data of Low Earth Orbiting (LEO) satellites like, e.g., CHAMP, GRACE, or JASON-1.

It was shown that this combination of different observation techniques and the data from ground- and space-based instruments improves the orbit quality of both, the LEO and GPS satellites. GFZ works on combining not only station coordinates, EOP, and orbit parameters, but also the gravity field information into one consistent global solution (see Table 1).

4. Conclusions
Today, with the strong involvement in the new IERS, the FGS and GFZ play a major role in this international service and thus take over important responsibilities within the global geodetic community. Due to the long-established and well-working cooperation between the institutions involved and the support of the IERS Central Bureau, major steps in the direction of a rigorous combination and integration of the space geodetic techniques have been achieved so far.

It is clear already now, that a large number of high-precision geodetic, geodynamic, and geophysical projects as well as present and future satellite missions enormously benefit (or will benefit) from the more accurate and more consistent products of the IERS resulting, to a considerable extent, from the activities carried out within this ambitious GEOTECHNO-GlEN-project.
GOCE (Gravity field and steady state Ocean Circulation Explorer) is the first core mission of ESA’s “Living Planet Programm”. It is currently under development and will be launched in 2006. In two years time it will generate a detailed global map of the Earth’s gravity field and of the geoid. Whereas GRACE is designed so as to determine temporal variations of the Earth’s gravity field with highest precision at medium wavelengths GOCE is tailored for a mapping of the quasi-stationary gravity field with focus on highest possible spatial resolution. The two dedicated gravity missions are therefore complementary. The gravity and geoid models derived from GOCE will be used in solid Earth geophysics, oceanography, geodesy and sea level research.

The core instrument of GOCE is a gravity gradiometer. It is complemented by a GPS receiver.

Figure 1: GOCE spacecraft with gravity gradiometer and GPS receiver.
for high-low satellite-to-satellite tracking to the Global Positioning System (GPS), compare Figure 1. The latter will provide the orbit trajectory with cm-precision and it will support gravity field determination at very long wavelengths. GOCE is equipped with drag free orbit and angular control in order to keep its extremely low orbit altitude, to diminish the effect of non-gravitational forces on the motion of the spacecraft and in order to maintain a smooth orbit in a known earth pointing orientation. Thus, the complete gravity sensor system consists of a gravity gradiometer, GPS-receiver, star sensor, and thruster systems for drag, orbit and angular control, see Figure 2.

Figure 2: GOCE gravity sensor system.

The gravity gradiometer is made of three orthogonally mounted one-axis gradiometers. Each of them consists of two three-axis accelerometers mounted at the end of a baseline of 0.5 meters. The accelerometers contain a rectangular test mass which is kept levitated electro-statically by means of a capacitive feedback mechanism, compare Figure 3. Due to the difference in position of these six test masses, each of them experiences the Earth's gravitational field in a slightly different manner. The acceleration differences monitored by each of the three gradiometer arms provide very sensitive measurements of the spatial details of the Earth's gravity field. The effect of the angular motion of the satellite in space on the acceleration measurements has to be eliminated, effects of time variable eigen-gravitation inside the spacecraft have to be avoided. In summary, the gravity gradiometer will furnish three independent but complementary detailed global maps of the Earth's gravitational field (derived from the radial, along-track and cross-track gradiometry components).

It will be the first gravity gradiometer in a satellite and it will be the first time that such sensor combination will be flown in space. Consequently a new data processing scheme, adapted to this approach, has to be developed. It is the purpose of the GOCE-GRAND project to develop and test such a processing scheme in a co-operation of several institutes. Furthermore, the main elements of it are planned to become part of a joint European data processing consortium, which is currently under preparation. Data processing means here the determination of a gravity field model, i.e. of a complete set of spherical harmonic coefficients, from the measured gravity gradients, GPS-measurements, and instrument orientation data. Furthermore the gravity model should be accompanied by a realistical quality assessment. The derived gravity model is then made available for use in geophysics, oceanography, geodesy, sea level research and others. GOCE-GRAND has been designed such that a complete processing chain will be established. Since the sensor system of GOCE and the gravity
diometer are novel developments the first step of the processing chain is a simulator. It contains all sensor system elements, their measurement and error characteristics as well as all external forces acting on the spacecraft and on the test masses. It provides a deeper insight into the propagation of individual effects through the system and into the interactions between the individual sensors. It should give realistic signal and error characteristics of GOCE. The satellite-to-satellite tracking part covers the path from GPS phase measurements onboard of GOCE to kinematic, three-dimensional orbit trajectories, from orbit to velocities and from there to long wavelength gravity field spherical harmonic coefficients either via the so-called energy-conservation method or via a semi-analytical perturbation theory. While the entire method has been successfully tested with CHAMP-data for the case of the energy-conservation approach, there remain still profound complications for the case of a semi-analytical perturbation theory. For the actual processing of satellite gradiometry measurements, several solution strategies are followed in parallel. At this point it is still difficult to predict what the pro’s and the con’s of the four methods will be. The methods are as follows:

- Semi-analytical method: Under the assumption of some – moderate – simplifications the method yields a solution strategy that can dwell on certain symmetries. This makes the method fast, flexible and easy but it requires several iterations. The method is suited, in particular, for quick-look analysis.

- Full solution: It is a method of great precision, based on a thorough analysis of the data and stochastic model, and it requires
parallel computing. As alternative solution strategies an iterative preconditioned conjugate multiple adjustment and a direct approach are under investigation.

- Regional solution: While the above two methods will result in a global spherical harmonic representation of the gravity field, the regional solution takes into account the regional variations of it in terms of signal variability and strength. It should permit maximum local exploitation of the measured gravity content.

- Spherical and Ellipsoidal solution based on a representation of the gravitational field in Cartesian coordinates: The expectation is that any use of base functions for gravity field representation, that will closer approximate the actual field than spherical harmonics, will result in better convergence of the solution and in higher precision.

Apart from the gravity modelling itself, it is necessary and desirable to prepare strategies for an objective validation and assessment of the various solutions and for an optimal combination and cross-fertilization of the results from GRACE and GOCE. Validation means, for example, comparison of the GOCE results with terrestrial gravity material, with GPS-leveling or with dedicated test data sets. GRACE data are expected to help in the correction of GOCE gradiometer measurements for time-variable gravity effects, such as those from the atmosphere, oceans, ice, hydrology or tectonics. The ultimate goal will be, however, to combine the ultra-precise GRACE results with the high-resolution GOCE measurements.
Abstract

The US-German twin-satellite mission GRACE (Gravity Recovery And Climate Experiment) was successfully launched on March 17th, 2002 into a low-altitude, almost polar orbit. Primary mission goal is the recovery of the long- to medium-wavelength features of the global gravity field and its temporal variations. The basic mission concept is to exploit inter-satellite measurements (satellite-to-satellite tracking SST) between the low-flying GRACE satellites and the sender satellites of the Global Positioning System (GPS) and the inter-satellite observations between the twin-satellites. In particular the measurements of the micrometer-precise low/low link, which correspond to the differential gravitational accelerations of the center-of-masses of the GRACE satellites along the inter-satellite range, are needed for an increased resolution of the gravity spectrum to medium wavelengths. Dominant non-gravitational forces such as air drag, Earth albedo and solar radiation pressure present at GRACE’s altitude – to be separated from the gravity signal part in the SST observables – are accurately measured by three-axis accelerometers, precisely located at the center-of-mass at each spacecraft. The orientation of the accelerometers’ axes with respect to a celestial reference frame are measured by star cameras rigidly connected to the satellite body. Figure 1 depicts the GRACE mission concept.

Figure 1: GRACE mission concept.
systems for the given SST observables are generated arc-wise, using 1.5 days arc length. The non-gravitational forces acting on the GRACE satellites are taken into account via the onboard accelerometry data. The resulting arc-wise equation systems are then combined to one global system and eventually solved through matrix inversion. The Stokes coefficients $C_{lm}$, $S_{lm}$ of degree $l$ and order $m$ of a spherical harmonic expansion of the Earth's gravitational potential are finally solved-for.

Based on GRACE science data collected during the commissioning phase, using the above method, preliminary estimates of the static gravity field of the Earth and its temporal variability are derived. The capability of the low/low SST link for precise gravity recovery is revealed in the determination of the geopotential with unprecedented accuracy. Validation by means of comparisons to external gravity-related data such as altimeter derived ocean surface data (corrected for dynamic topography) and gravity anomalies made in the spatial domain manifest the strength, quality and homogeneity of the estimated GRACE-only gravity field as geopotential reference model. When applied to precise dynamic orbit determination to a set of representative satellites the potential of the GRACE-only model as multi-purpose gravity information is revealed. Recovery of temporal variations of the Earth's gravity field from GRACE data is in reach but still needs intensive examination. This contribution presents current results and experiences from GRACE data analyses at GFZ.
The GEOSENSOR:
A New Instrument for Seismology

1. Introduction
Over the last 40 years ring laser gyroscopes became one of the most important instruments in the field of inertial navigation and precise rotation measurements. They have a high resolution, good stability and a wide dynamic range. These properties made them very suitable for aircraft navigation. Over the last decade we have developed very large perimeter ring laser gyroscopes for the application in geodesy and geophysics [1]. By increasing the effective ring laser area by up to a factor of 24000 the sensitivity of these ring lasers to rotation was increased by at least 5 orders of magnitude, while the drift rate of the instruments reduced by a similar amount. This led to the successful detection of rotational signals caused by earthquakes [2]. These observations stimulated the development of a highly sensitive ring laser gyro for specific seismological applications. The goal of the project named GEOSENSOR is to obtain and analyze additional rotational information from seismic activity of the region where the demonstrator will be deployed. Translational and rotational motions are recorded simultaneously. During the course of this project we have designed a demonstrator of this GEOSENSOR, which is now under construction. In this paper we report about the current status of the project.

2. Design features of the GEOSENSOR
The GEOSENSOR demonstrator consists of several major components: a large one-axis ring laser, a conventional three-axis broadband seismometer, a tilt meter to monitor changes in the orientation of the ring laser component and a GPS-station to provide time and reference frequencies for the data acquisition system. Auxiliary instrumentation such as thermometers, a barometer and laser power meters are used for diagnostic purposes in the evaluation phase of the GEOSENSOR. Since the most interesting data-sets for seismic studies are expected in the vicinity of an earthquake our instrument must be transportable. Once this hybrid sensor is completed, it can be relocated to any suitable observatory, which provides sufficient infrastructure namely a solid monument with as little temperature variations as possible, because the ring laser component is a highly sensitive device. Figure 1 shows the basic elements of the GEOSENSOR concept.

2.1 Ring laser component of the system
The resolution of a ring laser gyroscope is proportional to the ratio of the area and perimeter encircled by the two counter-rotating laser beams [3]. Therefore larger rings are more sensitive. For example, the 16 square meter ring laser G installed at the
Fundamental station Wettzell, Germany has a resolution of

$$\delta \varphi = 9 \cdot 10^{-11} \text{ rad} / \sqrt{s}$$  \hspace{1cm} (1)

This is extremely sensitive and well suitable for the detection of both teleseismic waves and small local events. The difficulty for the GEOSENSOR project is to find a suitable compromise between instrumental size and the demand for transportability and ease of installation. Furthermore we had to work out a design that is rigid, robust and cost effective at the same time. On top of that we also have to aim for a low thermal expansion of the ring laser construction in order to maintain stable single longitudinal mode for a reasonable length of measurement time. All these requirements distinguish this new design substantially from earlier ring laser projects. Figure 2 shows the design of the ring laser component.

The square ring laser contour is formed by four 1.6 m long stainless steel tubes, rigidly attached to the corner boxes, which contain the mirror holders. The four high-reflective super-mirrors form a low loss closed beam path. A thin capillary which is required for Helium-Neon laser excitation, is located in the middle of one of the connecting tubes, symmetrically with respect to the ring laser geometry. The mixing optics for the two counter rotating laser beams is also contained in one of the corner boxes. The enclosed area is 2.56m$^2$ and we expect a sensitivity to
rotation approximately one order of magnitude below the G ring as stated above. Since we plan to operate these rings in regions of high earthquake activity the expected resolution is more than enough. However the alignment of the optical beam path in the cavity is very critical. A folded lever system as shown on the right hand side in figure 2 has to ensure a precision of ±15 seconds of arc. As a consequence the encasing is designed to be very rigid as well as that the ring laser requires a solid monument of bedrock or concrete for the installation. Each of the corner boxes has a total weight of 120 kg and is mounted to the monument by 3 steel stubs in the bottom of the encasing.

2.2 Auxiliary sensors

Since ring lasers are inertial rotational sensors they need to be referenced to location of installation as well as to a standard seismometer collocated with the ring laser. For this purpose we are generating a combined dataset which contains simultaneous observations of the rate of rotation (acceleration) from the ring laser and velocities (acceleration) from the seismometer along with tiltmeter measurements. The latter is necessary in order to monitor small changes in tilt of the ring laser plane relative to the local g-vector, because ring laser measurements are sensitive to variations in orientation. All observations must be precisely time stamped. For this purpose we have integrated a GPS clock module in the GEOSENSOR design. In the end it may be important to correlate the observations with measurements of atmospheric pressure and ambient temperature in order to understand and correct the GEOSENSOR output data. Therefore we are also recording this information along with the rest of the data.

2.3 Sagnac Frequency Determination

Unlike other ring lasers the GEOSENSOR will be operated in regions of high earthquake activity. This places high demands on the data acquisition concept for the ring laser component. We have to consider strong accelerations with a rate of change as high as 20 Hz. Tele-seismic waves in comparison have frequencies typically around 0.05 Hz. The sensor output of a ring laser is the beat frequency between two counter-rotating laser beams. This beat frequency is proportional to the rate of rotation of the instrument around the normal vector of the ring laser plane. The application of frequency counters and numerical frequency determination procedures are inadequate when the rate at which the measurement frequency changes is as high as 20 Hz.

![Figure 3: Demodulator power spectrum of the earthquake in northern France from 22.2.03.](image_url)
Therefore we have to take a totally different approach to this problem. From a more generalised viewpoint this measurement task is similar to the detection of frequency modulation. In the absence of an earthquake the G ring laser in Wetzel records a stable frequency of 348.6 Hz which is caused by earth rotation. When an earthquake happens additional rapidly changing rotation contributions are »modulated« to this earth rotation induced bias frequency. By phase locking a voltage controlled reference oscillator to this Sagnac frequency one can obtain the rate of change of the Sagnac frequency as a time varying voltage from the feedback loop of the phase locking circuit.

A sample unit of this fm-demodulator approach has been built and tested on the G ring laser in Wettzell. A recent earthquake (22 Feb. 2003) about 400 kilometers away from the observatory was successfully recorded on this unit. Figure 3 shows the spectrum of the recorded seismic signal. It contains frequency contributions of up to 4 Hz. We believe that this data acquisition approach is an important key technology for the GEOSENSOR project.

3. Summary

A ring laser gyroscope as a rotational sensor has great potential for applications in seismology. Due to the high sensitivity of the instrument and the insusceptibility to accelerations the application of this device in the field of seismology is promising. The GEOSENSOR project has the goal to demonstrate and investigate this capability. Until now we have completed the design of the ring laser component and the fabrication of the instrument has started. Various aspects of the data acquisition have been tested and verified. We expect the beginning of the sensor integration to commence over the second half of the year 2003.

The authors wish to thank G. Kronschnabl for the help in the construction of the fm-demodulator. We also acknowledge the funding through the BMBF Geotechnology programme.


The measurement concept of the planned satellite mission GOCE will enable a recovery of the detailed structures of the Earth’s gravity field, which are represented by a set of the order of fifty to one hundred thousand parameters. This large number of parameters must be derived from an even larger number of correlated observations. But only the fusion of various sensors and information guarantees an accurate solution over the whole spectral range. The derived geoid model will become known with an accuracy of better then 1cm on a global scale with shortest half wavelength of less than 100km.

Beside the huge numbers of parameters and observations, also physical conditions have to be taken into account. In particular, the design matrix is a dense matrix, because the mathematical representation of the Earth’s Gravity field has to fulfill the Laplace equation. In addition, all the measurements are correlated, due to the limited measurement bandwidth of the gradiometer. The measurements taken along a satellite’s track are not homogeneously distributed with respect to the spatial domain of the sphere. Therefore, the orthogonality properties of the base functions are lost and polar gaps bring about numerical instabilities. Because of all these circumstances the solution of this least squares problem turns out to be a pretentious task.

In the last decade, several approaches have been developed to handle this huge, ill-posed inverse problem. While the direct method individually processes the gravity field observations, the semi-analytic approach considers the observations along the orbit as an equispaced time series.

Semi-Analytic Approach – Quick-Look Tool
Assuming a circular, repeat orbit and a complete gridded series of measurements on the entire repeat cycle the inclination function can be used to transform the observation equations and to end up in a sparse block-diagonal normal equation system. Applying Fourier techniques to the time series opens a very efficient way to handle the correlations of the measurements in the frequency domain. Of course, these assumed restrictions can not be fulfilled by realistic mission scenarios, but the deviations can be incorporated into this approach by means of an iterative procedure approximately (cf. Preimesberger et. al. 2003). Simulations show that the results are accurate enough to use this very fast (solution time: few hours) technique as a quick-look tool, to immediately check (in time) the performance of the measurement system.

Direct Approach
In contrast to the semi-analytic approach, the direct approach individually processes the original measurements and sets up the strict observation equations. Signal processing tools allow the decorrelation of the observations and clear a path for the application of a least squares adjustment by direct or iterative techniques with sequential access to these observations. But nevertheless, this approach runs into severe problems, when the normal equation system is assembled. This huge and
dense equation system extends the capacity of today's computer systems. However there are two ways out of this dilemma. On the one hand iterative procedures can be adapted to avoid the assembling of the normal equations to solve this giant task directly from the observation equations, and on the other hand an ensemble of computers can be used to split up the computational and storage workload.

Iterative Solution Strategies – Tuning-Machine
As an iterative solution strategy the method of preconditioned conjugate gradients was identified to determine the potential coefficients of a realistic measurement scenario with perturbed orbits, satellite manoeuvres, calibration phases and measurement interruptions. Several mathematical and numerical tools are necessary to overcome some barriers underlying this task. The conjugate gradient procedure was adopted to avoid the explicit computation of the normal equation system of the SGG observations. To accelerate the convergence rate a block-diagonal preconditioner was introduced using the knowledge of the numerical behavior of regularly distributed data sets. Special numbering schemes render the possibility to efficiently merge dense low degree systems (e.g. SST-normal equation systems) with high degree SGG-systems. For the decorrelation of the measurement series linear discrete filters were incorporated. This opens a way to work out the series of millions of measurements step-by-step in a sequential approach. All these considerations are implemented in the program system pcgma (Preconditioned Conjugate Gradient Multiple Adjustment), which is able to process real mission data (cf. Schuh 1996).

The present-day implementation requires a computation time of some months to perform all the computations for an entire mission on a single processor. However, this algorithm works efficient on a parallel workstation cluster, where the solution time decreases linearly with respect to the involved processing units (cf. Schuh 2002, Plank 2002). In a next step, the implementation of this prototype is redesigned and each single procedure will be time-optimized. With tailored algorithms we are going to speed up the whole procedure. In our opinion a computation time of a few days on a appropriate workstation cluster is realistic to perform the adjustment of a six month measurement period. Therefore, this tool will be able to provide accurate results in a suitable time. The only shortage of this tailored approach is that it can not deliver, up to now, the full variance-covariance information. But new research studies using Monte-Carlo simulations (cf. Gundlisch et. al. 2003) are very promising in that this problem will be solved.

Because of its flexibility and speed, the iterative approach is very suitable as a tuning tool, which allows to verify and tune all involved components. This tool suits extremely well to optimize the filter coefficients and to prepare the field for the final »brute force« computation.

Brute Force Solution – Final Solver
This final task is really a giant one. At the first glance it sounds extremely well when we say, that this job can be done in real-time. This means that the measurement time of six months is equal to the computation time, if we involve a cluster of 60 computers into the computations. The assembling of the normal equation system forms the crucial point. On the one hand the extent of computations is enormous – a single CPU (3GHz) takes approximately nine years (cf. Boxhammer 2003) – and on the other hand the required memory of 30 GByte for the storage of one normal equation system allows no flexibility in handling different components or in analyzing individual mission phases. Therefore, the iterative tuning machine suggests itself.

At this time two solution strategies are proposed. The DNA approach of the Graz group (cf. Plank 2002) uses the memory of a workstation-cluster to store the normal equations in-core. The symmetric system is distributed over the whole cluster and each node works on a particular part of the normal equation system. Therefore, each node has to deal with
all the observations, but only a specific part of each observation equation is treated by this node. In opposite to this approach the DPA approach of the Bonn group (cf. Boxhammer 2003) divides the observations into groups and each node processes the full information of the observation equation. This approach uses out-of-core storage devices to handle the huge system. The space in the mainmemory is used to speed up the computation by applying block algorithms it is tried to incorporate as often as possible matrix-matrix operations, which are speeded up by optimized BLAS3 libraries. This approach guarantees to take full advantage of the architecture of the modern processing units. The high computation speed should compensate for the loss of time during the I/O operations.

In a joint effort both groups now try to combine their approaches to benefit from the advantages of both strategies. The goal of this joint project is to come up with an optimized solution strategy, which is able to analyze a real mission scenario within one month on an appropriate workstation cluster. This brute force approach should be used to perform the final solution and the variance-covariance information.

Closed Loop Simulations
The performance of all these approaches have been proofed by closed-loop simulations. These closed-loop simulations start from an a priori known gravity field parameterized by spherical harmonics (OSU91a) up to degree 180. Two data sets were deduced. The geoid heights on a regular grid (0.25x0.25 degrees) on the Earth’s surface (altitude zero) were computed as a reference field. The observation functionals (three main diagonal elements of the gradient tensor) were computed on a sun-synchronous repeat orbit of 29 days with an initial altitude of about 250km and an inclination of 96.6 degrees. The simulated measurements are regularly distributed along the orbit with a sampling interval of 5s. These measurements were superimposed by colored noise generated by an ARMA process which reflects the proposed spectral behavior of the gradiometer measurements. This results in more than 1.5 million observations containing information about the Earth’s gravity field up to degree and order 180. Using the different approaches the spherical harmonic coefficients were reconstructed and compared with the a priori known coefficients in two ways. First, the corresponding coefficients are directly compared, and second, the re-computed geoid heights are compared with the original ones. The second comparison is very sensitive to an energy shift between the spherical harmonic coefficients of different degrees because of the downward continuation and integration process. In Schuh et. al. 2001 and Plank 2002 these simulations with different approaches are compared and the results are summarized. After removing the global trend, which can not be estimated with high accuracy because of the weakness of the gradiometer for long wavelengths, all the comparisons end up with differences in the range of a few centimeters (mean: 2cm, max: 8cm). If the measurement period is expanded to six months and the combination of SST and SGG measurements is used to recover also the low wavelength part with high accuracy, these results are very promising in that the centimeter level can be reached.

Summary
With respect to our experience a three step approach, where
- the semi-analytic approach is used as a quick-look tool,
- the iterative technique as a tuning machine prepares the optimal parameterization, and
- the brute force direct solver works out the final solution
is recommended as the optimal procedure for the GOCE gravity field determination.
References


1. Introduction

Within the research project »Integration der geodätischen Raumverfahren und Aufbau eines Nutzerzentrums im Rahmen des Erdrotationsdienstes (IERS)« all components (Technique Centers, Product Centers, Combination Centers, Analysis Coordinator, Central Bureau) of the IERS are involved. The primary objectives of the International Earth rotation and Reference systems Service (IERS) are to serve the astronomical, geodetic and geophysical communities by providing terrestrial and celestial reference systems (and their realizations) as well as Earth orientation parameters, global geophysical fluids data and standards, constants and models. According to the Terms of Reference the Central Bureau (CB) is responsible for the general management and the coordination of the IERS.

The Central Bureau is responsible for the development of a modern information and database system, to maintain all the described tasks and to represent the work done within the IERS in an efficient way. Therefore, the CB will utilize the latest technology in Internet-based information exchange with open access to data files and employing security features as required today. The provision of the products will be made available through the internet, ftp or electronic mail to professional customers as well as to a broad scientific and non-scientific community. The close connection of all IERS components within the research project facilitates the formulation and testing of the structure, requirements, efficiency and reliability of the new system.

The focus of this paper is to present the concepts for a new dynamic and database-driven information system for the IERS. Its goal is to coordinate the data and information flow between the participating institutions. Therefore, all relevant data and products of the IERS should be archived to guarantee their long-term availability. Additionally, the meta-data-information of all products should be modelled in a database to allow the users to search for specific data with respect to space, time and contents. The system will be completed by several tools to manage and coordinate the tasks of the CB and by an information system with respect to IERS related topics.

2. Present Status of the IERS Information System

All products within the IERS are generated by an enormous investigation of human and financial resources. They are used by professional customers and should be available also to a broad scientific and non-scientific community. Presently the IERS information system provides information on all IERS products (e.g. ITRF, ICRF, EOPs, etc.) including links to the Product Centers where the respective data is available for download. To collect the data the user has to navigate through various Web pages where he is able to download the data in the provided (fixed) format that is not unique for all the data. To link related data to each other he has to take care about the various formats. In addition to the product information the system contains information with respect to the IERS.
publications, its structure and components as well as news and general information on Earth rotation and reference frames. All this information is stored in static Web pages and the same information can be found in different places. Thus, it is tedious to keep the information consistent, without redundancy and up to date.

The current information system should be replaced by a new system, that manages its information dynamically, i.e. all time dependent information as well as information that appear within multiple pages will be get from a database. Additionally, the new system should allow a more flexible navigation through the metadata-information related to the IERS products that will be stored within a file archive system inside the new database and information system.

3. A Dynamic Information and Database System

3.1 Requirements
The new IERS database and information system should provide an easy, uniform and central access to the distributed IERS products and the related data and information via the Internet. Therefor, standard procedures of information technologies to distribute the data automatically to professional costumers have to be provided as well as an easy to use and self explaining Web interface to browse through the products with respect to special user requests of the broad scientific and non-scientific community. Only server-side technologies should be used, so that the user needs no special programs or browser plug-ins. The user should be able to navigate through the data using simple or complex search functions with respect to space, time and content and he should be able to evaluate, visualize, connect and download the data. Therefore, clear defined standard formats are necessary in order to be able to model the metadata-information about all products within a database that is necessary to perform efficient user requests upon the data.

3.2 First Steps
Because of the increased number of institutions involved in the various components of the IERS the management and coordination of the data and information flow between these components takes a considerable amount of time. To perform these tasks the Central Bureau manages an address database with more than 2500 entries. It is used to generate e-mail exploders to distribute various information in the form of Newsletters, Technical Reports, Annual Reports, organization of workshops, IERS Messages, etc. The current database has several disadvantages with respect to its usability: It is platform dependent because of its realization within Microsoft Access; all data stored in one table that does not follow the so-called normal forms for database design, i.e. the database is redundant and thus it is difficult to keep the data consistent and in an actual stage; all Web pages of the IERS information system containing information related to the address of IERS components or members are independent of the address database, i.e. if an update is necessary all Web pages containing the respective information have to updated in addition to the address database.

To overcome these disadvantages the address database has to be re-designed in accordance with the normal forms of database design. This will allow an easy maintenance of its contents by avoiding redundant and inconsistent data. The gained experience in database design can be used to build the even more complex database tables which will store the product related information for the metadata-information system. The quality of the
design of these tables will be critical for the flexibility of the system, i.e. how easy the users can browse through the available metadata information. Additionally, the new database should be platform independent and its contents have to be accessible from the IERS Web server to be included dynamically into the Web pages of the information system to avoid redundant data within the database and the information system.

4. Concept of a new IERS Archive and Metadata-Information System

4.1 Development of the new IERS Archive System

The primary task of the new IERS database system is to archive all IERS products and all the data necessary to re-compute these products and to provide a user-friendly interface to answer special user request with respect to the available data. Thus, metadata-information about the products and data has to be extracted from the archived data. It will be stored in database tables that are modelled to reflect the structure of the represented data and the dependencies between them. This database system will be the core of the above mentioned new information system and will allow to build a modern dynamic system with an efficient, consistent and non redundant content base that can be kept up to date more easily.

![Diagram of Web request processing with and without PHP](http://www.onlamp.com/pub/a/php/2001/02/22/php_foundations.html)
4.2 Technical Aspects
As recommended within a concept paper for the efficient geodata management of the federal government all components of the new information and database system are based on open source software. The mentioned report was compiled by the IMAGI (»Interministerieller Ausschuss für Geoinformationswesen«) and can be found in the Web (http://www.imagi.de/Meues/GDI-DE/Konzeption_Geodatenmanagement_des_Bundes.pdf).

The information system will be run on an Apache Web Server, while the open source relational database management system PostgreSQL is going to be used to model and store the metadata-information on the products. The Web interface to access and browse these information will be realized in PHP, a widely-used general-purpose scripting language that is especially suited for Web development and can be embedded into HTML.

PHP is a server-side technology that allows to dynamically construct a Web page based on data gathered from a database. It is a hypertext preprocessor, i.e. a Web server with PHP installed that takes the extra step of allowing PHP to process the requested document before displaying it to the user. From this extra step PHP can then perform any operation including access the database, send e-mail messages, or open a connection to another internet service, e.g. a web mapping service. Figure 1 shows this process flow in comparison with static Web pages.

4.3 Data Modelling
The first step when building a database-driven Web site is to model the database tables that will store the data to be provided. This has been done for the tables to represent the address data as well as for that to represent the product data. The latter are based on a list compiled by the group of the IERS Analysis Coordinator. It describes all IERS products by the same keywords. This list with metadata-information on the products has been translated into new product information Web pages of the IERS information system by the Central Bureau (e.g. http://www.iers.org/iers/products/eop/rapid_eop.html). This work is a good example for the excellent and fruitful cooperation between the components within this research project. In the very same way the CB will transform the SINEX V2.0 format into a database design to store the information of a variety of IERS products. This format has been developed under the leadership of the IERS Analysis Coordinator in cooperation with the space geodetic technique services in order to extent the primarily GPS product related format to the products of all services. This is the basis to be able to represent all products in a consistent form within a product database.

4.4 Test Application
In order to use the product related metadata-information a Web interface has to be developed to access these information and the related data. Figure 2 shows an example for such an application. Here the EOP data from the IERS Bulletin A can be plotted, viewed or downloaded by the user with respect to a specific time range and data type.

5. Outlook - Realization of the System
The work described in the previous sections is the basis towards a new dynamic and database-driven information system that meets modern requirements of an user-friendly and efficient database and information system. The proposed concept has been proven by a test application and now the database design has to be extended to all IERS products and data and the Web interface has to be build to provide all required tools described in section 3.1. The new system will support the CB in his routine work (e.g. distributing information and data electronically). It will provide a modern Web service to answer requests on the information and data with respect to the fields of Earth rotation and reference systems to support scientific work as well as to bring these topics into the broad public.
Figure 2: Web interface to browse the contents of the IERS Bulletin A.
Global Gravity Field Recovery with CHAMP: Data Pre-processing and Modeling Results

With the launch of the German geoscientific satellite CHAMP on 15 July 2000, a new era in Earth gravity field recovery from space began. High-low satellite-to-satellite tracking (SST) using the American Global Positioning System (GPS) and on-board accelerometry combined with a low-altitude and almost polar orbit made CHAMP the first satellite being especially designed for long- to medium-wavelength global gravity field mapping.

For the first time a satellite in such a low altitude is equipped with a GPS receiver. The Turbo Rogue Space Receiver (TRSR-2) is provided by NASA and manufactured at NASA's Jet Propulsion Laboratories (JPL). The purpose of this instrument is to allow a recovery of CHAMP's trajectory with an uncertainty of only a few centimetres. The receiver acquires up to 12 GPS satellites simultaneously and measures dual-frequency carrier phases and pseudo-ranges at a rate of 10 s. Monitoring CHAMP's orbit by GPS allows the observation...
of gravity induced orbit perturbations which then are analysed to map the global structure of the Earth’s gravitational field (Figure 1).

Earth gravity field recovery from observed satellite orbit perturbations has been applied since the beginning of the space age in the late 1950s and evolved to long-wavelength gravity field models that today resolve spatial features in the gravity field with half wavelengths larger than 500 km at the Earth’s surface. The models that were generated prior to the launch of CHAMP exploited mainly ground-based camera, microwave and laser tracking data from some tens of satellites at different altitudes and orbit inclinations. With CHAMP it becomes for the first time possible to derive a global gravity field model from orbit perturbations gathered over a short time interval of a few months from one satellite only (Figure 2). Moreover, the resulting model is up to four times more accurate than what has been achieved with the earlier multi-satellite solutions and multi-year tracking records. Geodesy, Oceanography and Geophysics benefit from the advanced knowledge of the Earth’s gravity field.

The advantages of the CHAMP mission with respect to all former geodetic gravity missions are the following: (1) Orbit configuration – The effect of the attenuation of the gravitational signal with altitude is minimized due to the low orbit altitude, and there is no restriction in ground track coverage thanks to the almost polar orbit. (2) GPS receiver – The on-board GPS receiver allows continuous tracking by up to 12 GPS satellites simultaneously compared to one-dimensional ground-based tracking of only short orbit pieces during satellites passes. (3) Accelerometer – CHAMP experiences at its low altitude enhanced accelerations due to air drag. These non-gravitational orbit perturbations have to be accounted for when using the GPS observed overall orbit perturbations for gravity field recovery. The on-board three axes

Figure 2: Global gravity field model (Geoid) from a few months’ worth of CHAMP data only.
accelerometer, provided by the French space agency CNES and manufactured by the French company ONERA, directly measures the vector of non-gravitational accelerations, i.e. air drag plus direct and indirect solar radiation pressure. These measurements replace air density models that are of insufficient accuracy and temporal resolution. The orientation of the accelerometer’s axes is known from two star cameras.

The new CHAMP-based global gravity field models are called EIGEN (European Improved Gravity model of the Earth by New techniques) and are generated within the close German/French cooperation between GeoForschungs-Zentrum (GFZ) Potsdam and Groupe de Recherches de Geodésie Spatiale (GRGS) in Toulouse. The breakthrough in global gravity field recovery from space is already documented in the early mission models based on three months’ worth of CHAMP tracking data. These models exist in the CHAMP-only version EIGEN-1 (Reigber et al. 2003a, 2003b) and in a combination with tracking data from 25 other satellites, EIGEN-1S (Reigber et al. 2002). The exploitation of six months of CHAMP GPS-SST and accelerometry data and an improved processing led to the even more accurate second generation of a CHAMP model, the CHAMP-only solution EIGEN-2 (Reigber et al. 2003c). All models were made available to the scientific community via the CHAMP Information System and Data Centre (ISDC). Numerous posters and presentations at the 2003 EGU-AGU General Assembly in Nice, France, have proven the acceptance and widespread use of these new models, and of the CHAMP data in general, already having inspired new approaches in global gravity field recovery applying the law of energy conservation to CHAMP’s orbit.

The tremendous gain in accuracy in global gravity field recovery is best illustrated in Figure 3, giving the spectra of the geoid differences as a function of resolution for the CHAMP-only model EIGEN-2 and the pre-CHAMP model GRIM5-S1 (derived from multi-year tracking records of 25 satellites) with respect to the American model EGM96 which incorporates surface gravity data. The agreement of EGM96 with EIGEN-2 is five times better than with GRIM5-S1. From the differences of two inde-
pendent CHAMP subset solutions and the estimated EIGEN-2 error spectrum, also given in Figure 3, one can conclude that CHAMP provides the geoid with an accuracy of better than 10 cm at a resolution of 500 km half wavelength which is an improvement of one order of magnitude compared to the latest pre-CHAMP global gravity field model GRIM5-S1.

Recent developments within GFZ have led to CHAMP models incorporating more than one year of CHAMP data that creates now the basis for investigating seasonal gravity field variations due to hydrologic and oceanic mass redistributions.

The CHAMP-only models, being important in oceanography to derive the sea surface topography from satellite altimetry, are also going to be combined with high-resolution surface gravity data (altimetry over the oceans and gravimetry over the continents). A special combination method has been found in order not to deteriorate the long-wavelength part of the solution that is homogeneously and precisely determined by the CHAMP measurements. The preliminary combined solution, EIGEN-2Cp, was presented during the 2003 EGU-AGU General Assembly.

References

Combination of Earth Orientation Parameters from VLBI

Steinforth Ch., Fischer D., Nothnagel A.
Geodaetisches Institut der Universitaet Bonn, Nussallee 17, 53115 Bonn, Germany, E-Mail: nothnagel@uni-bonn.de

Same abstract as

Nothnagel A. et al. - Combination of Earth Monitoring Products by IERS Combination Research Centers; this volume.
1. Introduction
The Institute of Flight Guidance and Control (IFF) of the Technical University of Braunschweig (TU BS) participates in the joint research project »Entwicklung der Fluggravimetrie unter Nutzung von GNSS-Satellitenbeobachtungen« (»Development of airborne gravimetry including GNSS satellite observations«). The goal of this project is to develop an airborne gravimetry system which reaches the requirements of science as well as of industry in consideration of accuracy and operating efficiency. During the process of the project three different principles of airborne gravimeters will be compared. In detail this means a comparison between the development potentialities of stable platform gravimetry, strapdown gravimetry and a gravimetry system on the basis of individual parts. During the project phase it is planned to achieve an accuracy of 1mGal with a resolution of 1km.

Different flight tests will be executed with the research aircraft Dornier Do 128-6 owned by the Institute of Flight Guidance and Control (figure 1) in order to compare the abilities of the systems. The three gravimetry systems will be mounted onboard the aircraft.

2. Experiences of the Institute of Flight Guidance and Control
The IFF is involved in the development of airborne gravimetry since 1985. Fundamental examinations of airborne gravimeters were carried out between 1991 and 1993 within the framework of a DFG-funded project. In 1998 a high-precision two-frame inertial platform and a gravimeter sensor were purchased and modified for airborne application in cooperation with the Russian manufacturer ELEKTRO-PRIBOR (figure 1).

Figure 1: Research aircraft Dornier Do 128-6 and Gravimeter CHEKAN-A mounted onboard.
The principle of measurement of the gravimeter CHEKAN-A is based on torsion gravimeters developed by Threlfall and Pollock (Noergaard gravimeter, 1945). The sensor element consists of two torsion frames with pre-stressed quartz fibres, each of which holds a pendulum with a reflector. Because the two pendulums are distorted by 180 degrees the effect of cross-coupling is sufficiently compensated. The pendulum system is mounted in a reservoir which is thermostatically controlled and filled with a viscous fluid. The fluid attenuates high dynamic accelerations and isolates the system against thermal effects. The entire gravimeter sensor is mounted on the two-frame inertial platform.

Additional to the gravity sensor three accelerometers are mounted on the platform. Two of them are placed in the horizontal plane for levelling of the system, one is mounted along the vertical axis and aids the navigation solution. The gravimetry system is stabilized with an air bearing gyro.

Successful flight tests have been executed in the recent years. So far the resolution achieved is 2km with a standard deviation of 3mGal (figure 2).

3. The gravimetric system evolution

For correction of earth rotation rate, Eötvös accelerations and the relatively great drift of the stabilizing gyro (3°/h) the platform was controlled with an analogue SCHULER-control. This was sufficient for the original design as navigation system for submarines. For airborne applications this kind of control is not applicable due to the high in flight dynamics. Therefore a digital control was established which was extended by an additional degree of freedom around the vertical axis (yaw). This is done by a strapdown calculation in the on-board computer using an external rate sensor.

Until now the heading information was gained from a separate inertial navigation system which is part of the basic equipment of the aircraft. Henceforth the two-frame inertial platform was upgraded with a laser gyro to a three-frame INS. The gyro is mounted on top of the platform in order to complete a standalone gravimetric system.

In figure 3 the levelling control loop block diagram is shown. Outstanding is the control on basis of position information obtained from GPS and barometric altitude in contradiction to control on velocity which is normally used for levelling. The advantage of control on basis of position information compared to a velocity-based control is a dead time which is in the order of one magnitude smaller. Furthermore the position information is ascertainable from GPS with very high accuracy. Nevertheless the

![Figure 2: Measured gravity anomaly.](image-url)
demand for a very precise altitude information emerged from simulations and flight tests. The critical sensor is not the gravimeter itself but the altitude sensor. So far the altitude information is obtained from the GPS-signal on a carrier phase basis.

In order to improve accuracy and resolution of the altitude information the IFF examines a complementary filtering of GPS and high precision barometric measurements. To increase the resolution of barometric altitude determination a differential principle is investigated.

Another item to be evaluated is the calibration of the system parameters in real time. Based on analysis of the technical construction of the sensors a nonlinear structure for the dynamic model is expected which can be parameterised. The parameters are estimated with respect to the constructive circumstances and evaluated by means of sophisticated parameter identification methods with both static and flight tests.

4. References


[10] Hammada, Y., Schwarz, K. P.: Airborne Gravimetry Model-Based versus Frequency-
Domain Filtering Approaches. KIS97. Banff, Canada, June 3-4, 1997


169
Abstract
Purely kinematic and dynamic approaches for precise orbit determination (POD) of Low Earth Orbiting (LEO) satellites were developed based on spaceborne GPS measurements and zero- and double-differencing with or without ambiguity resolution. Here, we present results for two LEO satellites, CHAMP and JASON-1, that orbit the Earth at very different altitudes, namely 410 km in the case of CHAMP and 1335 km in the case of JASON-1. In order to provide CHAMP kinematic orbits over a long time span for the various groups that perform gravity field determination, results of the CHAMP kinematic and reduced-dynamic orbit determination are presented for the period of one year (day 70/2002-70/2003).

We show that the kinematic orbit of a LEO satellite can be determined with an accuracy of 1-3 cm based only on the GPS phase measurements without using any information on satellite dynamics.

The quality of the kinematic orbits were assessed by comparing kinematic and reduced-dynamic orbits and by independent checks with SLR measurements. This shows that kinematic orbits with an accuracy comparable to the reduced-dynamic orbits can be achieved.

Kinematic orbit determination is based only on the GPS measurements and thus independent of the orbit height and orbital dynamics, e.g., gravity field, air-drag, solar radiation pressure. Therefore, kinematic POD is very appropriate as a POD strategy for any satellite, i.e. also for the forthcoming gradiometry GOCE mission, where drag-free control is applied in order to eliminate the large air-drag force (orbit height ≈ 250 km).

Due to the very low orbit of only 410 km, the CHAMP satellite experiences high perturbations due to the gravitational field of the Earth and air-drag. In contrast, JASON-1 at 1335 km is less sensitive to the gravity field and non-conservative forces like air-drag.

Due to the better performances of the CHAMP GPS receiver, kinematic and reduced-dynamic orbits of CHAMP satellite are at the moment more accurate than JASON-1 orbits (L2-ramps, phase breaks, multipath, number of GPS satellites tracked).

Introduction
CHAllenging Minisatellite Payload (CHAMP) was launched into a near polar LEO orbit (orbit height 410 km, inclination 87.227°) on 15 July 2000. The mission is, besides magnetic field determination and atmosphere sounding, primarily dedicated to gravity field determination. This very successful mission already provided new information about the Earth’s gravity and magnetic fields.
Designed as the follow-on mission of Topex/Poseidon, JASON-1 is an altimetry satellite launched at December 7, 2001 and has been successfully placed in a circular orbit of 1335 km (inclination 66.039°) around the Earth. The scientific objectives of the JASON-1 mission includes oceanography and ocean forecasting, climatology and climate prediction (El Niño), marine meteorology and geophysics. Both satellites, CHAMP and JASON-1, are equipped with a GPS receiver and a reflector for Satellite Laser Ranging (SLR). Like its predecessor, the JASON-1 satellite also carries the CNES Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system.

The Gravity Field and Steady-State Ocean Circulation Mission (GOCE) is going to be launched in the year 2006 in a very low orbit. The primary aim of the ESA GOCE Mission is to provide a unique model of the Earth’s gravity field and of its equipotential reference surface, as represented by the geoid, on a global scale with high spatial resolution and highest accuracy so far. Such an advance in the knowledge of the Earth’s gravity field and its geoid, together with the results from the CHAMP and GRACE missions, will help to develop a much deeper understanding of the processes in the Earth system.

GPS-Based Precise Orbit Determination of LEO Satellites

Dynamic orbit determination is based on the integration of the equation of motion using dynamical force models. Since the dynamic approach heavily depends on the quality of the force models involved, e.g. the gravity field, air-drag, or/and the quality of the non-gravitational accelerations measured by spaceborne accelerometers (as in the case of CHAMP), so-called empirical accelerations or pseudo-stochastic pulses are usually introduced because of the deficiencies in the dynamic models leading to so-called reduced-dynamic approaches. Dynamic POD can be performed by means of all satellite techniques (GPS, SLR, DORIS, etc.)

On the other hand, kinematic orbit determination is independent of satellite dynamics. It can only reasonably be performed by the GPS. In kinematic POD, the orbit is represented by a series of satellite positions estimated using the GPS measurements. Therefore, kinematic POD is very appropriate for any LEO orbits. Whereas – due to the equation of motion – a dynamic (or reduced-dynamic) orbit can be computed at any epoch of interest, kinematic POD provides satellite positions only at epochs, where GPS measurements were taken, e.g. at intervals of 30s or 10s (although, in principal, a sampling of the GPS receiver of 10-100Hz is possible).

By forming the ionosphere-free linear combination of the GPS L1 and L2 phase measurements, the effect of the ionosphere is eliminated and orbit determination can be carried out using undifferenced or so-called zero-difference phase measurements only. In the zero-difference case, GPS orbits and GPS satellite clocks are kept fixed and epoch-wise LEO GPS receiver clock parameters are estimated either with epoch-wise kinematic positions in the kinematic, or with dynamical orbital parameters in the dynamic approach. Since only phase GPS measurements are used, more than 400 zero-difference ambiguities are additional parameters for a 1-day orbit arc. In the double-difference approach, baselines between GPS measurements of a ground station and the LEO are formed and all clock parameters are thus eliminated. The main advantage of kinematic or reduced-dynamic POD based on double-differences is the possibility to resolve ambiguities to their integer values using ambiguity resolution strategies and thereby gain in accuracy. On the other hand, orbit determination based on zero-differences is a very fast and efficient approach, because only measurements between the LEO and the GPS satellites are involved and therefore, the processing of a ground IGS network is only required in a preceding, independent step in order to obtain GPS satellite orbits and clocks.
More details about zero- and double-difference approaches for kinematic and reduced-dynamic orbit determination with ambiguity resolution can be found in (Svehla and Rothacher 2002), (Svehla and Rothacher 2003a), (Svehla and Rothacher 2003b) and (Svehla and Rothacher 2003c).

**Precise Orbit Determination for CHAMP and JASON-1 Satellite**

As an example of the orbit quality achieved, namely 1-2 cm, Figure 1 shows the difference between the CHAMP kinematic and reduced-dynamic orbits for day 200/2002. One can immediately notice once-per-revolution signals in the along track component that are most probably due to air-drag modeling deficiencies in the reduced-dynamic POD. Kinematic POD can thus be used to identify orbit modeling problems. Based on Figure 1, we can also draw the conclusion that the radial component in kinematic POD is more sensitive to the number of GPS satellites tracked than the along- or cross-track component. This can be confirmed by variance-covariance analyses and the processing of simulated data (see, Svehla and Rothacher, 2003b).

Figure 1: Differences between CHAMP kinematic and reduced-dynamic orbit for day 200/2002.
Figure 1: RMS and bias of daily SLR residuals for CHAMP kinematic orbit, days 195-202/2002.

Figure 2: JASON-1 phase breaks over 8 days (195-202/2002).

Figure 3: RMS and bias of daily SLR residuals for CHAMP kinematic orbit, days 195-202/2002.
The main disadvantage of the kinematic POD compared to classical dynamic approaches is, that long continuous pieces of phase measurements are essential for the accuracy, because phase breaks or gaps in the data lead to jumps in the kinematic position series (as e.g. at around 23h in Figure 1). Looking at Figure 2, showing the data gaps in the JASON-1 GPS measurements, it is clear, that JASON-1 kinematic orbits cannot be expected to be at the astonishing level of the CHAMP results.

An independent validation of kinematic and reduced-dynamic orbits was performed with SLR measurements. Exact coordinates and velocities for the SLR stations were obtained from the International Laser Ranging Service (ILRS). To be as consistent as possible, the same reference frame, i.e. ITRF 2000, was used for both, POD and the SLR validation. Troposphere effects were modeled using the Marini-Murray model and standard corrections like ocean loading, Shapiro effect, and station velocities were applied. All SLR station and all SLR measurements were used in the orbit validation (cut-off elevation 10°).

Figures 3 and 4 summarize the validation results and demonstrate that both, the kinematic and reduced-dynamic CHAMP orbits have a very similar accuracy of about 2 cm with no significant bias.
References


Svehla D., M. Rothacher, CHAMP double-difference kinematic orbit with ambiguity resolution. First CHAMP Science Meeting, Potsdam, Germany. First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, Reigber Ch., Lühr H., Schwintzer P. (Eds), Springer-Verlag pp. 70-77, 2003.


1. Introduction
The space geodetic techniques VLBI (= Very Long Baseline Interferometry), GPS (= Global Positioning System), SLR (= Satellite Laser Ranging) and DORIS (= Doppler Orbitography and Radiopositioning Integrated by Satellite) offer the possibility to measure the orientation of the Earth in space, i.e. the nutation angles, as well as the daily rotation of the Earth, i.e. Universal Time, and the x- and y-pole coordinates describing the location of the rotation axis with respect to an Earth-fixed reference frame which is given by coordinates of the observing stations. And, of course, the variations in time of all the parameters mentioned before can be observed as well. But not every technique can determine all of these parameters with the same quality and certain techniques may not be able to determine some of them at all. Therefore it is necessary to combine the results of all techniques using the strength of each of them to compensate the weaknesses of others. Such a combination is already done within the International Earth Rotation Service (= IERS) for a terrestrial reference frame called ITRF (= International Terrestrial Reference Frame) and for the Earth orientation parameter (pole coordinates, UT1-UTC, nutation and their rates), but at the moment both combinations are done completely independently. Therefore the existing combined products are not fully consistent, and several studies are in progress to derive methods for consistent terrestrial reference frame and Earth orientation parameters (EOP), that are computed together from the space geodetic techniques.

2. IERS SINEX Combination Campaign
This presentation will deal with the contribution of FESG to the »IERS SINEX Combination Campaign« that was started in May 2002 as one step toward more consistent products. The campaign itself is divided into two parts: Analysis Centres of all space geodetic techniques produced weekly, monthly or daily solutions for the whole year 1999 including at least station coordinates and Earth rotation parameters (ERPs), and delivered them in SINEX format to the SINEX Data Pool that was built up for this campaign and is maintained at the FESG. In the second part of this campaign, institutions that are interested in combination studies, especially the IERS Combination Research Centres (CRCs), can take these SINEX files from the first part of the campaign and start their combination studies.

3. Comparison and Combination Studies at FESG
At FESG, one of the CRCs, we selected the following SINEX series for our combination studies:  - session (= daily) VLBI files from DGFI (= Deutsches Geodätisches Forschungsinstitut),  - weekly GPS files from CODE (= Center for Orbit Determination in Europe),  - weekly SLR files from ASI (= Agenzia Spaziale Italiana).
All three series contain station coordinates, pole coordinates and UT1-UTC. In addition, the VLBI solutions contain the two nutation angles and the GPS and SLR solutions contain the rates for the pole coordinates and LOD (= Length of Day, rate UT1-UTC). The station

Comparison and Combination of GPS, VLBI and SLR Solution Series

Thaller D., Rothacher M.
Forschungseinrichtung Satellitengeodaesie (FESG), Technische Universitaet Muenchen, Arcisstrasse 21, 80290 Muenchen, Germany, E-Mail: daniela.thaller@bv.tum.de
coordinates are given as one set per solution (i.e. per week or per day) whereas one set of ERPs per day is included in the solutions. For all solutions, the complete variance-covariance information or directly the free normal equations (only for VLBI solutions) are given in the SINEX files, including the apriori values and the statistical information. Therefore, the free reduced normal equation system can be recovered and then used for the combination.

But before an inter-technique combination can be done, the solution series themselves must be tested separately. Different sorts of tests were performed for each solution series:

For the VLBI solutions we tried to reproduce the EOP results from the »IERS Analysis Campaign to Align EOPs to ITRF 2000/ICRF« to see whether we are able to exactly reproduce this ITRF 2000-fixed solution independently. The comparison showed differences smaller than 0.01 mas (and the equivalent for UT) and therefore this reproduction can be judged as successful. For the SLR and GPS solutions we made another test. Both solution series must have three rotational degrees of freedom. Therefore solutions with coordinates fixed on a network that was rotated w.r.t. ITRF2000 were computed. As expected for solutions with rotational degrees of freedom, these rotations that were applied to the coordinate set can be seen with opposite sign in the estimated ERPs.

As next step, one-year combinations for each series were computed to get access to the quality and to derive weighting factors for the inter-technique combination later on. We used different methods for defining the reference frame:

- »fixing« the coordinates of the selected stations with _ = 0.00001 m,
- constraining the coordinates with _ = 0.01 m for VLBI and SLR and _ = 0.001 m for GPS respectively,
- apply so-called minimum constraints, i.e., no-net-rotation conditions for GPS and SLR with _ = 0.001 m and no-net-rotation plus no-net-translation conditions for VLBI (_ = 0.001 m).

At this stage, a set of »good« stations was selected in an iterative process. That set was then used for the definition of the reference frame: If the a posteriori RMS for one component of a station’s coordinates was larger than three times the repeatability for the entire series, this station was excluded in all other solutions. The repeatabilities were derived from a 7-parameter Helmert transformation (3 translations, 3 rotations, scale) between each single solution (week or session) and the one-year combination using all stations. For the minimum constraints solutions the repeatabilities look as follows (see table 1):

<table>
<thead>
<tr>
<th></th>
<th>ASI (SLR)</th>
<th>CODE (GPS)</th>
<th>DGFI (VLBI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>20,39</td>
<td>2,60</td>
<td>3,80</td>
</tr>
<tr>
<td>East</td>
<td>19,84</td>
<td>3,41</td>
<td>3,87</td>
</tr>
<tr>
<td>Up</td>
<td>21,09</td>
<td>8,48</td>
<td>8,33</td>
</tr>
</tbody>
</table>

Table 1: Repeatabilities for station coordinates.
It is typical for GPS that the horizontal components are about three times better than the height component. A similar phenomena can be seen for the VLBI solutions but not as pronounced. Both solution series (CODE and DGFI) have a comparable quality regarding the repeatabilities, whereas the SLR solution series is not as good. For SLR there are no differences between the three components.

Looking at the other parameter types that are included in the solution series – the Earth rotation parameters – interesting effects can be seen. The ERP series that were obtained from the single solutions were compared to official ERP series (like C04 or Bulletin A). For the GPS and SLR solutions it is clearly visible that UT cannot be determined very well by satellite techniques because even if the first UT value was kept fixed, the other values for the week are drifting away because of satellite orbit modeling problems. Regarding the two pole coordinates, all three solution series show an offset compared to C04, especially for the y-pole (see figure 1).

The mean offsets derived from minimum constrained solutions over one year are:

- for the x-pole: 0.036 mas (DGFI, VLBI)
- -0.100 mas (CODE, GPS)
- -0.062 mas (ASI, SLR)

- for the y-pole: 0.206 mas (DGFI, VLBI)
- 0.209 mas (CODE, GPS)
- 0.217 mas (ASI, SLR)

It is astonishing that the offset for the y-pole are quite big but the results for the GPS and the VLBI solutions are nearly identical. It must be mentioned that the scatter of the values is much smaller for the GPS solutions than for the two other series: 0.17 mas for GPS compared to 0.32 mas and 0.73 mas for VLBI and SLR, respectively (for the x-pole). In addition, it seems that the estimated ERPs depend on how

---

**Figure 1:** Differences to C04 for minimum constraints solutions.
the datum definition is realised, especially for the GPS solutions, because differences in the mean offsets of about 0.1 mas (for CODE GPS) can be seen between the solution with station coordinates fixed on ITRF2000 values and solutions with other realisations of the reference frame, e.g., only small constraints on coordinates or minimum constraints.

Another topic that can be studied at the level of each technique is the evolution in time of the station coordinates. A time series of station coordinates can be obtained from the single solutions (weekly or session) and one set of coordinates + velocities for each station was estimated in the one-year combination. These two results can be compared with the ITRF2000 values that were used as apriori. It is obvious that only stations that are included in most of the single solutions are interesting for such a study because only then the estimated velocities are reasonable. Another criteria for the selection of stations to be studied in more detail is the colocation with other techniques, i.e., the availability in at least two solution series. But the problem with colocations is that there are only a few sites with VLBI and SLR together whereas the connection with GPS is much better. One station that contributes to all three techniques and is included in the three solution series is Wettzell. A time series of Wettzell’s station coordinates can be seen in figure 2.

It is obvious that such colocation stations like Wettzell are of high interest for a combination of the techniques because the so-called local ties between the reference points of each technique at one station can be used as connection between the technique solutions. Normally, these local ties are obtained from terrestrial measurements at the stations, but the problem is, that good local ties do not exist for all stations or there is even no information about the ties available. Therefore, the local tie information is not yet used in our combination so

Figure 2: Time series of station coordinates of Wettzell (compared to the one-year combination).
that the connection between the techniques is done only through the ERPs at the moment. For the combination we change to an ERP parameterization with offsets only, equally distributed over time (one per day), with a piece-wise linear representation of the ERPs (but without rates). Each set of offset + rate in the single solutions are mapped to the two offsets at the interval boundaries of the piece-wise linear representation. Then the single solutions can be stacked together.

In a first step the inter-technique combination was done for each week including the appropriate VLBI sessions. Besides of scaling problems for the normal equations the combination for the x-pole seems to be more problematic than for the y-pole. The reason for large residuals in the pole is in most cases a single VLBI session, e.g., a solution with only a few stations or the solutions from European sessions because then the coverage of the Earth is very bad to determine the rotation axis. Figure 3 shows the results for the combined pole compared to the single solutions. It can be seen that the big scattering, especially of the SLR solutions, is compensated in the combination. The combination for UT is more problematic because, as already mentioned, the satellite techniques are not able to determine UT but only the time derivative. VLBI is the only technique that delivers the information about UT and, therefore, the estimated values for the combination are good if at least one VLBI session contributes to it but for all other epochs the results for UT are drifting away if they are not constrained.

4. Conclusions
The study of the one-year combinations for each solution series showed interesting differences between the three techniques that are important for the inter-technique combination. The combination results for the pole coordinates already works whereas the combination for UT and respectively LOD still needs further investigations. Another topic to study will be the inclusion of the local tie information if it is available because then the combination can be done as well via the colocation stations and not only by the ERPs.
Abstract
Gravity estimates directly obtained from the new satellite missions CHAMP, GRACE, and GOCE are restricted concerning resolution in time as well as in space, and these missions will alias non-resolved oceanic motion. By means of numerical oceanographic models it could be shown that the ocean affects the recovery of the gravity field on subdaily up to seasonal time scales (c.f., Wahr et al. [1998], Wünsch et al. [2001]). Thus, the application of models is required to perform the necessary corrections of the satellite derived gravity field by eliminating high-frequency effects. To estimate ocean induced gravity anomalies, which manifest in time variable bottom pressure fields, numerical simulations of the transient physical state of the ocean with global ocean circulation and ocean tide models are performed during the satellite missions CHAMP, GRACE, and GOCE.

Introduction
Mass redistributions within and mass exchanges between the subsystems of the Earth are reflected by variations of global parameters of the Earth, e.g., the Earth’s shape, rotational parameters, and the Earth’s gravity field. Thus, in principle, high accuracy determinations of sea surface heights and of the gravity field by the new satellite missions as well as observations of rotational variations can be used to measure geophysical aspects of global change. However, interpretation of geodetic observations, i.e., attribution of specific dynamical processes in the subsystems to variation pattern of the Earth’s parameters, requires incorporation of additional methods from theory and modelling and presupposes an adequate elimination of non-resolved geophysical processes aliasing the missions.

Applied numerical models
The impact of various components of transient ocean dynamics on the time variable Earth’s gravity field is estimated by means of numerical simulations with two types of models: a global, three-dimensional, baroclinic, coupled model for circulation and tides and a global, vertically integrated, barotropic tidal model with data assimilation.

The first model is the Hamburg Ocean Model for Circulation and Tides (OMCT), which already proved successful in many interdisciplinary applications [Thomas et al., 2001; Wünsch et al., 2001; Thomas, 2002]. It was developed by coupling the Hamburg Ocean Primitive Equation Model (HOPE, Version C) of the Max-Planck-Institut für Meteorologie with an ephemeral tidal model, including a thermodynamic, prognostic sea-ice model. Higher order effects such as nonlinearities are accounted for as well as the secondary potential due to loading and self-attraction (LSA) of the water masses. Since the OMCT dispenses with the conventional separation of circulation and tides in global models and, consequently, allows a simultaneous consideration of the main components of motion of the world ocean, for the first time a realistic numerical description of the actual, instantaneous dynamics in the ocean is possible. In the present
configuration, the model uses a timestep of 30 minutes, a horizontal resolution of 1.875° and 13 layers in the vertical. The model is driven by time varying wind stress fields, atmospheric pressure anomalies at the sea-surface as well as heat and freshwater fluxes. From the hydrographic variables temperature, salinity, density and sea-surface height, the model generates three-dimensional distributions of currents and mass with a resolution of 30 minutes. Mass and current distributions are used for routine calculations of bottom pressure (e.g., as coefficients of an expansion into spherical harmonics) and integral quantities such as angular momentum, the components of the tensor of inertia, the coordinates of the center of mass and ocean induced variations of the Earth’s rotation.

The second model concerns the global Hamburg tidal model [Zahel, 1995, 1997; Zahel et al., 2000]. This model includes the full loading and self-attraction effects (LSA), and as a free model, i.e., when being operated without the variational data assimilation procedure, it also includes the nonlinear shallow water effects. The global Hamburg tidal model has been applied with and without data assimilation to the computation of the most important semidiurnal and diurnal tidal fields, using a spatial resolution of 0.5°. When making use of the variational data assimilation procedure with the tidal dynamics as weak constraints, a computational expense is required which exceeds that of the corresponding free model by approximately two orders of magnitude. With the computational facilities presently available, a refinement of the horizontal resolution up to 1/12° can be realized. This degree of resolution, which corresponds to the maximum accuracy of the available bottom topography, can also be realized for the model with variational data assimilation, when this maximum degree of resolution is adequately restricted to the shelf regions. The model yields the tidal fields of pressure and motion and quantities derived from these fields, e.g., loading gravity fields and earth rotation parameters. On the other hand, data of all quantities being uniquely determined by the model variables can be assimilated into the model.

An essential step towards realizing a high resolution global tidal model for computing the tide-generated mass redistribution for given time periods has recently been done by developing and applying variational data assimilation approaches allowing to properly take into account nonlinear shallow water tides. According to their specific properties, which have intensively been studied in realistic scenarios, the three methods made available are ready to be used for fulfilling the requirements in question [Taguchi, 2002]. Each of the methods guarantees that the assimilation of measured quantities, being uniquely determined by the model variables, very efficiently contributes to improving the computed tidal fields and the geophysical fields and quantities essentially affected by them. The computational expense required for applying these methods in realistic data assimilation scenarios strongly depends on which method is used, and this also applies to the power of extracting information on the model physics from the respective data induced dynamical residuals. In any case, the high resolution global tidal model can be provided with model components considering shallow water effects and data essentially determined by such effects. For obtaining highly realistic minor tidal constituents, nevertheless noticeably contributing to the full tidal signal in the ocean, the frequency dependent response of the barotropic ocean to external forces is estimated by means of the free oscillations of the global ocean. For this purpose the complete set of global damped free oscillations has been computed in terms of the fields of sea surface elevation and barotropic currents. The set is at present available for the time interval between 6 and 80 hours. These oscillations clearly reveal the extended oceanic areas showing quasi-resonant response to specific astronomical tidal constituents according to the excitation period and spatial dependence. Data of the correspondent oceanic tidal constituent may be used to also
detect deficiencies of the free oscillation model and by this to improve determining the response behaviour of the ocean.

**First results**

With the OMCT five model runs covering a time interval of 45 years with different forcing conditions were performed in order to separate gravity anomalies caused by ocean tides, thermohaline, wind- and pressure driven circulation, so-called secondary effects arising from nonlinearities between circulation and tides and from loading and self-attraction of a baroclinic water column. The resulting bottom pressure fields were expanded in time-dependent gravity field spherical harmonic coefficients and transformed to variations in geoid heights.

In Figure 1, a snapshot of anomalies in geoid heights is given resulting from a model run of the general oceanic circulation, including the contributions of the thermohaline, wind- and pressure driven circulation as well as the effects arising from loading and self-attraction. Typically, circulation-induced geoid height varies in the range –5 to +5mm. Slightly prevailing positive anomalies in Figure 1 have to be attributed to seasonal effects in the context of asymmetrical land-sea-distributions on both hemispheres.

The effects of LSA are generally accounted for in global tidal models, but have been neglected in global general circulation models, so far. From Figure 1 the contribution to geoid height anomalies were extracted arising solely from LSA (Figure 2). In general, LSA-induced anomalies are one order of magnitude smaller than those caused by the general circulation and lead to a slight elliptical enhancement.

**Further work**

At the moment, numerical simulations of actual periods with atmospheric forcing fields provided by the European Center for Medium-range Weather Forecast (ECMWF) are prepared. The corresponding time-dependent gravity field spherical harmonic coefficients that are relevant for processing data from the satellite missions will be made accessible. In addition to a separation of relevant causative physical processes the bottom pressure fields are to be analysed in order to get insight in typical spatiotemporal patterns of oceanic mass redistributions and consequently to identify oceanic regions of high impact on gravity changes. When geodetic measurements and model data will have been mutually corrected and validated, the combination of both self-contained methods, remote sensing and numerical modelling, will allow a comprehensive interpretation of gravity as well as altimetric data with respect to ab-solute ocean currents, heat transport and storage, and other questions in the context of global change.

**References**


Figure 1: Total circulation-induced anomalies in geoid height in [mm] on 1st September 1985.

Figure 2: Anomalies in geoid height in \(10^{-1}\) [mm] caused by loading and self-attraction (1st September 1985).
1. Introduction
The new gravity field satellite mission GOCE is expected to deliver a gravity field model with very high accuracy and resolution. However, the huge amount of measurement data as well as the large number of unknowns are posing new challenges in terms of computing strategies. As an alternative to a direct solution which solves a least squares adjustment with approx. 6 million observations and 90,000 unknowns (for a maximum spherical harmonic degree 300), the semi-analytical approach has been developed. There some simplifying assumptions are introduced, so that FFT-techniques can be used, to process the large amount of data. The resulting system of normal equations is block-diagonal, which speeds up the whole process enormously. The errors caused by the simplifying assumptions can be overcome by iteration.

The whole concept of semi-analytic gravity field solution is based on a linear relationship between the measurable satellite gravity quantities and the so-called »Lumped Coefficients«. In the case of GOCE there are gravity gradiometer and orbit perturbations or disturbance potential data, derived from SST. The Lumped Coefficients, in turn, are a linear combination of the spherical harmonic potential coefficients. The latter are estimated from the Lumped Coefficients in a block wise least squares adjustment according to the spherical harmonic order \( m \). Two different semi-analytic solution strategies (1D-FFT and 2D-FFT) have been implemented and tested. For the 1D-FFT method a repeat orbit is necessary. The 1D GOCE measurement time series is Fourier-transformed, and the coefficients are mapped on the Lumped Coefficients by spectral projection. For the 2D-FFT, the observations are projected on a regular torus-grid in orbit co-ordinates at constant orbit height and inclination. The Lumped Coefficients are simply obtained by a 2D-FFT of the torus-grid values.

2. Quicklook Gravity-Field-Analysis Tool
The semi-analytical approach will be used as Quicklook Gravity-Field-Analysis Tool. It serves mission performance diagnosis in almost real time. It is possible to compute gravity field solutions from partial datasets, with short latency, and use it for an analysis of gradiometer measurement noise, drag-free-control behaviour and other critical mission parameters. This tool is developed in close cooperation with TU Graz in the frame of European co-operation.

Partial data sets will be complemented by simulated data from a priori gravity models. The data is transformed to the spectral domain, where filtering is applied, and potential coefficients are estimated. Based on the resulting residuals, better assumptions on the coloured measurement noise can be made, and thus the used filters be adapted. Drag-free-control deficiencies can be detected from deviations in an SST- or combined solution, and monitored back to Level 0 to 1B processing or mission control.
3. Case Studies
Several case studies have been carried out mainly for SGG observations. As test data several realistic mission scenarios were used. They were generated with an orbit integrator which was developed at IAPG.
- Proof of Concept: A »perfect« mission scenario with repeat-orbit, no measurement errors and no data gaps produces "perfect" results.
- Realistic Scenario: A mission scenario with realistic non-repeat orbit, coloured measurement noise and data gaps produces results which still meet the accuracy requirements, and deviations from periodicity can be overcome by iteration (cf. figure 2).
- Comparison of 1D-FFT and 2D-FFT method: A comparison of the two methods shows, that both have advantages and drawbacks. While the 2D-FFT method is less sensitive to deviations from periodicity, filtering works better for the 1D-FFT method.
- The combination of 4 gradiometry components and SST-energy integral observations shows the contribution of each of the observables. While using the zz-gradiometer component only results in an ill-posed problem, the inclusion of the xx- and yy-components introduce stability to the system. The inclusion of SST-data improves especially the low-frequent terms.
- Comparison of semi-analytical approach with direct GFA on real CHAMP-SST data. This case study shows, that the results of the semi-analytical approach are competitive for real data at least up to degree 120.
Figure 2: Degree RMS of the differences between the a
priori and the resulting gravity model, for an iterative
solution of a realistic simulation of SGG-measurements.
Abstract
Motivated by the first gradiometer satellite mission GOCE (Gravity Field and Steady State Ocean Circulation Explorer), a possible concept for an external calibration procedure has been developed. In this concept, the gradients predicted from terrestrial data are used for the calibration of the observed gradients. In the present study, the three in-line gravitational gradients of the disturbing potential \( T \), i.e., \( T_{xx} \), \( T_{yy} \), and \( T_{zz} \), are considered. A test with simulated gravity anomalies from EGM96 is carried out. The simulated anomalies are upward continued using least-squares collocation, followed by a comparison of the predicted gradients with the values computed directly from the EGM96 model. The main purpose of this study is to check the algorithm and computer programs and to get an idea on the signal contents at higher spherical harmonic degrees. The necessary covariances, the formal prediction errors and the differences between the predicted and directly computed gradients are discussed.

1. Introduction
The objective of the gradiometer satellite mission GOCE (in preparation for launch in 2006) is the determination of the Earth’s gravitational field up to a spherical harmonic degree of about 270. The lower degrees are determined by satellite-to-satellite tracking using GPS, while the higher degrees (above degree 20) are mainly derived from the gradiometer observations. The gradiometer comprises six accelerometers in a diamond configuration. Taking centrifugal forces into account, gravitational gradients (i.e., second derivatives of the gravitational potential) can be derived from the acceleration differences between the accelerometers. The gradient tensor for the disturbing potential \( T \) reads:

\[
\text{grad}\left(\text{grad}(T)\right) = \begin{bmatrix}
T_{xx} & T_{xy} & T_{xz} \\
T_{yx} & T_{yy} & T_{yz} \\
T_{zx} & T_{zy} & T_{zz}
\end{bmatrix}
\] (1)

To reduce systematic errors, the gradiometer has to be calibrated both on ground and in orbit. In order to meet the strong accuracy requirements for the gradients (about 1 mE in the measurement bandwidth of 5 up to 100 mHz), external gravity information can be introduced for the calibration. In this contribution, the prediction of gravitational gradients from terrestrial gravity data (i.e., simulated gravity anomalies from EGM96) by least-squares collocation is discussed. These gradients then serve as external input for the calibration of the GOCE gradients.

In the next section, the general concept of the calibration procedure with external data is described, while in the third section the results from the simulation study are explained.

2. Concept of the calibration with external data
The calibration procedure is divided into two steps:
I) upward continuation of the terrestrial data, and
II) comparison with the GOCE gradient observations.

The general procedure is outlined in Figure 1.
The predicted gradients are given in a local geographical reference frame (x: East, y: North, and z: Up direction). The observed gradients, however, are provided in a local orbital reference frame (LORF). Therefore, a rotation of the predicted full tensor and its covariance matrix is necessary between the first and second step in order to compare the predicted gradients with the GOCE gradients in the LORF. However, this paper deals only with the first step, the upward continuation.

To check the consistency of the algorithm in a first numerical test, gravity anomalies (computed from the EGM96 model on a sphere with radius $R_E = 6371$ km) serve as terrestrial input data. The resulting upward continued gradients from the collocation solution are then compared with the corresponding values computed directly from EGM96.

3. Upward continuation of terrestrial data

Least-squares collocation is used as the upward continuation method. The three diagonal components of the gravitational tensor, $T_{xx}$, $T_{yy}$, and $T_{zz}$, are predicted on a sphere with a radius of $R_{GOCE} = R_E + 250$ km, which is assumed to be the mean altitude of the GOCE orbit.

3.1 Least-squares collocation procedure

The general algorithm of least-squares collocation is described in Moritz (1980). As observations, EGM96 gravity anomalies in a $10' \times 12'$ grid are used, covering an area of $10^\circ \times 15^\circ$ in central Europe. From these anomalies, $\Delta g^{GM}$, the long wavelength part up to degree 200 from the EGM96 model, $\Delta g^{GM}$, is subtracted:

$$\Delta g' = \Delta g^{obs} - \Delta g^{GM}$$  \hspace{1cm} (2)

This leads to the residual anomalies, $\Delta g'$, which only contain high frequency signals and may be used to study the signal contents at higher spherical harmonic degrees. As no real data are used here, the effect of the topography is not taken into account in the remove step. The prediction of the gradients, $T'_{xx}$, $T'_{yy}$, and $T'_{zz}$, is computed according to the collocation formula

$$\hat{T}_{ii} = C_{T_{ii} \Delta g'} \left( C_{\Delta g' \Delta g'} + C_{\text{noise}} \right)^{-1} \Delta g'$$  \hspace{1cm} (3)

$i = x, y, z$

The covariance matrices $C_{\text{Grd}}$ and $C_{\text{Dgrd}}$ contain the covariances between the functionals, $T'_{xx}$, $T'_{yy}$, and $T'_{zz}$, as well as $Dg'$, respectively. $C_{\text{noise}}$ is the noise covariance matrix for the gravity anomalies, where the noise is assumed to be uncorrelated with a variance of 1 mgal. Finally, in the restore step, the signal of the global model (here EGM96 gradients up to degree 200) has to be added again. However, in this investigation the restore step is not preformed, because we are only interested in studying the high frequency gravity field components. The predicted signal from the reduced gravity anomalies (degree 200

Figure 1: Overview of the calibration procedure. In a first step, least-squares collocation is used for the upward continuation of the gravity anomalies. The comparison between the predicted gradients and those observed by GOCE follows in a second step, where the calibration parameters are derived.
to 360) is very small, only about 1 to 2 mE maximum at GOCE altitude, and would not be clearly visible after adding also the low-frequency parts from EGM96. This also indicates that it will be difficult to recover spherical harmonic degrees above about degree 200 from the GOCE observations.

The prediction error for the computed gradients is calculated by

\[ E_{T_{i,j}} = C_{T_{i,j}} - C_{T_{i,j}} \cdot (C_{\delta, \delta} + C_{m})^{-1} C_{T_{i,j}} \delta, \]

\( i = x, y, z \)  

\[ (4) \]

The signal covariances are computed from the signal degree variance model of Tscherning and Rapp (1974), where the degree variances up to degree 200 are set to zero, i.e., the EGM96 is assumed to be errorless up to degree 200:

\[ \sigma_{T_{i,j}}^2 = \begin{cases} 0 & l \leq 200 \\ \frac{A}{(l-1)(l-2)(l+24)} & l > 200 \end{cases} \]

\[ A = 425.28 \text{ mgal}^2 \]

\[ R_g = R_E - 1220 \text{ m} \]  

\[ (5) \]

The above parameters are taken from the global model of Tscherning and Rapp (1974). No attempt is made to compute local covariance parameters. The computation of the covariances is done with the FORTRAN routines COVAX, COVBX, and COVCX, kindly provided by C.C. Tscherning (Tscherning 1976, updated version of 2002). The inversion and multiplication of the matrices is performed with the help of BLAS and LAPACK routines (see ATLAS, Automatically Tuned Linear Algebra Software, http://math-atlas.sourceforge.net/, 01/2003).

### 3.2 Results of the collocation

The predicted gradients, \( T_{xx}, T_{yy}, \) and \( T_{zz} \), from the collocation solution are shown in Figure 2. In this investigation, the remaining signal at the higher frequencies (above a spherical harmonic degree of 200) is very small (about 2 mE maximum). The maximum prediction errors are \( S_{T_{xx}} = 0.11 \text{ mE}, S_{T_{yy}} = 0.11 \text{ mE}, \) and \( S_{T_{zz}} = 0.18 \text{ mE}. \) The prediction errors are also very small in this simulation because of the chosen simulation parameters. With real terrestrial data, additional significant signals would enter especially below degree 200 due to the differences between the global model and the terrestrial data, resulting from the errors of the global model and the terrestrial data. Moreover, also at higher degrees (above about degree 360) significant signals are contained in the terrestrial data at the Earth's surface. A study with a more realistic simulation scenario is under way.

Figure 2: Predicted gradients in mE units. The signal is very small because the long wavelengths of the EGM96 (below degree 201) are not considered.
3.3 Comparison with EGM96 gradients

A statistics of the differences between the gravity gradients from the collocation solution and the values computed directly from the EGM96 model is provided in Table 1. The maximum differences for all three gradients are below 0.2 mE (see Table 1), while the standard deviations of the differences (bold values in Table 1) are below 0.1 mE. Moreover, the differences are fully compatible with the prediction errors of about 0.1 mE (see above). Thus, the results confirm that the LSC scheme and programs work correctly.

Table 1: Statistics of the comparison between directly computed EGM96 gradients and the LSC predictions. The maximum, minimum, mean and the standard deviation of the directly computed gradients, the predicted gradients, and their differences are given. The standard deviations of the differences (bold values) are below the corresponding prediction errors.

<table>
<thead>
<tr>
<th>Statistics for $T_{xx}$</th>
<th>Max [mE]</th>
<th>Min [mE]</th>
<th>Mean [mE]</th>
<th>Std Dev [mE]</th>
<th>Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.878</td>
<td>0.857</td>
<td>0.010</td>
<td>0.284</td>
<td>$T_{xx}$ EGM96</td>
<td></td>
</tr>
<tr>
<td>0.835</td>
<td>-0.824</td>
<td>-0.013</td>
<td>0.272</td>
<td>$T_{xx}$ predicted</td>
<td></td>
</tr>
<tr>
<td>0.098</td>
<td>-0.090</td>
<td>0.003</td>
<td>0.038</td>
<td>differences</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics for $T_{yy}$</th>
<th>Max [mE]</th>
<th>Min [mE]</th>
<th>Mean [mE]</th>
<th>Std Dev [mE]</th>
<th>Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.233</td>
<td>-1.310</td>
<td>-0.018</td>
<td>0.476</td>
<td>$T_{yy}$ EGM96</td>
<td></td>
</tr>
<tr>
<td>1.221</td>
<td>-1.259</td>
<td>-0.019</td>
<td>0.461</td>
<td>$T_{yy}$ predicted</td>
<td></td>
</tr>
<tr>
<td>0.150</td>
<td>-0.123</td>
<td>0.001</td>
<td>0.052</td>
<td>differences</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics for $T_{zz}$</th>
<th>Max [mE]</th>
<th>Min [mE]</th>
<th>Mean [mE]</th>
<th>Std Dev [mE]</th>
<th>Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.937</td>
<td>-1.961</td>
<td>0.028</td>
<td>0.630</td>
<td>$T_{zz}$ EGM96</td>
<td></td>
</tr>
<tr>
<td>1.869</td>
<td>-1.964</td>
<td>0.032</td>
<td>0.607</td>
<td>$T_{zz}$ predicted</td>
<td></td>
</tr>
<tr>
<td>0.207</td>
<td>-0.232</td>
<td>-0.004</td>
<td>0.073</td>
<td>differences</td>
<td></td>
</tr>
</tbody>
</table>

4. Summary and Outlook

A possible concept for an external calibration procedure of the gradiometer observations from GOCE has been developed. In this investigation, the three in-line tensor components $T_{xx}$, $T_{yy}$, and $T_{zz}$, are predicted by upward continuation of EGM96 gravity anomalies using least-squares collocation. The resulting gradients are compared, as a first numerical test, with the values computed directly from the EGM96 model. In this study, emphasis is put on the high-frequency signals. The differences between the directly computed EGM96 gradients and those upward continued from the gravity anomalies are below 0.1 mE in terms of standard deviations, thus proving the consistency of the results. The formal prediction errors are also below 0.1 mE, which is fully compatible with the differences mentioned above. The quite small differences and high accuracies are mainly achieved because in the simulation an errorless global model up to degree 200 is assumed. For a more realistic scenario, the differences and prediction errors will degrade. Furthermore, for real terrestrial data, the task of estimating a realistic covariance function based on the gravity anomalies remains. This covariance function will affect the predictions and error estimates. The error estimates are an important quantity for the second step of the calibration, when observed GOCE gradients are compared with the predicted ones for the derivation of the calibration parameters. As one of the next steps, the computation of all gradients of the gravitational tensor and the subsequent rotation into the local orbital reference frame will be carried out, and the computations will be performed on the basis of more realistic assumptions, e.g. regarding the error contribution from the global model.
5. References


Tscherning, C.C. and Rapp, R.H. (1974): Closed covariance expressions for gravity anomalies, geoid undulations, and deflections of the vertical implied by anomaly degree variance models, Reports of the Department of Geodetic Science, Report No.208, The Ohio State University, pp.89, Columbus.
Dedicated Low Earth Orbiting (LEO) missions such as CHAMP and GRACE have a strong impact on detecting temporal variations of Earth’s gravity field. CHAMP and GRACE generate on-board observations such as accelerations, K-band range and range rate. SLR data via ground tracking is also provided. The most important data in this context are the measurements of the GPS on-board receivers. For the restitution of LEO orbits from GPS data, presently the ‘two-step’ approach is widely adopted. In this approach, in the first step, orbits of the GPS sender satellites are adjusted by using GPS ground station data. In second step, LEO orbits and gravity field coefficients are estimated using GPS data from the LEO on-board receiver only. The ephemeris of the sender satellites enter this part of the overall process as fixed quantities. By this procedure the orbits of the GPS satellites are used only as ‘geometric reference points’. An alternative concept is the so-called ‘one-step’ method, where orbits of LEOs, GPS satellites, gravity field, EOP and ground station positions are recovered in the same solution by simultaneously using the various observation types (e.g. GPS, SLR, accelerometry data, K-band range and range rate, attitude and thruster data, etc.).

GPS satellites on the one hand and LEOs on the other fly at altitudes that differ by almost 20,000 kms. Their sensitivity towards a given set of parameters therefore is quite different. So if we use either GPS satellites or LEOs alone in a parameter adjustment process we introduce advantages and weaknesses that are specific to either group of satellites. If we combine them however in the above-mentioned one-step procedure the weakness of the one kind of satellites is compensated by the strength of the other. Thus it can be expected that the solutions are more consistent and homogeneous. Guided by this reasoning, the EPOSOC software has been updated provisionally for the one-step solution capability.

With this updated s/w tests were performed using GPS data from CHAMP, GRACE and 40 ground stations. The solutions were done by using GPS measurements alone. SLR and K-band range and range rate data served only for external quality assessment via their measurement residuals. The arc length was 36 hour as used for gravity recovery solutions at GFZ.

The following tables show the results of the routinely used two-step solution vs. the experimental one-step procedure. Table 1 shows the comparison of the sum of residual fits of the LEO orbits. It is clearly visible that the one-step method improved the K-band residuals by 20%-40%. For the SLR residuals, the improvement is not as dramatic, but still perceptible.

Table 2 is the comparison of restituted orbits of the GPS satellites with final IGS orbits. The first solutions were computed from some 40 ground stations. In the second set of solutions data from the same ground stations were augmented by CHAMP and GRACE GPS-SST measurements (one step method). No ambiguity fixing was applied. Although in the latter case the amount of data increased only by 3/40 = 7.5%, the orbit accuracy improved by almost
40%. That means, adding three LEOs is of higher importance than simply adding three ground stations.

This is due to the fact that a dynamically moving LEO has some useful properties for a terrestrial network without having the disadvantages of a ground station. For instance, at LEO orbit altitude we have only traces of atmosphere with negligible effect on GPS signal propagation. As a consequence, no tropospheric correction needs to be estimated for a receiver station on a satellite; we thus have removed a parameter subset that otherwise, if present, would exhibit high correlations with station heights and the radial component of the orbit. For the same reason, we can drop any zenith angle limitations and observe down to almost zero degree elevation which significantly strengthens the solution. Furthermore, the ground tracks of a LEO cover the whole surface of the Earth, which, in a sense, simulates a homogenous ground station network that evenly covers the globe. And, last but not least, a satellite as a moving vehicle is much more sensitive to the geocenter position.

As for the geocenter of the reference frame, the one-step procedure is also superior for ground station solution, especially in the z component. For the x- and the y- components, the one-step method improves the internal precision by 10%-20% compared to the ground-station-only case, but for the z component this improvement is 70% (i.e. a reduction from 12.5 to 4.6 mm).

The estimated geocenter z-component variation results are given in table 3. The maximal fluctuations are 58.8 mm and 15.0 mm respectively. The latter one is much more reasonable.

Conclusions: GPS orbits (highest layer), CHAMP and GRACE orbits (middle layer) and the terrestrial reference frame (lowest layer), all benefit from the one-step procedure, which combines the data from all three layers together in one consistent solution.

Table 1: Comparison of the LEO orbits (rms residuals): 2-step vs. 1-step (units: cm for K-band range and SLR; micrometer per second for range rate).

<table>
<thead>
<tr>
<th>arc</th>
<th>K-range</th>
<th>K-range rate</th>
<th>SLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>010502-020502</td>
<td>1.05 / 0.79</td>
<td>9.10 / 6.14</td>
<td>3.16 / 3.04</td>
</tr>
<tr>
<td>030502-040502</td>
<td>0.98 / 0.81</td>
<td>10.1 / 7.98</td>
<td>3.41 / 3.36</td>
</tr>
<tr>
<td>040502-050502</td>
<td>1.07 / 0.81</td>
<td>8.60 / 6.83</td>
<td>7.08 / 6.03</td>
</tr>
</tbody>
</table>
Table 2: Comparison of the GPS orbits with IGS. rms differences before and after Helmert transformation (mm).

<table>
<thead>
<tr>
<th>day</th>
<th>2-step</th>
<th>1-step</th>
<th>JPL</th>
<th>JPL vs. CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>020502</td>
<td>75 / 70</td>
<td>38 / 37</td>
<td>26 / 24</td>
<td>39 / 36</td>
</tr>
<tr>
<td>020503</td>
<td>66 / 64</td>
<td>43 / 41</td>
<td>35 / 34</td>
<td>38 / 37</td>
</tr>
<tr>
<td>020504</td>
<td>70 / 66</td>
<td>41 / 36</td>
<td>29 / 26</td>
<td>39 / 35</td>
</tr>
<tr>
<td>020505</td>
<td>59 / 55</td>
<td>38 / 34</td>
<td>27 / 25</td>
<td>36 / 34</td>
</tr>
</tbody>
</table>

Table 3: Estimated geocenter variation in z-directions with unit mm.

<table>
<thead>
<tr>
<th></th>
<th>020502</th>
<th>030502</th>
<th>040502</th>
<th>050502</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground only</td>
<td>16.2 +/- 13.0</td>
<td>3.8 +/- 11.7</td>
<td>-39.4 +/- 13.1</td>
<td>19.4 +/- 12.1</td>
</tr>
<tr>
<td>ground+LEO</td>
<td>-7.7 +/- 4.2</td>
<td>7.3 +/- 4.7</td>
<td>-0.5 +/- 4.7</td>
<td>0.9 +/- 4.7</td>
</tr>
</tbody>
</table>
Index

<table>
<thead>
<tr>
<th>A</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdelmoula F.</td>
<td>22</td>
</tr>
<tr>
<td>Ackermann Ch.</td>
<td>48</td>
</tr>
<tr>
<td>Alkhateb H.</td>
<td>8</td>
</tr>
<tr>
<td>Angermann D.</td>
<td>12, 17, 108, 120, 137</td>
</tr>
<tr>
<td>Austen G.</td>
<td>63</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barthelmes F.</td>
<td>161</td>
</tr>
<tr>
<td>Baur O.</td>
<td>56</td>
</tr>
<tr>
<td>Behrends K.</td>
<td>132</td>
</tr>
<tr>
<td>Bode A.</td>
<td>161</td>
</tr>
<tr>
<td>Boedecker G.</td>
<td>22, 24</td>
</tr>
<tr>
<td>Bölting K.</td>
<td>56</td>
</tr>
<tr>
<td>Boxhammer Ch.</td>
<td>27</td>
</tr>
<tr>
<td>Braune St.</td>
<td>132</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campell J.</td>
<td>120, 137</td>
</tr>
<tr>
<td>Choi S.</td>
<td>101</td>
</tr>
<tr>
<td>Cochard A.</td>
<td>67, 148</td>
</tr>
<tr>
<td>Cremer M.</td>
<td>22, 31, 166</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denker H.</td>
<td>32, 112, 188</td>
</tr>
<tr>
<td>Dill R.</td>
<td>36, 134</td>
</tr>
<tr>
<td>Drewes H.</td>
<td>12, 40, 137</td>
</tr>
<tr>
<td>Drewitz W.</td>
<td>148</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eicker A.</td>
<td>104</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feuchtinger M.</td>
<td>71</td>
</tr>
<tr>
<td>Fischer D.</td>
<td>44, 120, 164</td>
</tr>
<tr>
<td>Flaws A.</td>
<td>67, 148</td>
</tr>
<tr>
<td>Flechtnr F.</td>
<td>45, 48, 146</td>
</tr>
<tr>
<td>Flury J.</td>
<td>142</td>
</tr>
<tr>
<td>Földváry L.</td>
<td>51, 185</td>
</tr>
<tr>
<td>Förste Ch.</td>
<td>161</td>
</tr>
<tr>
<td>Freibergh S.</td>
<td>132</td>
</tr>
<tr>
<td>Frommknecht B.</td>
<td>54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galas R.</td>
<td>129</td>
</tr>
<tr>
<td>Gerstl M.</td>
<td>108, 120</td>
</tr>
<tr>
<td>Grafarend E.W.</td>
<td>56, 59, 63</td>
</tr>
<tr>
<td>Gruber Th.</td>
<td>142</td>
</tr>
<tr>
<td>Grünreich D.</td>
<td>137</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>H</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haak V.</td>
<td>101</td>
</tr>
<tr>
<td>Hein G.W.</td>
<td>92</td>
</tr>
<tr>
<td>Heise S.</td>
<td>76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Igel H.</td>
<td>67, 148</td>
</tr>
<tr>
<td>Ilk, K.-H.</td>
<td>71, 104</td>
</tr>
</tbody>
</table>
# Index

<table>
<thead>
<tr>
<th>J</th>
<th>Jakowski N.</th>
<th>Jarecki F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Kargoll B.</td>
<td>Kelm R.</td>
</tr>
<tr>
<td>L</td>
<td>Loehnert E.</td>
<td>Lühr H.</td>
</tr>
<tr>
<td>N</td>
<td>Neumayer K.-H.</td>
<td>Niehuus K.</td>
</tr>
<tr>
<td>P</td>
<td>Palm H.</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Raimondo J.-C.</td>
<td>Reigber Ch.</td>
</tr>
<tr>
<td>S</td>
<td>Schmeling H.</td>
<td>Schmidt A.</td>
</tr>
</tbody>
</table>
Index

S
Sharifi M.A. .................. 56, 63
Spohnholtz T. .................. 24
Steinforth Ch. ................. 120, 165
Stelkens T.H. .................. 22, 31, 166
Stubenvoll R. ................. 161
Stürze A. ..................... 24
Svehla D. ..................... 170

T
Tesmer V. ..................... 17
Thaller D. .................... 120, 134, 176
Thomas M. .................. 181
Timmen L. ................... 112
Tsybulya K. .................. 76

V
Velikoseltsev A. ............. 67, 148
Vennebusch M. ............... 44, 120

W
Wermuth M .................. 51, 185
Wolf K.I. .................... 32, 188

Z
Zahel W. ..................... 181
Zhu S.Y. .................... 48, 137, 146, 161, 193
GEOTECHNOLOGIEN Science Report’s – Already published

No. 1 Gas Hydrates in the Geosystem – Status Seminar, GEOMAR Research Centre Kiel, 6-7 May 2002, Programme & Abstracts, 151 pages

No. 2 Information Systems in Earth Management – Kick-Off-Meeting, University of Hannover, 19 February 2003, Projects, 70 pages
Notes
Notes
Observation of the System Earth from Space

The investigation of the spatial and temporal variations of the Earth’s gravity and magnetic field using new satellite technologies has received wide international attention in the past years. Geoscientific satellites such as CHAMP (German/US), GRACE (US/German) and the planned GOCE Mission (ESA’s first Core Earth Explorer mission) allow measurements with hitherto unprecedented accuracy. They open a new segment in Earth system research.

In Germany a significant part of the data evaluation and interpretation is carried out under the umbrella of the R&D-Programme GEOTECHNOLOGIEN. Under the thematic focus »The Observation of the System Earth from space« eleven collaborative research projects are funded by the Federal Ministry for Education and Research (BMFB) and the German Research Council (DFG). They are carried out in close co-operation of various national and international partners from academia and industry and focus on the recovery and optimal use of the spatial and temporal variations of the Earth’s gravity and magnetic field for geodynamics. The ultimate aim is the establishment of mass anomalies within the solid Earth, of glacial, oceanic and hydrological mass transport, and of mass exchange and balance in Earth system.

The abstract volume contains the presentations given at a science meeting held in Munich, Germany, in June 2003. The presentations reflect the multidisciplinary approach of the programme and offer a comprehensive insight into the wide range of research opportunities and applications, including solid Earth sciences, glaciology, oceanography, hydrology, meteorology, and geodesy.

The GEOTECHNOLOGIEN programme is funded by the Federal Ministry for Education and Research (BMFB) and the German Research Council (DFG)

ISSN: 1619-7399