**Paper Reprint:**
**Gruber Th., Rummel R., Koop R.: The GOCE High Level Processing Facility**

Proceedings of the Workshop:

# GOCINA: Improving modelling of ocean transport and climate prediction in the North Atlantic region using GOCE gravimetry

April 13-15, 2005

Novotel
Luxembourg-Kirchberg
Grand-Duchy of Luxembourg

Organized by
The European Center for Geodynamics and Seismology (ECGS)

Supported by

European Center for Geodynamics and Seismology (ECGS)
Ministère de la Culture, de l'Enseignement Supérieur et de la Recherche
Fonds National de la Recherche de Luxembourg
Musée national d'histoire naturelle
Danish National Space Center

**Scientific Organizing Committee**:

P. Knudsen (DNSC, Denmark)
J. Johannessen (NERSC, Norway)
T. Gruber (IAPG, Germany)
D. Stammer (IfM, Germany)
T. van Dam (ECGS, Luxembourg)

**Local Organizing Committee:**

O. Francis (UL / ECGS, Luxembourg)
T. van Dam (ECGS, Luxembourg)
P. Codran (ECGS, Luxembourg)

**Edited by:**

P. Knudsen, J. Johannessen, T. Gruber, S. Stammer and T. van Dam
Luxembourg - 2006

**PUBLIE AVEC LE SUPPORT DU**

**MINISTERE DE LA CULTURE,
DE L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE
&
FONDS NATIONAL DE LA RECHERCHE**

ISBN N° 2-9599804-2-5

Centre Européen de Géodynamique et de Séismologie

Musée national d'histoire naturelle
Section Astrophysique et Géophysique, Luxembourg

Imprimerie Centrale, 15 rue du Commerce, L- 1351 Luxembourg
Imprimé en 400 exemplaires

# The GOCE High Level Processing Facility

Th. Gruber, R. Rummel
Institut für Astronomische und Physikalische Geodäsie (IAPG)
Technische Universität München, Arcistrasse 21, 80333 München, Germany
e-mail: Thomas.Gruber@bv.tu-muenchen.de

R. Koop
Space Research Organisation Netherlands (SRON)
Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
e-mail: R.Koop@sron.nl

**Abstract.** The High Level Processing Facility for GOCE (HPF) will produce so-called GOCE level 2 products. These are in particular orbits and gravity field models of different kind. While so-called quick-look or rapid products are mainly of interest for the GOCE performance monitoring, final and precise products will represent the official ESA GOCE level 2 products. They are provided to the GOCE users (in oceanography, solid Earth physics, geodesy and other fields of application). Ten European institutes with complementary expertise, which form together the European GOCE Gravity Consortium (EGG-C), have been contracted by ESA to develop and operate the HPF throughout the whole GOCE mission lifetime. The group is jointly managed by IAPG and SRON. The paper summarizes the architecture of the HPF, the status of its development and provides an overview of the planned products and their characteristics. A special section is dedicated to the product validation of the level 2 orbit and gravity field products.

**Keywords:** GOCE, Orbit, Gravity Field

## 1 Introduction

The GOCE ground segment is composed of several elements dealing with data processing and data analysis. Figure 1 shows the layout of the ground segment elements (for more details see, Muzi et al, 2004). The Payload Data Segment (PDS) is responsible for the generation of the level 1b products. These are the internally calibrated gradiometer and GPS observations. The HPF is responsible for the determination of quick-look and final precision GOCE orbits and gravity field products based on these level 1b data (see chapter 4). The processing chain inside the HPF includes various steps from scientific pre-processing and external calibration to the final product validation. In addition the HPF handles several interfaces to external data providers, which are required for level 2 data processing (e.g. International GNSS Service (IGS), International Laser Ranging Service (ILRS) and European Centre for Medium Weather Range Forecast (ECMWF). The Calibration and Monitoring Facility (CMF) will monitor the GOCE space segment and payload performance by applying specifically designed monitoring and testing algorithms to the satellite and instrument housekeeping data, to the level 1B data and to the quick-look level 2 products. Special emphasis is given in the CMF to the control of the calibration parameters before they are applied in the space segment. By closely linking the available expertise in all ground segment elements the GOCE products to be delivered to the user community shall be optimally calibrated, monitored and processed.

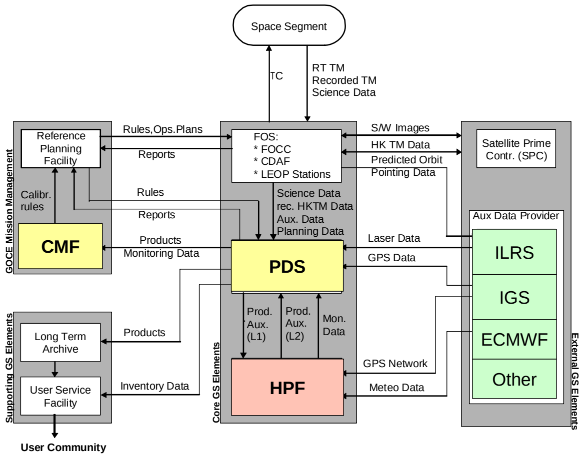


**Figure 1:** GOCE Ground Segment

## 2 High Level Processing Facility: Tasks and Structure

The HPF is as a distributed system composed of several processing nodes. The development and operation of the HPF is done under ESA contract by the European GOCE Gravity Consortium (EGG-C). In addition the consortium contributes with its own resources to the overall project goal, which is the production of the best possible GOCE orbits and gravity field solutions.

### 2.1 Tasks of the HPF

The mission objective of GOCE is to provide a model of the quasi-static global gravity field and geoid with highest possible accuracy and spatial resolution. More specifically the objective of GOCE is to determine the Earth's gravity field with an accuracy of better than 1 mGal, the global geoid with an accuracy of better than 1-2 cm and to achieve both with a spatial resolution of 100 km (half-wavelength) or better, which corresponds to a spherical harmonic expansion up to degree and order 200 (ESA, 1999). In order to fulfil these objectives, a dedicated scientific data analysis is required. Starting from these objectives the major tasks for the HPF are as follows:

(1) The generation of level 2 products (orbits and gravity fields) from level 1b data generated by the PDS (nominal and calibrated products from the gradiometer and the GPS-receiver): The level 1b products consist mainly of gravity gradients in the gradiometer reference frame and pseudo-ranges and phases from the GPS receiver. They require a comprehensive scientific data processing before they can be translated into satellite positions, the corresponding velocities and gravity information in terms of a set of spherical harmonic coefficients (including the corresponding error variance-covariance matrix), as well as geoid heights, geoid height errors, geoid slopes and gravity anomalies. These are the main products expected by the scientific users from the GOCE mission in geodesy, oceanography, geophysics, glaciology, and other fields of application.

(2) The generation of GOCE calibration and validation products (external calibration of gradiometer data, quick-look gravity field and orbit solutions for data validation): The level 1b gradiometer products are internally calibrated. This means that calibration and non-linearity parameters are applied. They are derived from data analysis of observations taken during satellite and proof-mass shaking manoeuvres. At that point no relation between the observed gravity gradients and the real gravity field has been established. In order to do so an external scientific calibration of the gravity gradients is performed by comparison with existing gravity information. Further-more level 1b products from both sensors, SST and SGG, have to be validated continuously in order to warrant a high quality data flow, which is required to meet the mission objectives. For this reason the HPF implements several validation tools. This means orbit and gravity field solutions are systematically generated from partial data sets of new GOCE observations with latencies of a few days. These solutions are validated in order to find out whether the mission performance requirements are met.

(3) The acquisition of auxiliary data needed for level 2 product generation: For level 2 data processing various ancillary data are required on a continuous basis. The most important are Earth rotation parameters from the International Earth Rotation Service (IERS), GPS orbit, clock and ground station data from the International GNSS Service (IGS), satellite laser ranging data from the International Laser Ranging Service (ILRS) and atmospheric parameters from the European Centre for Medium Range Weather Forecast (ECMWF). Apart from this a variety of supporting data like planetary ephemeris, solar flux, geomagnetic indices, tide models, digital terrain models, external gravity field information and others have to be collected. The HPF will acquire all ancillary data, check their quality and store them in a local HPF processing archive as well as in the long term GOCE archive, in case they are required for later reprocessing.

In summary one can state, that the HPF represents the interface between the pure satellite system (which is represented by the pre-processed level 1b products) and the science level 3 users. It applies scientific analysis techniques to the satellite observations in order to derive quantities adequate for scientific use. This enables the multi-disciplinary exploitation of the mission.

## 2.2 Structure of the HPF

The HPF is developed and operated by the European GOCE Gravity Consortium (EGG-C). It is composed of ten European university and research institutes combining the needed expertise to process the GOCE data up to orbits and gravity field models. The members of the consortium are shown in Figure 2.

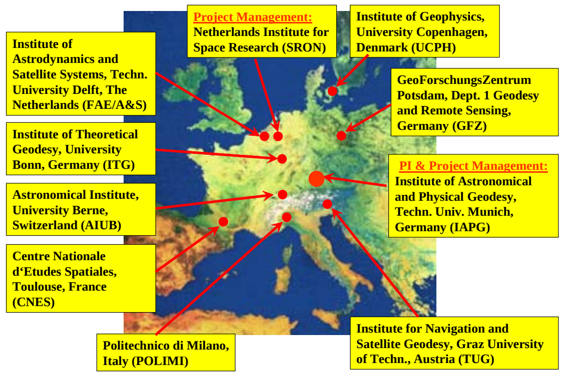


**Figure 2:** The European GOCE Gravity Consortium

The HPF system development and operation is coordinated by a principal investigator and a management team. A central processing facility is implemented in order to facilitate the data flow from and to the other ground segment elements and internally within the HPF. Six work packages, which represent the major steps for level 2 processing have been defined. For these work packages individual teams have been formed under the responsibility of a work package manager. They are assumed to represent some of the best available expertise for each of these tasks. These teams are composed of on the one hand existing institutionally/nationally funded personnel and on the other hand additional personnel specifically working for the HPF development and operations. Table 1 lists the participating groups, their activities and roles within the HPF development and operations.

| Institution | Activities / Work Packages | Role in Work Package |
|---|---|---|
| IAPG: Institute of Astronomical and Physical Geodesy, Technical University Munich, Germany | • Financial, contractual and technical management<br>• Scientific pre-processing and external calibration<br>• Orbit determination<br>• Gravity field determination: time-wise approach<br>• Level 2 products validation | • Principal investigator & team management<br>• Partner institute<br>• Partner institute<br>• Partner institute<br>• Work package manager |
| SRON: Netherlands Institute for Space Research, Utrecht, The Netherlands | • Technical and project management<br>• Central processing facility<br>• Scientific pre-processing and external calibration | • Team management<br>• Work package manager<br>• Work package manager |
| FAE/A&S: Delft University of Technology, Faculty of Aerospace Engineering, Astrodynamics and Satellite Systems, The Netherlands | • Scientific pre-processing and external calibration<br>• Orbit determination<br>• Level 2 product validation | • Partner institute<br>• Work package manager<br>• Partner institute |
| CNES: Centre Nationale d'Etudes Spatiale, Toulouse, France | • Gravity field determination: direct approach | • Work package manager |
| TUG: Institute of Navigation and Satellite Geodesy, Technical University Graz, Austria | • Gravity field determination: time-wise approach | • Work package manager |
| POLIMI: DIIAR - Sez. Rilevamento Politecnico di Milano, Italy | • Gravity field determination: space-wise approach | • Work package manager |
| AIUB: Astronomical Institute, University Bern, Switzerland | • Orbit determination | • Partner institute |
| GFZ: GeoForschungsZentrum Potsdam, Dep. 1 Geodesy and Remote Sensing, germany | • Gravity field determination: direct approach | • Partner institute |
| ITG: Institute for Theoretical Geodesy, University Bonn, Germany | • Gravity field determination: time-wise approach | • Partner institute |
| UCPH: Department of Geophysics, University Copenhagen, Denmark | • Gravity field determination: space-wise approach | • Partner institute |

**Table 1:** Roles and Responsibilities within the HPF

The management ensures the establishment of any interface to other GOCE ground system elements. Operational data processing is performed in a distributed manner. The work package managing institutions provide computational resources for the operational data processing. Rapid and quick-look products generation require a nearly continuous processing. All sub-processing facilities are linked to each other via the central processing facility, which also establishes the interface to the other ground system elements.

## 3 Processing Strategy

The layout of the sensor system of GOCE combined with the challenging mission goals require a data processing strategy tailored to the mission. EGG-C has developed such an approach. It comprises all necessary elements of pre-processing, external calibration and validation of level 1b data as well as the determination of quick-look and ultimate precision level 2 products, namely rapid and precise GOCE orbits, and quick-look and precise models of the Earth gravity field derived from GOCE observations. Figure 3 shows the processing sequence and the product flow through all processing steps from level 1b data to intermediate level 2 and finally to level 2 products. In particular the following processing tasks are performed:

***Scientific pre-processing and external calibration:***
External calibration is intended to determine bias, scale factor, trend and possible other slowly varying systematic effects in the gravity gradients, that remain in the level 1b data after the in-flight calibration, by comparison with known absolute gravity signals (Bouman et al, 2004). The calibrated level 1b products undergo scientific pre-processing, which consists of identification and possible correction of data gaps and outliers using geodetic information, transformation to an Earth fixed reference frame including an error estimate for the transformed gravity gradients and the provision of corrections for the tidal and non-tidal time variable components of the Earth gravity field. The calibrated and scientifically pre-processed gradiometer data are the basis for all further data processing to level 2 products.

***Orbit determination:***
GPS code and phase (SST) observations undergo a first pre-processing during the rapid science orbit determination process. These SST observations or the derived orbit information together with the pre-processed gradiometer observations are the input for the gravity field processors. The GOCE orbits will be determined in two different quality levels (depending on the latency of the product) and with two different approaches (reduced-dynamic and kinematic). While reduced-dynamic orbits make

use of the best available force models, kinematic orbits are computed in a pure geometric manner. Both orbit types are necessary for the subsequent processing steps. Rapid science orbits, having a short latency, are necessary for the pre-processing of the gradiometer data and for the determination of quick-look gravity field products to be used for GOCE validation. Precise orbits will have the ultimate accuracy for satellite positions and velocities and use the most precise available supporting data sets. Precise orbits represent one of the two fundamental input data sets, complementary to the gradiometer data. For precise gravity field determination the former will determine the long wavelength regime of the gravity spectrum, while the gradiometer data will provide the short wavelength gravity information.

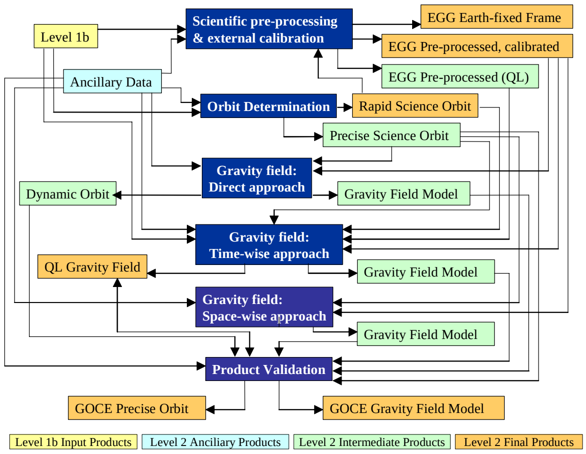


**Figure 3:** Processing Flow from Level 1b to Level 2 Products

***Gravity field determination: direct, time-wise and space-wise approach:***

For gravity field processing three analysis techniques are implemented in parallel representing the classical approach as well as newly developed dedicated approaches for GOCE. All three approaches are aiming at producing a GOCE gravity field model with the highest possible resolution (degree and order 200 and beyond in terms of spherical harmonics). (1) The classical method combines orbit and gravity modelling using orbit perturbation theory (direct method). It represents an extension of the established expertise in gravity modelling at CNES & GFZ. The direct method uses a-priori orbits and an a-priori gravity field model, SST observations and common mode accelerations for setting up normal equations for gravity field determination in an iterative manner. Gradiometer observations are processed in a separate linear step that results in a partial system of normal equations which is finally combined with the SST normal equations. The complete system is solved for the unknown gravity field coefficients and the quality information is provided in the a-posteriori variance-covariance matrix (2) The second method is based on the so-called time-wise method. It views the gradient and SST observations as time series along the orbital track following the least-squares principle. It comprises a gravity gradient (SGG) modelling part, an SST gravity modelling component employing the energy integral approach and the kinematic orbits and a quick look tool that is capable to give a fast feedback based on partial data sets about the validity of the SGG/SST data for gravity modelling. (3) Finally, as a third method there is the space-wise method, which retrieves the gravity field coefficients from observations which are transformed into a regular global grid on a reference surface or into a global spatial grid. Spatialized observations are produced from SST and SGG observations using a Wiener orbital filter. The spherical harmonic coefficients of the gravity field are computed using fast least squares collocation or numerical integration.

***Product validation:***

The official orbits and gravity field solutions are selected after a comprehensive evaluation of the products has been done. Internal and external comparisons using independent test data sets are performed in order to select the best solution. The independent data tests and test methods are chosen such as to check the various spectral bands of the GOCE model. The validation sequence includes orbit tests, comparison with terrestrial gravity, with GPS levelling, ocean topography models and other available reference data. All test results are summarised in a validation report, which is then the basis for selection of the final GOCE products. A scientific GOCE products advisory group will be established, which will formulate the recommendation of official GOCE products on basis of the validation report. More details about the product validation applied to the level 2 products are provided in chapter 5.

## 4 GOCE Level 2 Products

As shown in Figure 3 during the level 2 processing various intermediate products are generated. They contain intermediate results necessary for the next processing step in the sequence. These products are not foreseen to be provided as standard GOCE products to the users. Final level 2 products, which will be accessible by the GOCE user community are identified in Figure 3, too. Table 2 provides a more detailed specification of these level 2 products, which are produced by the HPF. The latencies of the final products are related to data availability of the level 1b products. Three classes of products can be distinguished from that point of view. The rapid and quick-look validation products will be available within a few days after level 1b data are provided. For the quick-look gravity field model it is planned to compute weekly a new model that is based on the previous week of new level 1b

| Identifier | Description | Latency |
|---|---|---|
| Pre-processed & calibrated gradiometer data | • Externally calibrated and corrected gravity gradients in GRF<br>• Corrections to gravity gradients due to temporal gravity variations<br>• Flags for outliers, fill-in gravity gradients for data gaps with flags<br>• Statistical information | 2 weeks |
| Gravity gradients in Earth-fixed frame | • Externally calibrated gravity gradients in Earth fixed reference frame including error estimates for transformed gradients<br>• Transformation parameters to Earth fixed reference frame | 6 months |
| Precise science orbits | • GOCE precise science orbits final product<br>• Quality report for precise orbits | 2 weeks |
| Final GOCE gravity field models | • Final GOCE Earth gravity field model as spherical harmonic series including error estimates<br>• Variance-covariance matrix of final GOCE Earth gravity field model<br>• Grids of geoid heights, gravity anomalies and geoid slopes computed from final GOCE Earth gravity field model including propagated error estimates<br>• Quality report for final GOCE gravity field model | 9 months |

**Table 2:** Overview of GOCE Level 2 Products accessible by GOCE Users

data. Pre-processed and calibrated gradiometer data and precise science orbits will be available with a latency of two weeks. Both products represent the main input to the gravity field processors. The final gravity field solution, which will be selected from the three alternative approaches after an extensive validation (see chapter 5) will be available about 9 months after completion of each measurement operations phase. The transformed gravity gradients in an Earth fixed frame will be available after approximately 6 months. In order to reduce the transformation errors as much as possible several months of data will run through that procedure simultaneously.

All GOCE level 2 products identified in table 2 will be accessible by the user community via the ESA GOCE user service interface. The products will be provided in XML format in order to enhance the products readability and the in-file data definitions.

## 5 Validation of Level 2 Products

The final level 2 products generated by the HPF will be subject to an extensive validation in order to select the best products available and in order to provide a quality estimate together with the products. We distinguish here between validation of precise science orbits and of final gravity field solutions. In the following sections the methods to be applied for level 2 products validation will be discussed based on examples from the CHAMP and GRACE missions. We will see from these examples that especially the validation of the gravity fields becomes a more and more difficult task. The quality of the gravity field models from the new missions, within their sensitivity spectrum, is superior to the quality of any existing independent comparison data set. This implies that in practise it is very difficult to independently derive absolute quality estimates for these models.

### 5.1 Methods for Orbit Validation

The HPF produces different types of GOCE orbits. These are reduced-dynamic (positions and velocities) and pure kinematic (position) solutions (Svehla and Rothacher, 2003a and 2003b). Orbits are generated on a daily basis always including the last 3 hours of the previous day and 3 hours of the next day. All together one orbit solution covers 30 hours. For validation purposes the 3 hours overlaps can be used in order to check consistency of the subsequent orbit solutions by computing position and, in case of reduced dynamic orbits, also velocity differences. These differences can be statistically analyzed and provide some insight into the internal orbit consistency. It shall be noticed that this method does not provide any measure about the absolute position and velocity quality of these orbits. More information about the absolute quality can be derived from the position differences between the reduced dynamic and the kinematic solutions over each day. As both orbits are computed completely independent the position fits between both solutions are a good indicator for the quality of the orbits. In the same way position (and velocity differences) can be computed to any external available orbit solution. Such orbits for example are computed within the HPF during gravity field restitution by a pure dynamic approach. Also any orbit computed outside the level 2 processing system can be used for such an analysis. In order to estimate the quality of the HPF orbit solutions some knowledge about the quality of these external orbits is required. The only independent orbit validation method is the analysis of independent observation residuals, which have not been used for the orbit determination itself. For this purpose satellite laser ranging data are well suited, because they provide distances between the ground stations and the satellite with an accuracy of a few millimetres. If the station positions are well determined they provide an absolute measure of the quality of the satellite positions. In order to perform a statistical analysis of these satellite laser ranging residuals sufficient observations must be taken from different stations. This ensures that observation outliers or station dependent systematic errors can be removed or at least taken into account. Limitations in the availability of enough satellite laser ranging data for such comparisons could arise from difficulties for some stations in tracking satellites orbiting as low as GOCE (250 km). This became obvious when satellite tracking data to the GFZ-1 cannonball satellite were acquired and analyzed (König et al, 1999). The number of observations can be quite small and it might be that they are not sufficient for a thorough orbit quality analysis. Table 3 provides an overview of the methods to be applied for GOCE orbit validation together with their limitations as discussed above.

| Method | Test Data | Quality Parameters | Limitations |
|---|---|---|---|
| Overlaps of Orbits | GOCE precise Science Orbits | Position & Velocity Differences at Overlaps | Internal Obit Consistency Check |
| Satellite Laser Ranging Residuals | Laser Ranging Data to GOCE Satellite | RMS and Mean of Laser Ranging Residuals | Difficult to track GOCE Satellite with Lasers |
| Comparisons with internal & external provided Orbits | External GOCE Orbit Solutions | Position and Velocity Differences | Quality of external Orbits not known |

**Table 3:** Methods for Orbit Validation and their Limitations

## 5.2 Methods for Gravity Field Validation

The HPF produces gravity field solutions by different approaches from which the best one will be selected and distributed as the official GOCE gravity field. In order to identify the best solution a gravity field validation strategy has been developed, which involves a wide range of test scenarios. These test scenarios have to cover the complete spectral range of the GOCE gravity field model, that means from the very low degree harmonics to the full resolution (e.g. at least degree and order 200). For this, various tests will be performed each one targeting at different spectral ranges. Table 4 provides an overview of these test methods together with their sensitivity and their limitations. In the following, examples for some of these tests are shown and commented in detail.

***Precise Orbit Determination of other Satellites***

In order to identify the quality of the long wavelength spherical harmonics of a gravity field solution, orbits for a set of selected satellites covering different inclinations and altitudes are recomputed by a dynamic approach and residuals to different kinds of tracking data are statistically analyzed. This validation method has been applied to most of the general purpose gravity field solutions like GRIM5-C1 (Gruber et al, 2000) and EGM96 (Lemoine et al, 1998) before CHAMP and GRACE. The tracking data residuals for these models and a set of different satellites are clear indicators about the quality of the low harmonic spectrum of the gravity field. With the first gravity field models from CHAMP and GRACE it was expected that orbits for geodetic and altimeter satellites become more or less free of errors from the used gravity field models and that tracking data residuals significantly decrease. Results of orbit re-computations using the EIGEN-2 CHAMP model (Reigber et al, 2003) show, that tracking data residuals for the CHAMP satellite itself significantly decreased while residuals for some other satellites even slightly increased. Such behaviour is an indicator for a strong tailoring effect of a model to a specific satellite mission. In contrast orbit re-computations for the GGM02 GRACE model (Tapley et al, 2005) show a reduction of residuals of about 25% to 50% for some geodetic satellites as compared to EGM96. RMS of laser residuals is now in the range of 3 cm for these satellites. There seems to be some lower limit of tracking data residuals reflecting remaining errors in non-conservative force modelling, in the tracking data quality and in the mathematical models used for orbit determination. The tracking data residuals obtained by Tapley et al (2005) for the GGM02 model seem to represent a lower limit, which can be reached by this approach. This also makes clear that tracking data residuals never can provide absolute error measures for a gravity field model under test, because they are affected by the combination of many other effects contributing to the total error budget. This conclusion is also supported by the fact that positions for low Earth orbiters can be determined with an accuracy of down to about 2 cm (Svehla, 2003a).

***Variance-Covariance Matrix***

GOCE gravity field models will be determined by several kinds of least-squares approaches. For each solution the full variance-covariance matrix will be available for further quality analysis. This means, correlations between the coefficients of the spherical harmonic series can be plotted and visually analyzed, error propagations to different quantities can be performed and error degree variances can be computed in different representations. All methods are based on the error estimates of the least squares solution. Errors directly derived from the least squares solution tend to be too optimistic when compared to externally derived errors. Therefore, errors of gravity field solutions in the past have been calibrated by comparisons with external data in order to provide realistic error estimates. What concerns the results of the GRACE and GOCE missions there are some difficulties to calibrate least squares errors, because

| Method | Test Data | Spectral Range | Quality Parameters | Limitations |
|---|---|---|---|---|
| Precise Orbit Determination of independent geodetic and Altimeter Satellites | Satellite Laser Ranging, Microwave and Altimeter Tracking Data | Degrees 0-70, Resolution 300-20000 km | Tracking Data Residuals, Altimeter Crossover Differences | Tracking & Altimeter Data Quality; Sensitivity of Satellites; Non-gravitational Force Models applied |
| Error Propagation of Variance-Covariance Matrix of Spherical Harmonic Series | Variance-Covariance Matrix | Full Spectrum of Solution | Error Degree Variances; Propagated Geoid Height Variances; Correlations of Spherical Harmonic Coefficients | No absolute Error Measure; Dependent on internal Error Calibration of Spherical Harmonic Series |
| Comparison with independent Geoid and Gravity Observations | GPS-Levelling Geoid Heights; Gravity Anomalies | Full Spectrum of Solution | RMS and Mean of Differences at the Observation Points and of Differences in Slopes | Treatment of Omission Error; Low-pass Filter Model; Quality of long Wavelengths |
| Analysis of Sea Surface Topography Solutions | Mean Sea Surfaces from Altimetry; Oceanographically derived Sea Surface Topography Solutions | Long and medium Wavelengths with Resolution down to a few hundred km | Differences between geodetic and oceanographic Solutions; Test of remaining oceanographic Signals | Quality of Mean Sea Surfaces and Sea Surface Topography Solutions; Low-pass Filter Models; Treatment of Ocean-Continent Boundaries |

**Table 4:** Methods for Gravity Field Validation and their Limitations

the predicted errors for these missions are, within their spectral range (or measurement bandwidth), far below any error of external data sources. So error calibration seems to be impossible and one has to rely on the errors provided by the least squares solutions. Such errors are shown in Figure 4. There, the square root of cumulative error degree variances in terms of geoid heights for some older and actual gravity field models are shown with respect to their resolution in [km] (computed by 20000 [km]/degree). The models shown are the pre-CHAMP combined model GRIM5-C1 (Gruber et al, 2000) the CHAMP models TUM-1S (Gerlach et al, 2003), TUM-2SP and EIGEN-3P (Reigber et al, 2005) and two GRACE models from the GFZ and UTCSR GRACE science data systems (covering 66 days and one month of data). In addition the predicted cumulative error degree variances for the three gravity field missions CHAMP, GRACE and GOCE are shown. From this plot we can conclude that neither the CHAMP models nor the GRACE models can reach the predicted errors yet. Nevertheless we can see that with the GRACE models the geoid can be determined with 1 cm accuracy with a spatial resolution of about 250 km, if we trust the least squares derived errors. In conclusion it can be stated that errors directly derived from the "un-calibrated" variance-covariance matrix can not be regarded as absolute quality estimates, but, with some precaution, they can be used for relative comparisons between models computed from one and the same satellite data set. In this sense these errors can also be compared to the differences between such gravity field models providing a comparison between the coefficient differences degree variances and the error degree variances.

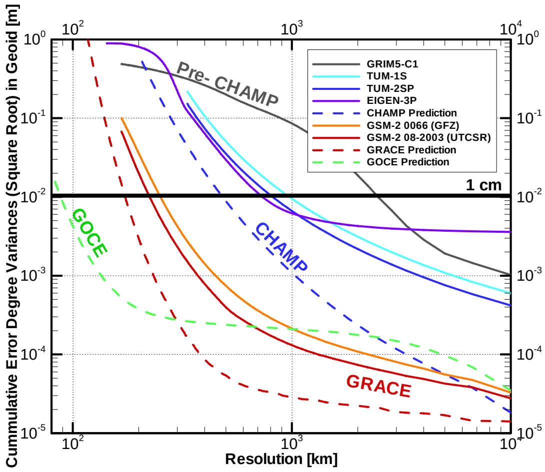


**Figure 4:** Cummulative Error Degree Variances (Square Root) in terms of Geoid Heights

### *Comparison to Geoid Heights and Gravity Data*

In order to independently determine the quality of a gravity field model, comparisons to externally observed and computed gravity field quantities can be performed. Such quantities are for example geoid heights or gravity anomalies available from different sources. Validating a band-limited global gravity field model (truncated at a specific degree of the spherical harmonic series) with full gravity signals on the Earth's surface addresses the principle problem of comparability. Before such comparisons can be made either the omission error has to be estimated or the surface data set has to be filtered in order to eliminate the spectral content from a maximum degree of the series to infinity. For the test procedures shown here the second approach was applied. We used two methods to remove the signal beyond the maximum degree of the series. One method is least squares prediction and collocation by applying global covariance functions of the gravity field while the other approach uses ultra-high degree models of the

Earth gravity field derived by a combination of existing multi-purpose high resolution gravity field models (e.g. EGM96) and gravity field spherical harmonic coefficients determined from the attraction of the Earth's topography. Such models are for example the GPM98 gravity field series (Wenzel, 1999). All following results are based on the filter approach using the high resolution global model GPM98C up to degree and order 720.

For comparison geoid heights on GPS-levelling points and mean or point gravity anomalies can be used. Here we show results for several data sets of geoid heights from GPS-levelling campaigns in the US, in Canada, Europe, Germany, Australia and Japan. The number of available observation points varies significantly between a few hundreds and several thousands. What could be a problem in these data sets are systematic effects between the geoid surface applied and the height datum as it is derived from levelling. Such a problem for example has been identified for the Australian data set (Johnston, personal communication), where the error between both surfaces is latitude dependent and reaches up to ±50 cm. Similar effects could also be present in any other data set. For this reason a very careful pre-analysis of the comparison data sets has to be performed before they are used for such validation activities. For the present preliminary results a thorough analysis of the comparison data sets was not yet performed. Table 5 shows the RMS values of the differences between the filtered GPS-levelling geoid heights and several global gravity field models up to degree and order 60. From these numbers one can clearly identify a tendency for the sequence of gravity field models. In summary the two GRACE models perform best, while the pre-CHAMP model GRIM5-C1 shows the worst fit to the test data sets. Remarkably well performs the EIGEN-3P pure CHAMP model. This picture changes when the cut-off degree for the global models is increased. Then the GRACE models perform significantly better than the CHAMP models and partly also than the combined pre-CHAMP models as long as the cut-off degree is within the GRACE sensitivity (about degree and order 100 to 120).

The geoid height differences at the GPS-levelling stations can be further analyzed by computing differences of the geoid height differences between any two stations. In detail, these geoid height "double-differences" between two stations are computed by subtracting the filtered geoid heights at the two GPS-levelling stations from each other. Then the same is done for the geoid heights derived from the global models at these stations. By subtracting the "observed" from the model derived geoid height differences the "geoid height double-difference" is computed for the two stations under investigation. This procedure can be repeated for any combination of two GPS-levelling stations for a data set. By collecting the "double differences" in distance classes and by computing RMS values for each distance class a tool is available, which shows the accuracy level per distance class for a gravity field model, which can then be translated into the corresponding spherical harmonic degree (20000 km/distance). For the US data set with more than 5000 points we get by this procedure up to nearly one million differences for some distance classes.

Figure 5 shows the results for such an analysis for the European GPS-levelling data set using a series of global gravity field models. As before, GPS-levelling geoid heights have been filtered with the GPM98C ultra-high degree gravity field model and all global models under test have been truncated at degree and order 60. The curves are a clear indicator that the GRACE models perform best, while the pre-CHAMP model performs worst. The TUM-2SP CHAMP model performs significantly better than the GRIM5-C1 model, but generally less well than the GRACE models. It is remarkable that for the very long distances the GRACE models seem to perform worse than the CHAMP model. Knowing from other analysis that the very low harmonic coefficients from GRACE are not very well determined (Tapley et al, 2005) this could be an indicator that this validation procedure provides some valuable information. As it can be seen in figure 5 for the shorter distances the results are not as clear as for the medium to long distances. Here, the limitations resulting from the area of investigation as well as the low number of sample values per distance class play a role.

***Sea Surface Topography Solutions***

Similar as for geoid heights and gravity anomalies over land the stationary part of the sea surface topography can be used for validating the global

| GPS-Levelling Data Set | Number Points | GRIM5-C1 | TUM-2SP | EIGEN-3P | GSM-2 0066 (GFZ) | GSM2 08-2003 (UTCSR) |
|---|---|---|---|---|---|---|
| USA | 5168 | 0.453 | 0.471 | 0.421 | 0.416 | 0.410 |
| Canada | 1587 | 0.549 | 0.600 | 0.528 | 0.522 | 0.524 |
| Europe | 180 | 0.397 | 0.331 | 0.296 | 0.283 | 0.280 |
| Germany | 675 | 0.303 | 0.257 | 0.194 | 0.195 | 0.194 |
| Australia | 197 | 0.543 | 0.527 | 0.532 | 0.502 | 0.501 |
| Japan | 837 | 0.594 | 0.548 | 0.502 | 0.515 | 0.514 |

**Table 5:** RMS of Geoid Height Differences between global Gravity Field Model truncated at Degree and Order 60 with filtered Geoid Height Data at GPS-Levelling Stations. For filtering the GPM98C Model from Degree 61 to 720 was used.

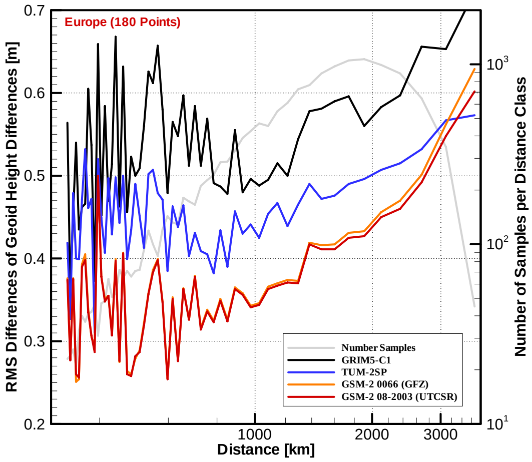


**Figure 5:** RMS of for distance classes of differences of geoid height differences for European GPS levelling data set.

gravity field models over the oceans. For this method altimetry derived mean sea surfaces have to be used in order to compute the sea surface topography by subtracting the geoid from the global models under validation. As for the GPS-levelling geoid heights also the mean sea surfaces have to be filtered such that they are comparable to the band-limited signal derived from the global models. For the example shown below the Goddard mean sea surface (Wang, 2001), after some pre-processing, was analyzed into a spherical harmonic series up to degree and order 720. Land values were filled with geoid heights derived from the EGM96 model in order to avoid sharp jumps at the ocean-continent boundaries. Then the mean sea surface and the gravity field model spherical harmonic series are solved up to a maximum degree. The selection of the maximum degree is strongly dependent on the sensitivity of the gravity field model for the stationary sea surface topography. Land and shallow water areas are eliminated, because they contain no or less good information from altimetry. By subtracting the geoid from the mean sea surface we get the derived sea surface topography, which can be further investigated by visual analysis or comparison to oceanographic results. By this method only the long to medium wavelengths of the global model can be analyzed.

Figure 6 shows the sea surface topography solutions in the Gulf stream area up to degree and order 60 for the CHAMP EIGEN-3P model and for one of the GRACE models (here GFZ 66 day solution). From both figures we can see that the GRACE based solution contains more realistic information for this frequency range. The CHAMP based solution shows some unrealistic features, which are caused by the coefficients between degree and order 30 and 60. Previous investigations have shown that for CHAMP the sensitivity for the sea surface topography signal is limited to about degree and order 30 (Gruber and Steigenberger, 2003). Additional analysis can be made by comparison of these geodetic derived sea surface topography models with oceanographically determined solutions.

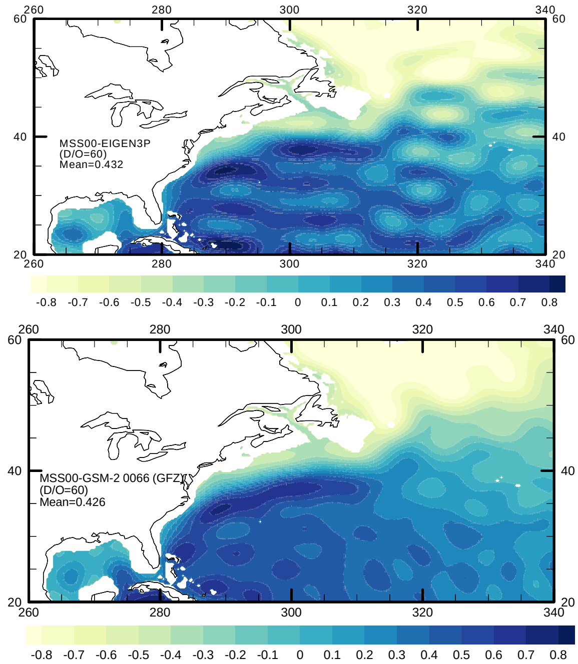


**Figure 6:** Sea Surface Topography Solution by Subtraction of EIGEN-3P Gravity Field Model from Goddard Mean Sea Surface (top) and by Subtraction of GFZ GRACE Model (bottom). All fields truncated at Degree 60.

## 6 Conclusions

The HPF is part of the ESA GOCE ground segment and is in charge of the production of level 2 products i.e. precise orbits and gravity field solutions. These level 2 products represent the official outcome of the mission and are available for further scientific studies in various disciplines of Earth sciences. The HPF has been developed, implemented and operated by the European GOCE Gravity Consortium under contract of ESA. All EGG-C member institutions (all together 10 university/research institutes across Europe) contribute in an important manner to the HPF. They provide additional institutionally/nationally funded personnel and computer resources. Quick-look processors are foreseen as a continuous validation tool for level 1b data. Any degradation in the GPS or gradiometer observations should immediately become visible in these rapid gravity field and orbit solutions. For the ultimate precision gravity field model it is planned to run three processors in parallel. Two have been developed directly for GOCE and one is an extension of a proven classical approach based on perturbation theory. By this the quality of the solutions can be assessed against each other.

The level 2 orbit and gravity field products undergo a thorough validation procedure. The product validation aims at providing realistic error parameters and at the selection of the official level 2 gravity field products to ESA. The final selection of the GOCE gravity field model will be done by ESA in cooperation with the HPF team based on the results of the validation. The orbit validation is done by the analysis of overlaps between consecutive orbital arcs, by statistical analysis of position and velocity differences between different orbit solutions and by a comparative analysis of satellite laser ranging residuals. The latter method is the only one, which provides an "absolute" error measure for position accuracies. Because of the low altitude of GOCE, for many satellite laser ranging stations it might however be difficult to track GOCE with sufficient accuracy. In conclusion, it is expected that GOCE orbits can be validated at a level of a few centimetres by internal comparisons and hopefully also by independent satellite laser ranging observations. For the validation of the GOCE gravity fields several methods will be applied. Internal errors will be investigated by the analysis of the variance-covariance matrix of the gravity field solutions. Here, error degree variances as well as errors propagated to other gravity field quantities and correlations between the spherical harmonic coefficients will be regarded. The internal errors shall be investigated in order to determine how realistic they are in view of external error estimates. External errors are determined by re-computation of orbits of other geodetic and altimetry satellites and the analysis of the tracking data residuals and by comparison to independent gravity field information over land and oceans. The former method specifically investigates the performance of the long wavelength components of the gravity field. For the latter method geoid heights on GPS-levelling stations, observed gravity anomalies and sea surface topography solutions shall be taken into account. For them, low-pass filters have to be applied in order to eliminate the signal above the maximum degree of the spherical harmonic series under test. The design of these filters as well as information about the quality of the comparison data sets is essential for the results of the gravity field validation. From the application of some validation methods to GRACE gravity field solutions it became obvious that it will be a very difficult task to derive absolute error estimates for the gravity field solutions. But, what these results have shown is, that it can be clearly identified, which global model performs better and worse. In conclusion, for GOCE we expect that, by further development of the filter procedure, by acquiring more and better test data and by developing additional test procedures we can identify the quality of the individual solutions and that we are able to quantify, whether the mission goal is met by these models.

## References


Bouman J., Koop R., Tscherning C.C., Visser P.: *Calibration of GOCE SGG Data using high-low SST, terrestrial Gravity Data and global Gravity Field Models*. Journal of Geodesy, 78, No. 1-2, pp. 124-137, 2004.

ESA: *Reports for Mission Selection 'The Four Candidate Earth Explorer Core Missions', Gravity Field and Steady-State Ocean Circulation Mission*; ESA SP-1233(1), ESA Publication Division, 1999.

Gerlach Ch., L. Földvary, D. Svehla, Th. Gruber, M. Wermuth, N. Sneeuw, B. Frommknecht, H. Oberndorfer, Th. Peters, M. Rothacher, R. Rummel, P. Steigenberger: *A CHAMP-only gravity field model from kinematic orbits using the energy integral.* Geophysical Research Letters, **30**, **20**, 2003. doi:10.1029/2003GL018025, 2003.

Gruber Th., Bode A., Reigber Ch., Schwintzer P., Balmino G., Biancale R. Lemoine J-M.; *GRIM5-C1: Combination Solution of the Global Gravity Field to Degree and Order 120*; Geophysical Research Letters, Vol. 27 No. 24, p. 4005-4008, 2000.

Gruber Th., Steigenberger P.: *Impact of new Gravity Field Missions for Sea Surface Topography Determination*; in Proceedings of 3rd Meeting of the International Gravity and Geoid Commission: Gravity and Geoid 2002, Ed. I.N. Tziavos, Editions Ziti, Thessaloniki, 2003

König R., Chen Z., Reigber Ch., Schwintzer P.; *Improvement in global Gravity Field Recovery using GFZ-1 Satellite Laser Tracking Data*, Journal of Geodesy, Vol. 73, 398-406, 1999.

Lemoine F.G., Kenyon S.C., Factor J.K., Trimmer R.G., Pavlis N.K., Chinn D.S., Cox C.M., Klosko S.M., Luthcke S.B., Torrence M.H., Wang Y.M., Williamson R.G., Pavlis E.C., Rapp R.H., Olson T.R.; *The Development of the Joint NASA GSFC and National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96*. NASA Technical Paper NASA/TP-1998-206861, Goddard Space Flight Center, Greenbelt/Maryland, 1998.

Muzi D., Popescu A., Floberghagen R., Demond F.J., Emanuelli P.P:, *Development Status of the GOCE Project*, Proceedings of the 2nd International GOCE User Workshop, ESA-SP569, 2004.

Reigber Ch., Schwintzer P., Neumayer K.H., Barthelmes F., König R., Förste Ch., Balmino G., Biancale R., Lemoine J.M., Loyer S., Bruinsma S., Perosanz F., Fayrad T.: *The CHAMP-only Earth Gravity Field Model EIGEN-2*, Advances in Space Research, Vol. 31, No. 8, pp.1883-1888, 2003.

Reigber, Ch., Jochmann, H., Wünsch, J., Petrovic, S., Schwintzer, P.,Barthelmes, F., Neumayer, K.-H., König, R., Förste, Ch., Balmino, G., Biancale, R., Lemoine, J.-M., Loyer, S., Perosanz, F.: *Earth Gravity Field and Seasonal Variability from CHAMP* . In: Reigber, Ch., Lühr, H., Schwintzer, P., Wickert, J. (eds.), Earth Observation with CHAMP - Results from Three Years in Orbit, Springer, Berlin, 25-30, 2005.

Svehla, D., Rothacher, M.: *Kinematic and Reduced–Dynamic Precise Orbit Determination of Low Earth Orbiters*, Advances in Geosciences, 1, 1, 47-56, 2003a.

Svehla, D., Rothacher, M.: *Testing Kinematic and Dynamic Orbit Determination Approaches for GOCE Mission with Data from the CHAMP and JASON-1 Satellite.* Geotechnologien Science Report, Rudloff, A., Stroink, L. (Ed.), 2003, 3, 170-175. Koordinationsbüro Geotechnologien, Potsdam. 1619-7399, 2003b.

Tapley B.D., Ries J.,Bettadpur S.,, Chambers D., Cheng M., Condi F., Gunter B., Kang Z., Nagel P., Pastor R., Poole S., Wang F.: *GGM02 – An improved Earth Gravity Field Model from GRACE*, submitted to Journal of Geodesy, 2005.

Wang Y.M.: *GSFC00 mean Sea Surface, Gravity Anomaly, and vertical Gravity Gradient from Satellite Altimetry*. Journal of Geophysical Research, Vol. 106, C12, pp. 31467-31174, 2001.

Wenzel H.G.: *Schwerefeldmodellierung durch ultra-hochauflösende Kugelfunktionsmodelle*; Zeitschrift für Vermessungswesen, 5/1999, 144-154, 1999.