Status and Goals of the GOCE Mission and the GOCE-GRAND II Project

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Abstract & Introduction

GOCE is the first core mission selected for the ESA Earth science satellite programme "Living Planet". The objective of this programme is to provide data from space necessary for an improved understanding of the interactions of atmosphere, oceans, ice and solid Earth. GOCE will be launched in spring 2008. It aims at the determination of the stationary part of the Earth's gravity field and geoid with maximum spatial resolution and accuracy (1-2 cm geoid height accuracy with spatial resolution of approximately 100 km). The mission is complementary to GRACE, which is primarily designed to measure the temporal variations of gravity and geoid.
The first phase of the GOCE-GRAND project (2002-2004) was dedicated to the development of a gravity analysis system for GOCE data. It included kinematic orbit computation, the determination of the long wavelength gravity field from these orbits and from common mode accelerometry based on the so-called energy conservation method, several gradiometric gravity analysis methods and development of algorithms for data reduction (temporal effects) and for external calibration and internal validation. GOCE-GRAND II is refining and extending the developed algorithms aiming at the adaptation of these algorithms to the final characteristics of the sensor system as it will be brought into orbit. This implies that all design changes are taken into account, that realistic stochastic models are developed for all sensor components and that the analysis algorithms are capable to cope with a large number of measurements and unknown parameters. In addition GOCE-GRAND II will address questions concerning the combined GRACE/GOCE data analysis and validation of the GOCE results by means of methods such as GPS-levelling and ocean dynamic topography. In short, GOCE GRAND II yields an important segment of GOCE gravity field analysis, of GOCE data combination and of in-depth and independent validation of GOCE gravity products.

GOCE Mission

To reach the science goals, precondition is that GOCE can determine gravity and geoid with a precision of $10^{-6}\cdot g$ (corresponding to 1 mgal) and 1-2 cm, respectively, both with a spatial resolution of better than 100 km half wavelength and that these results are achieved free of long wavelength systematic errors. The mission performance depends on the gravity sensor system on-board GOCE. Core instrument is a three axis gravity gradiometer. It consists of three pairs of orthogonally mounted 3-axis accelerometers. The gradiometer baseline of each axis is about 50 cm. The accelerometer precision is 10^{-12} m/s^2 per square-root of Hz along two axes and a third axis with less sensitivity. From the measured gravitational acceleration differences the three main diagonal terms of the gravitational tensor can be determined with high precision. The extremely high gradiometric performance of the instrument is confined to the so-called measurement bandwidth (MBW). In addition, the gradiometer yields the angular acceleration about the out-of-plane axis of the gradiometer. It is required for angular control and for the removal of the angular effects from the gradiometer data. The gradiometric angular rates (in the MBW) in combination with the angular rates as derived from the star sensor readings are used for angular control of the spacecraft. The satellite has to be guided well controlled and smoothly around the Earth in one full revolution per orbit revolution. Angular control is attained via magnetic torquers, which leaves part of each orbit revolution uncontrolled. In order to prevent non-gravitational forces acting on the spacecraft to "sneak" into the measured differential accelerations as secondary effect, the satellite is kept "drag-free" in along-track direction by means of a pair of ion thrusters. The necessary control signal is derived from the available "common-mode" accelerations (=mean accelerations) along the three orthogonal axes of the accelerometer pairs of the gradiometer. The gradiometric and angular contribution to the common mode acceleration, which is a result of the imperfect symmetry of the gradiometer relative to the spacecraft centre of mass, has to be modelled.

The second gravity sensor device is a newly developed European GPS receiver. From its measurements the orbit trajectory is computed to within a few centimetres, either purely geometrically, a so-called kinematic orbit, or by the method of reduced dynamic orbit determination. As the spacecraft is kept in an almost drag-free mode (at least in along-track direction within an extended measurement bandwidth) the orbit motion is purely gravitational. It complements the gradiometric gravity field determination by covering the long wavelength part.

The orbit altitude is extremely low, only about 250 km. This is essential for a high gravitational sensitivity. No scientific satellite has been flown at such low altitude. Its altitude has to be maintained through orbit manoeuvres, which are carried out at regular intervals. Again, this very low altitude results in high demands concerning drag-free and attitude control. Finally, any time varying gravity signal of the spacecraft itself must be excluded. This results in very high requirements on metrical stiffness and thermal control.

In summary, GOCE is a technologically very complex and innovative mission. The gravitational field sensor system consists of a gravitational gradiometer and GPS receiver as core instruments. Orientation in inertial space is derived from star sensors. Common mode and differential mode accelerations from the gradiometer and orbit positions from GPS are used together with ion thrusters for drag-free control and with magneto-torquers for angular control. The system elements are summarized in the following table.

Sensor	Measurements
3-axis gravity gradiometer	Gravity gradients Γ_{xx}, Γ_{yy}, Γ_{zz} in instrument system and in MBW (measurement bandwidth) Angular accelerations (high accurate around y-axis, less accurate around x, z axes) Common mode accelerations
Star sensors	High rate and high precision inertial orientation
GPS receiver	Orbit trajectory with cm-precision
Drag control with 2 ion thrusters	Common mode accelerations from gradiometer and GPS orbit
Angular control with magnetic torquer	Based on angular rates from star sensors and gradiometer
Orbit altitude maintenance	Based on GPS orbit
Internal calibration (and quadratic factors removal) of gradiometer	With cold gas thrusters (random pulses)

GOCE-GRAND II Project Overview

GOCE GRAND-II aims at

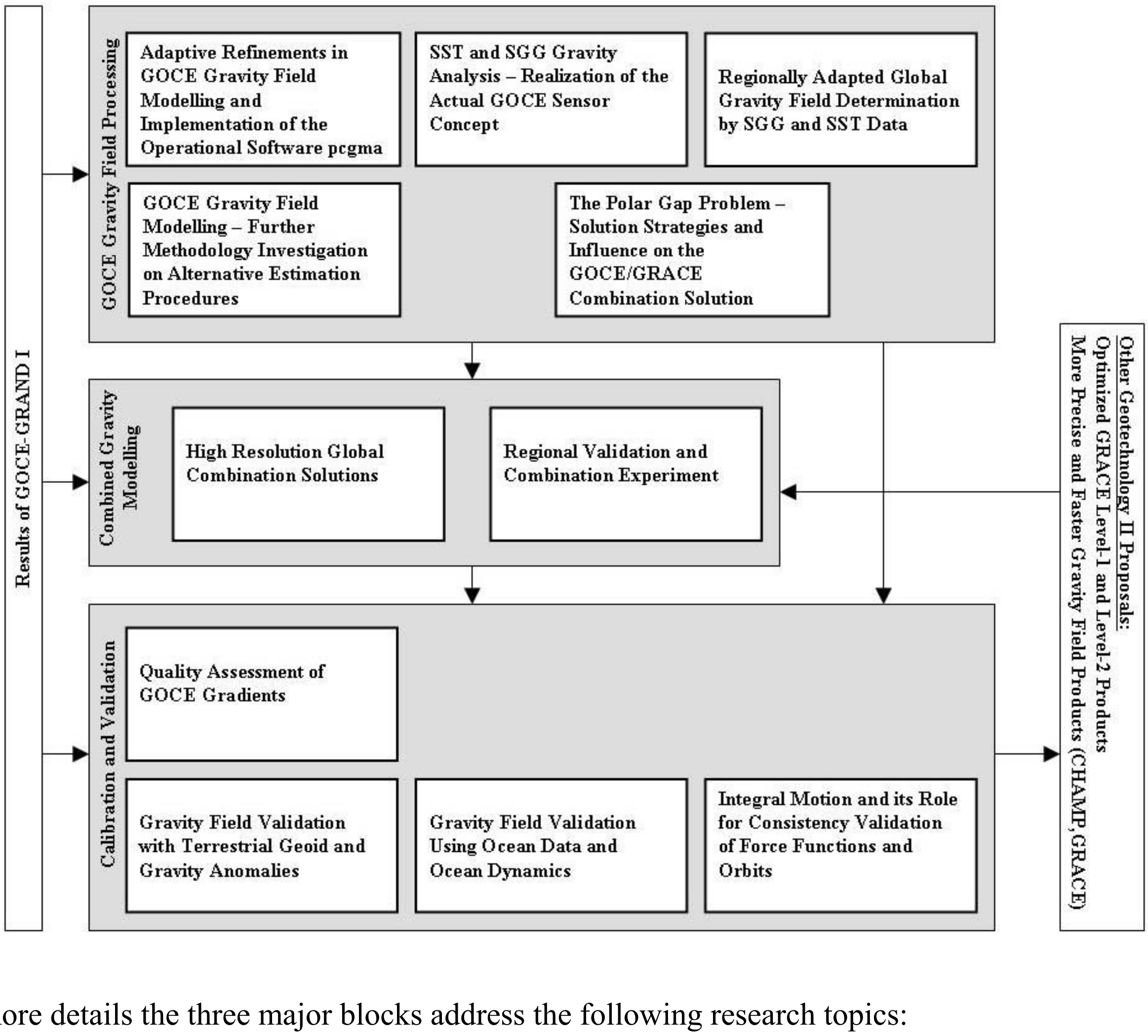
(1) an accurate high resolution gravity modelling from a combined analysis of gravity gradiometry measurements and high-low GOCE to GPS tracking taking into account the actual GOCE sensor configuration, orbit characteristics and mission profile,

(2) a combination of GOCE with on the one hand CHAMP and GRACE data and on the other hand regional terrestrial data with the objective to attain best possible global and regionally refined gravity and geoid products and

(3) a comprehensive external calibration, quality assessment and validation based on independent data.

This is to be achieved before the background of the novelty of the sensor system and spacecraft characteristics as well as the expected high quality of the GOCE gravity and geoid products. The project leads to fully operational processing modules that will be applied to actual GOCE mission data. GOCE GRAND II will be based on the algorithms and findings of GOCE GRAND I.

The project is organized along three main blocks in accordance with the three basic objectives given above. Each block consists of several work packages (compare with the figure below showing the work packages and the partners involved). There is a logical flow of results from block one to block two to block three. Combined gravity modelling requires an exchange of data and know-how with the GRACE project. In turn GRACE and CHAMP will benefit from validation experiments carried out in GOCE GRAND II.



In more details the three major blocks address the following research topics:

Block 1: GOCE Gravity Field Processing

The major challenges of GOCE gravity analysis are as follows:

- Adequate exploitation of the high resolution gravity sensor system requires a very large and complex system of equations to be solved.
- The gravity gradiometer on-board of GOCE has a limited measurement bandwidth. Thus, at long wavelengths the gravity gradiometer data has to be complemented by high-low GPS to GOCE tracking. This, in turn requires very precise orbit

determination, high quality gravity reconstruction from these orbits and an optimal mechanism of data combination of satellite-to-satellite tracking with gradiometry.
- The GOCE sensor system had to be modified. The originally planned FEEP's had to be replaced by angular control by magneto-torquing. This has severe implications on the measurement model, on the gravity field recovery procedure and on the stochastic model of the gradiometer components.
- It is expected that global gravity representation e.g. in terms of a spherical harmonic series does not fully exploit the information content in certain regions with high gravity variations. Regional adaptive methods will lead to local focussing in these areas.
- GOCE will have a sun-synchronous orbit. As a result the polar caps with an opening circle of 6.5° will not be covered with data. Adequate analysis strategies and complementary polar gravity data are needed to cope with this problem.

The resulting work packages of the GOCE-GRAND II project (as shown in the figure above) are studies in a close cooperation by the project partners IAPG (Technical University Munich), ITG (University Bonn) and GIS (University Stuttgart).

Block 2: Combined Gravity Modelling
The GOCE and GRACE global gravity field models and terrestrial data sets complement each other in various ways. GOCE models will contribute to the highly accurate medium and short wavelength gravity field components up to degree and order 200 in terms of spherical harmonics, while GRACE is able to provide the long wavelength part and the temporal variations of Earth's potential. Global and regional terrestrial data sets add shorter wavelength field structures (above degree and order 200). Hence, global and local combination solutions of GOCE, GRACE and terrestrial data have the potential to provide the complete geoid spectrum covering all wavelengths with a total accuracy of about 1 cm. Within GOCE-GRAND II global as well as a local combinations are investigated by the project partners GFZ, BKG and IFE (University Hannover).

For global solutions, several terrestrial and altimetric data sets are collected and unified in one homogenous data base. These data will be combined on the basis of rigorous normal equations, with all available GOCE and GRACE data, in particular GOCE-SGG data, using the classical direct combination method, and block diagonal techniques for the short wavelength part. The resulting high resolution gravity field model, complete up to degree and order 360, will be the basis for local refinements.

Within a regional validation and combination experiment in Germany, terrestrial gravity and terrain data, GPS/levelling data and deflections of the vertical are employed. Before combination, the terrestrial gravity data are validated by spot-checks with absolute gravity data at selected points. In addition, a transportable zenith camera is used for the observation of deflections of the vertical along two profiles, one North-South and one East-West with a length of several hundred kilometres each. This allows a cross validation of GPS/levelling and astronomic results. The validated terrestrial data sets then are combined with GOCE geo-potential models using various modelling techniques.

Block 3: Calibration and Validation
A first quality assessment of GOCE gradiometer measurements can be performed at satellite level by comparing the observed gravity gradients with reference gradients. These reference values are computed from existing geopotential models and from terrestrial gravity data by upward continuation or obtained from satellite measurements itself. For the latter purpose, a

near real-time validation by cross-over (XO) analysis is investigated and applied operationally. In addition, regional gravity data are upward continued to gradients at GOCE altitude, serving as reference gradients for the calibration and validation of the GOCE data. In this context, also the functional model for the external calibration is investigated, and appropriate statistical quality parameters are defined to assess the calibration results. The validation on gradient level is performed by IFE (University of Hannover).

The gravity models are validated by means of independent gravity field information, i.e. information not already included in the GOCE gravity field determination. Thus, validation means independent assessment or control of GOCE gravity field models. Such independent information is:

- terrestrial point or mean gravity anomalies (based on gravity measurements and levelling),
- ocean point, profile or mean gravity anomalies (based on ship gravimetry or satellite altimetry),
- geoid height differences (derived from GPS and levelling),
- sea surface topography (from ocean modelling or ocean levelling),
- assimilation of GOCE fields in ocean circulation models for estimation of ocean circulation and transports.
- satellite orbits,
- gravity models (from previous missions such as GRACE, CHAMP and others).

A fundamental difficulty of any validation experiment is that GOCE is expected to provide the best possible gravity field model ever. In other words, the GOCE gravity field model is expected to be the best global gravity information in the spherical harmonic "band" up to its maximum degree. At most, the independent validation data sets can be expected to be of comparable (or better) quality regionally and/or in certain spectral windows. Employing for validation regional data sets with point or mean values leads to the problem of how to compare their quality with that of a set of spherical harmonics, representing global but band limited information. As a result within GOCE-GRAND II methods are investigated and developed to validate the global GOCE gravity field models with independent information as listed above taking into account the problem of comparability of the band-limited spherical harmonic series with these "test" data sets. This work is performed by the project partners IAPG (Technical University Munich, IFM (University Hamburg) and ITG (University Bonn).

Summary and Conclusions

During the first two year of the GOCE-GRAND II project significant progress has been made in all three of the above areas. In order to test the implemented algorithms for gravity field determination a realistic simulated data set is used. For the combination and validation activities an observation campaign mostly has been executed, which provides a significant amount of new test data. Also several validation methods on gradient and on gravity field level (including oceanographic methods) have been implemented and successfully applied.

Further Information and Related Theses

Further information on the GOCE mission and its applications can be found on the Web-pages of the German GOCE Project Office and ESA (see: www.goce-projektbuero.de and www.esa.int/esaLP/LPgoce.html).

As a result from the GOCE-GRAND project a series of PhD theses has been published or are close to finalization. The following list provides an overview of finalized and planned dissertations related to the GOCE GRAND project:

- Boxhammer Ch./ITG Universität Bonn: Effiziente numerische Verfahren zur sphärischen harmonischen Analyse von Satellitendaten (16.6.2006).
- Wolf, K.I./IFE Universität Hannover: Kombination globaler Potentialmodelle mit terrestrischen Schweredaten für die Berechnung der zweiten Ableitungen des Gravitationspotentials in Satellitenbahnhöhe (13.2.2007).
- Baur O./GIS Universität Stuttgart: Die Invariantendarstellung in der Satellitengradiometrie (20.3.2007).
- Alkhatib, H./ITG Universität Bonn: On Monte Carlo methods with applications to the current satellite gravity missions (1.6.2007).
- Kargoll, B./ITG Universität Bonn: On the Theory and Application of Model Misspecification Tests in Geodesy. (20.6.2007)
- Siemes Ch./ITG Universität Bonn: Digital Filtering Algorithms - Tools for Decorrelation within Large Least Squares Problems in the Context of Satellite Gravity Gradiometry (in preparation 2007).
- Wermuth M./IAPG TU München: Gravity field analysis from satellite missions (in preparation 2007)
- Eicker A./ITG Universität Bonn: Regionale/globale Schwerefeldbestimmung mit ortslokalisierenden Basisfunktionen aus SST- und SGG-Daten (in preparation 2007)
- Löcher A./ITG Universität Bonn: Die Verwendung von Bewegungsintegralen zur Schwerefeldbestimmung und zur Evaluierung von Schwerefeldmodellen (in preparation 2007)