

ESA's Gravity Field and Steady-State Ocean Circulation Explorer GOCE

Reiner Rummel, Thomas Gruber, Jakob Flury and Anja Schlicht

Summary

GOCE has been launched on March, 17, 2009. It is the first satellite of the Living Planet Programme, which is ESA's Earth science programme. It is aiming at a better understanding of the Earth system. The mission objective of GOCE is the determination of the Earth's gravity field and geoid with high accuracy and maximum spatial resolution. The geoid, combined with the actual mean ocean surface as derived from twenty years of satellite radar altimetry, will yield global dynamic ocean topography. It will serve ocean circulation and ocean transport studies and sea level research. GOCE geoid heights will allow conversion of GPS heights to high precision heights above sea level. Gravity anomalies from GOCE will be used for gravity-to-density inversion and in particular for studies of the Earth's lithosphere and upper mantle.

GOCE is the first satellite carrying a gravitational gradiometer. In essence the spacecraft together with all its sensors can be regarded as a satellite gravimeter. The mission is unique and novel in several ways. Precise GPS-tracking with a newly developed European receiver is providing the orbit with cm-precision. Orbit analysis will give the long wavelength part of the gravity field and be complementary to the high resolution gravimetric data of the gradiometer. The extremely low orbit of only 265 km is kept free of drag by ion-thrusters. The spacecraft is guided smoothly around the Earth by magnetic torquers. The gradiometer and star sensors deliver the data necessary for drag-free and angular control. The high demand on the purity of the gravimetric signal is achieved via extreme levels of thermal control and material stiffness.

Zusammenfassung

Am 17. März 2009 wurde GOCE gestartet. Er ist der erste Satellit des Living Planet-Programms, dem Erdbeobachtungsprogramm der ESA. Das Ziel der GOCE-Mission ist die Bestimmung des Erdschwerfeldes und des Geoids mit maximaler räumlicher Auflösung bei möglichst hoher Genauigkeit. Das Geoid in Verbindung mit der gegenwärtigen mittleren Ozeanoberfläche, gewonnen aus 20 Jahren Satellitenradaraltimetrie, ist der Schlüssel zur globalen dynamischen Ozeantopographie. Diese dient zu Studien der Ozeanzirkulation, der Transporte im Ozean und der Meeresspiegeländerungen. Geoidhöhen, wie sie GOCE bestimmt, sind nötig um GPS-Höhen in sehr genaue Höhen über dem Meeresspiegel umzurechnen. Schwereanomalien hingegen werden für die Inversion von Schwere in Dichte und dabei speziell in Studien über die Lithosphäre und des oberen Erdmantels benötigt.

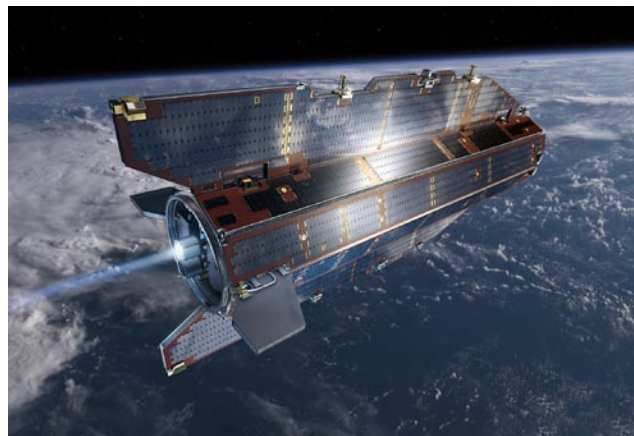


Fig. 1: GOCE in orbit (ESA)

GOCE ist der erste Satellit, der ein Gravitationsgradiometer mit sich führt. Im Wesentlichen kann der ganze Flugkörper mit all seinen Sensoren als Satellitengravimeter betrachtet werden. Diese Mission ist neu und einmalig in mehreren Beziehungen. Ein neuer in Europa gebauter GPS-Empfänger erlaubt die Bahnbestimmung in cm-Genauigkeit. Aus der Analyse der Bahn kann auf den langwelligen Anteil des Erdschwerfeldes geschlossen werden, komplementär zu den hoch aufgelösten gravimetrischen Daten des Gradiometers. Die extrem niedrige Umlaufbahn von nur 265 km wird durch ein Ionentriebwerk reibungsfrei gehalten. Der sanfte Flug des Satelliten um die Erde wird durch Magnetic Torquer sichergestellt. Sowohl das Gradiometer als auch die Sternsensoren liefern die notwendigen Daten, die einen reibungsfreien, lagekontrollierten Flug ermöglichen. Der hohe Anspruch an die Reinheit des gravimetrischen Signals hat auch eine extreme Anforderung an die Temperaturstabilität und die Steifigkeit des Materials zur Folge.

1 Introduction

»The Intergovernmental Panel on Climate Change (IPCC) was established to provide the decision-makers and others interested in climate change with an objective source of information about climate change« (first sentence of »IPCC mandate«, www.ipcc.ch/about/index.htm). Its first report was published in 1990. The fourth assessment report published in 2007 points out a rather rapid climate change. It also claims that to a large extent this change may be anthropogenic. During its preparation it has been debated in several publications that the key to more certainty in our understanding of the complexity of the Earth as a system is more and better data (Hogan

2005 and the references therein). For sure, satellite data are playing a prominent role in removing this data deficiency. They are global, repetitive and uniform, near-simultaneous and near-real-time. An important contribution comes from geodetic satellites, providing global and unique observations on surface geometry and deformations, on Earth rotation, and on variations of the Earth gravity field and mass distribution. In the mid-nineties the importance of a consistent observing and modelling strategy of the Earth as a system has been formulated by the European Space Agency (ESA). The Agency's »Living Planet« Programme for Earth Observation (ESA 1999a) is aiming at an improved understanding of the various components of the Earth System as well as their interactions. The programme has been revisited and new challenges been formulated in 2006, resulting in the new document »The Changing Earth« (ESA 2006).

The Gravity and steady-state Ocean Circulation Explorer (GOCE) is the first core mission of this ESA programme. It has been selected in 1999 (ESA 1999b) and developed since then. Its launch has been delayed several times, it took finally place on March 17, 2009. In 2009 also two other missions of the »Living Planet« programme will go into orbit: the ice altimetry satellite mission CRYOSAT-2 and the soil-moisture and ocean salinity mission SMOS. The mission objective of GOCE is the determination of the Earth's gravity field and geoid with high accuracy and maximum spatial resolution. More specifically, geoid heights will be determined with cm-accuracy and gravity variations with 1 part-per-million of »g«, in both cases with a spatial resolution of about 100km on the Earth's surface. It should be noted that these mission objectives are complementary to those of the GRACE mission. The primary goal of GRACE is the measurement of the temporal variations of the Earth's gravity field, caused by the transport of masses and their redistribution in the Earth system. While the goal of GOCE is maximum spatial resolution, the GRACE mission aims at maximum precision at some expense in terms of highest spatial resolution. Both types of gravity field information are complementary and important for Earth system science. The GRACE time series shows the path and size of mass movements, related to processes such as melting ice sheets, the global seasonal water cycle, sea level variations, post glacial mass re-adjustments and others. For the first time it is now possible to quantify – so to speak to weigh – global mass re-distribution. GOCE, on the other hand, will give one global and detailed map of spatial gravity and geoid variations, with applications in geodesy and Earth sciences.

The geoid corresponds to the world oceans at complete rest, their surface purely determined by gravity, without any exterior forces from winds, pressure variations or tides. Over the oceans the geoid serves as reference for studies of dynamic ocean topography (DOT). DOT is the small deviation of the global mean ocean surface from the geoid. It is derived from comparing the geoid with the mean ocean surface as measured by radar ocean alti-

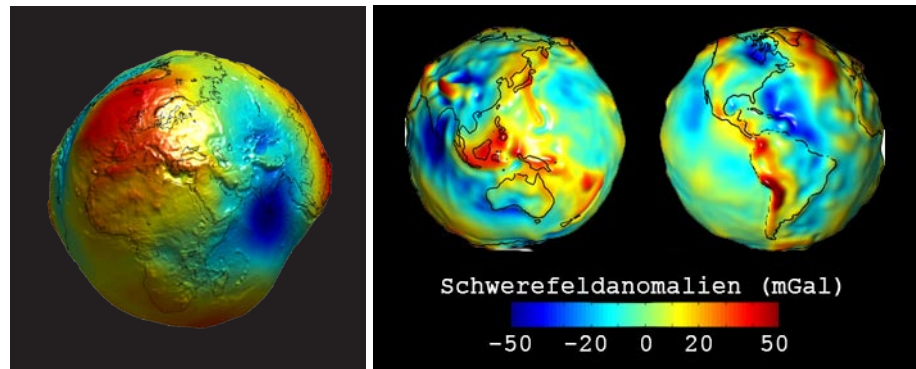


Fig. 2: The geoid (left) and gravity anomalies (right) (ESA)

metry. Altimetric observations of the ocean surface are available since more than twenty years and will continue in the future. Assuming geostrophic balance, DOT can be translated into global ocean surface circulation. The effect of climate change on ocean circulation patterns and on mass and heat transport will show up as time variations of ocean circulation. The temporal gravity changes as measured by GRACE provide variations of ocean bottom pressure and add therefore information about ocean circulation at depth. Again one can see the complementarity of the two missions. The geoid as derived from GOCE will also serve as a uniform global height reference for sea level research and geodesy. Tide gauges will become referenced to one level surface and their sea level records will become comparable on a global scale. In the future, connections such as from the British Islands to the European continent will not lead to height offsets in the order of decimeters any more. On land, geoid models are an increasingly important component of height reference systems (Heck and Rummel 1990). GOCE will introduce a new standard in this field where major progress in accuracy has already been achieved due to the GRACE geoid models. The GOCE geoid will be an essential step to establish the well known principle of GPS leveling to convert any GPS-(ellipsoidal) height into a height above sea level. This will be used by all national mapping agencies and in geodetic engineering, and many secondary benefits will result from it. A longer term objective is the development of a unified world height system. One of the advantages would be a consistent height reference for geographical information systems (GIS) worldwide. GOCE will also allow a better reconstruction of ocean bathymetry, in ocean areas where no direct soundings are available. Gravity anomalies, the second of GOCE's mission objectives, provide a look into the Earth's interior,

albeit not a unique one. One is faced with an inverse problem. Gravity anomalies represent a detailed picture of the total of the gravitational attraction of all masses. It is not possible to distinguish individual effects. Nevertheless gravity anomalies contain a wealth of information about the composition of the Earth's interior and its dynamics. Gravity anomalies are a measure of mass imbalance; they represent therefore a »frozen« picture of the geodynamics of the past hundred millions of years, in particular of the continental and ocean lithosphere and the Earth's upper mantle. There is no direct way to look into the interior. Inversion requires joint modelling based on all available information such as seismic tomographic data, magnetic data, topographic and crustal models, plate tectonic models and laboratory results about structure and composition.

GOCE is a cornerstone of the Global Geodetic Observing System (GGOS), the central integrated research component of the International Association of Geodesy (IAG). A primary objective of GGOS is to provide »metric« to Earth system measurements. This requires the unification of all geodetic space techniques in one Earth-fixed coordinate system with a precision of one-part-per-billion (1 ppb). While techniques such as geodetic VLBI (Very Long Baseline Interferometry), satellite laser ranging and GPS will help to tie the Earth's geometric shape, as well as all changes of shape, to this coordinate frame, GOCE will help to establish a corresponding height reference. These are heights above sea level, or more accurately, above the geoid, i.e. physical heights as determined by the geometry of the Earth's gravity field. Since Earth processes in the atmosphere, hydrosphere and cryosphere take place under the action of gravity, geoid and plumb lines are the natural geometric reference for monitoring these processes.

2 The GOCE Launch

It took as far as the 17th of March 2009 until the Rockot launcher lift off the launch site of Plesetzsk, Russia, at 15:21:13 CET to put GOCE into orbit. But it was a textbook launch and all went well since then.

After one orbital revolution, about 90 minutes after launch, the separation of the satellite from the third stage of the rocket took place and the first signals of GOCE reached ESA's mission control center in Darmstadt. Soon it turned out that the injection orbit was close to perfect. With an altitude of 283.5 km, only 1.5 km lower than planned, and an inclination of 96.5° GOCE was released into its sun-synchronous, near polar orbit with very low angular rates; best foundations to reach the sun pointing mode to fill up the batteries and successively switch on the instruments. So on the 7th of April ESA could announce »GOCE heart is beating« as the

delicate main instrument, the gravitational gradiometer, had successfully overcome the first tests. The very low sun-synchronous orbit is the reason, why GOCE reached a period of sun eclipses on 16th of April. In this phase the satellite is too long in Earth shadow to fill up the batteries completely and run all instruments in the measuring mode but the energy should last to calibrate the gradiometer.



Fig. 3: Rocket launcher with GOCE at the launch pad (ESA)

At the end of August GOCE will start its first measurement phase at an altitude of 263 km extending until April 2010. The propellant will last at least for a second measurement phase scheduled for September until April 2011.

3 The GOCE Mission

The GOCE satellite mission is unique in several ways. In the following we will summarize its main characteristics. The mission consists of two complementary gravity sensing systems. The large scale spatial variations of the Earth's gravitational field will be derived from its orbit, while the short scales are measured by a so-called gravitational gradiometer. Even though satellite gravitational gradiometry has been proposed already in the late fifties (Carroll and Savet 1959), the GOCE gradiometer will be the first instrument of its kind to be put into orbit. The principles of satellite gradiometry are described in (Rummel 1986), compare also (Colombo 1989) and (Rummel 1997). The purpose of gravitational gradiometry is the measurement of the second derivatives of the gravitational potential. In total one could measure nine second-derivatives in the orthogonal coordinate system of the instrument. Due to symmetry only six of them are independent; because of Laplace condition holding for the diagonal terms, only five components remain indepen-

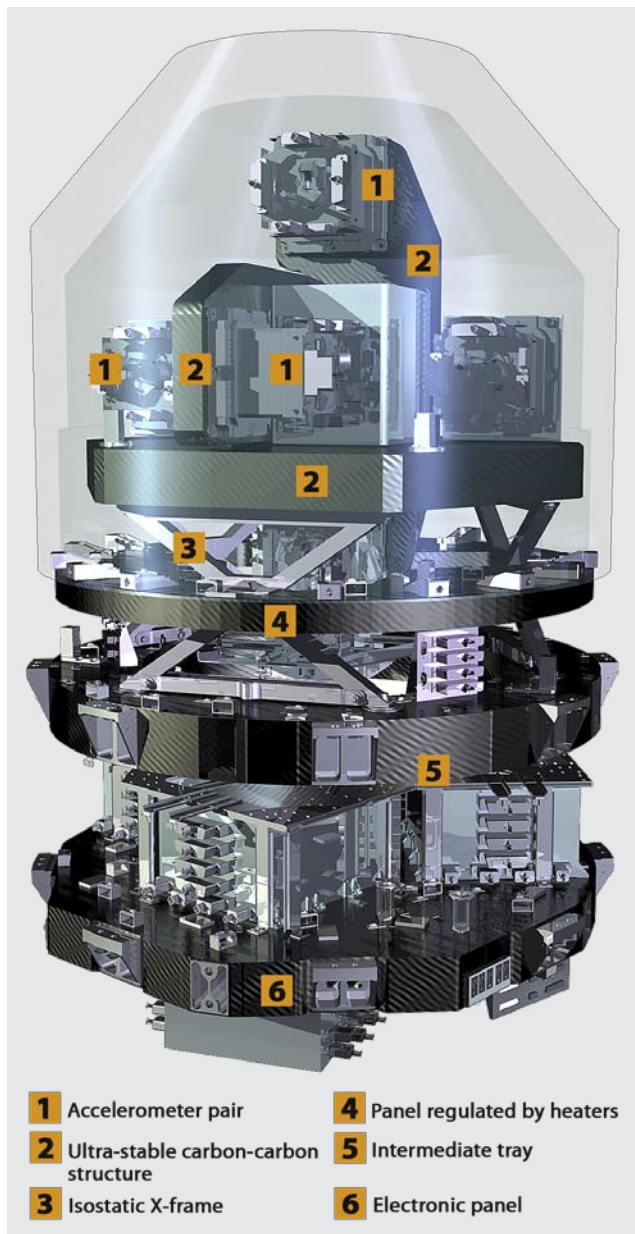


Fig. 4: GOCE gravitational gradiometer

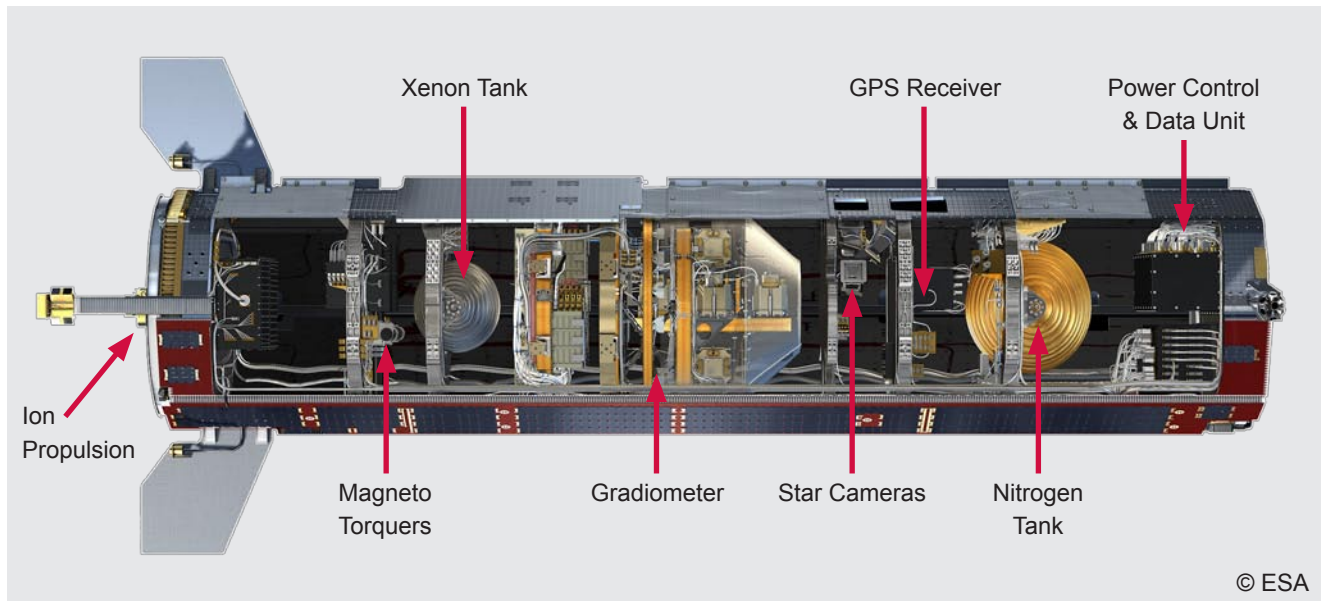
dent. The GOCE gradiometer is a three axis instrument and its measurements are based on the principle of differential accelerometry. It consists of three pairs of orthogonally mounted 3-axis accelerometers (see fig. 4). The gradiometer baseline of each axis is 50 cm. The precision of each accelerometer is 10^{-12} m/s^2 per square-root of Hz along two axes, the third axis has much lesser sensitivity because of the required pre-launch calibration on ground. From the measured gravitational acceleration differences, the three main diagonal terms and one off-diagonal term of the gravitational tensor can be determined with high precision. These are the three diagonal components Γ_{xx} , Γ_{yy} , Γ_{zz} as well as the off-diagonal component Γ_{xz} , while the components Γ_{xy} and Γ_{yz} are less accurate. Thereby the coordinate directions of the instrument are in flight direction (x), cross direction (y) and in radial direction (z).

The extremely high gradiometric performance of the instrument is confined to the so-called measurement bandwidth (MBW).

The gradiometric principle based on differential accelerometry does only hold if all six accelerometers (three pairs) are perfect twins and if all accelerometer test masses are perfectly aligned. In real world small deviations from such an idealisation are unavoidable. Thus, calibration of the gradiometer is of utmost importance. Calibration is essentially the process of determination of the differential parameters of an affine transformation between an ideal and the actual set of accelerometer measurements. The unknown calibration parameters are therefore differential scale factors, rotations and mis-alignments. They are derived in orbit by randomly shaking the satellite by means of a set of cold gas thrusters and comparing the actual output with the theoretically expected one. Before calibration the non-linearities of each accelerometer are removed electronically, i.e. the capacitive electronic feedback system of proof mass and electrodes is brought into its linear range.

The gradiometric signal is superimposed by the effects of angular velocity and angular acceleration of the satellite in space. Knowledge of the latter is required for angular control and for the removal of the angular effects from the gradiometer data. The separation of angular acceleration from the gradiometric signal is possible from a specific combination of the measured acceleration differences. The angular rates (in the MBW) from the gradiometric data in combination with the angular rates as derived from the star sensor readings are used for attitude control of the spacecraft. The satellite has to be guided well controlled and smoothly around the Earth. While being Earth pointing it performs one full rotation per orbit revolution. Angular control is attained via magnetic torquers, i.e. using the Earth's magnetic field lines as orientation. This approach leaves, however, uncontrolled one directional degree of freedom at any moment. In order to prevent non-gravitational forces, in particular atmospheric drag, that act 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 (sum instead of differences of the measured accelerations) along the three orthogonal axes of the accelerometer pairs of the gradiometer. Some residual gradiometric and angular contribution will also add to the common mode acceleration. This is a result of the imperfect symmetry of the gradiometer relative to the spacecraft centre of mass and 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



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Fig. 5: GOCE satellite and instruments

(at least in along-track direction) the orbit motion can be regarded as purely gravitational. It complements the gradiometric gravity field determination by covering the long wavelength part of the gravity signal.

The orbit altitude is extremely low, only about 265 km. This is essential for a high gravitational sensitivity. No scientific satellite has been flown at such low altitude so far. Its altitude is maintained through the drag-free control and additional orbit manoeuvres, which are carried out at regular intervals. Again, this very low altitude results in high demands on drag-free and attitude control. Finally, any time varying gravity signal of the spacecraft itself must be excluded. This results in extreme tight 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 together with magneto-torquers for angular control. The satellite and its instruments are shown in fig. 5. The system elements are summarized in tab. 1.

4 GOCE Activities in Germany

GOCE is a truly European mission with significant German contributions. The prime contractor of the mission is an Italian company, the accelerometers were produced in France, while the highly sophisticated and dedicated satellite platform was built by EADS Astrium in Friedrichshafen, Germany. The GOCE satellite is designed to meet extremely demanding rigidity requirements in

Tab. 1: Sensor elements and type of measurement delivered by them (approximate orientation of the instrument triad: x = along track, y = out-of-orbit-plane, z = radial)

Sensor	Measurements
3-axes gravity gradiometer	Gravity gradients Γ_{xx} , Γ_{yy} , Γ_{zz} , Γ_{xz} in instrument system and in MBW (measurement bandwidth) Angular accelerations (highly accurate around y-axis, less accurate around x-, z-axis) 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	Based on common mode accelerations from gradiometer and GPS orbit
Angular control with magnetic torquers	Based on angular rates from star sensors and gradiometer
Orbit altitude maintenance	Based on GPS orbit
Internal calibration (and quadratic factors removal) of gradiometer	Calibration signal from random shaking by cold gas thrusters (and electronic proof mass shaking)

order to minimize acceleration disturbances due to platform deformation. The platform backbone consists of a dedicated carbon-carbon structure. Another challenge was the implementation of the novel and continuous drag free orbit and attitude control system. The residual atmospheric drag is also the reason for the unusual streamlined shape of the satellite.

The GOCE gravity field processing is carried out for ESA by a consortium of ten European universities and research institutes, with three of them being located in Germany: Technische Universität München – which leads the overall processing –, the University of Bonn and Deutsches GeoForschungsZentrum in Potsdam. The consortium will provide data products such as precise orbits, gravity gradients, as well as gravity and geoid models expressed in grid values and in spherical harmonic representation. First products are expected to be released to users after the end of the first measurement phase in 2010. The university of Hannover participates in calibration and validation experiments. Parts of the gravity field processing algorithms were developed and implemented with support from the German »Geotechnologien« research and development programme (Flury et al. 2006; Flechtner et al. 2009). Applications in Earth sciences such as the determination of the dynamic ocean topography from GOCE and satellite altimetry data are currently investigated within the priority research programme »Mass Transport and Mass Distribution in the Earth System« of Deutsche Forschungsgemeinschaft.

To support GOCE activities and research in Germany, the German Space Agency Deutsches Zentrum für Luft- und Raumfahrt (DLR) established the GOCE-Projektbüro Deutschland (German Project Office) at Technische Universität München in 2001. Since then, the Project Office contributed to coordination activities for research projects in geodesy and Earth sciences. Further on, the Project Office provided a website information material to the science community and to the public, and carried out numerous outreach activities (www.goce-projektbuero.de).

5 Conclusions

With the successful launch of ESA's gravity field satellite GOCE, the first gravity gradiometer instrument is in orbit, on the lowest orbital altitude ever of a scientific satellite. In orbit testing of the science payload ran smoothly so far. From gradiometer data together with GPS tracking data, geoid and gravity field models with very high spatial resolution will be derived. Broad benefits in geodesy and Earth sciences are expected. GOCE data will be used to determine oceanic transport and to investigate climate change. They will set a new geoid standard for geodetic engineering, and will provide new insight into the structure of the Earth's interior.

Acknowledgement

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Authors' addresses

Prof. Dr.-Ing. Reiner Rummel | Dr.-Ing. Thomas Gruber | Dr. Anja Schlicht
 Institut für Astronomische und Physikalische Geodäsie
 Technische Universität München
 Arcisstraße 21, 80290 München
rummel@bv.tum.de | thomas.gruber@bv.tum.de | schlicht@bv.tum.de

Prof. Dr.-Ing. Jakob Flury
 Institut für Erdmessung
 Leibniz Universität Hannover
 Schneiderberg 50, 30167 Hannover
flury@ife.uni-hannover.de