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The European Earth Explorer Mission GOCE: Impact for the Geosciences

P.N.A.M. Visser [1], R. Rummel [2], G. Balmino [3], H. Sünkel [4], J. Johannessen [5], M. Aguirre [6], P.L. Woodworth [7], C. Le Provost [8], C.C. Tscherning [9], and R. Sabadini [10]

GOCE will be the first ESA Earth Explorer Mission with a foreseen launch date in 2004. It will also be the first satellite to fly a capacitive gradiometer operating at room temperature. The mission objective is the production of a homogeneous high-resolution, high-accuracy model of the earth's static gravity field, 1 mgal and 1 cm accuracy for gravity anomalies and geoid heights, respectively, at a resolution of 100 km or less. Impact studies have indicated that with such a model significant advances can be made in the fields of solid-earth physics, ocean circulation, geodesy, sea level change monitoring, ice-sheet modeling and positioning.

1. INTRODUCTION

The geodetic and geophysics communities have strived for a dedicated gravity field mission for many years. Such a gravity field mission is the only way to obtain a homogeneous global high-accuracy and high-resolution model of the earth's gravity field free from parasitic signals such as contained in *e.g.* altimeter data. For a long period, dating back more than two decades, several workshops and committees indicated the importance of high-accuracy, high-resolution gravity field mapping [*SESAME,* 1986; *Gravity Workshop,*1987; *NRC,* 1997] and several satellite concepts have been proposed and studied, *e.g.* GRM [*Keating et al.*, 1986; *Wagner and McAdoo*, 1986] and ARISTOTELES [*ESA*,1991; *Rummel and Schrama*,1991; *Lambeck*,1990]. None of these concepts were selected, either due to immaturity of technology or due to budget constraints or insufficient political support. However, the current situation looks very favorable with the launch of CHAMP on 15 July 2000 and the advent of the GRACE and GOCE gravity field missions [*Reigber et al.*,1996; *Watkins et al.*,1995; *Wahr et al.*,1998; *ESA*,1999*b*]. Two of these missions, GRACE and GOCE, may be regarded as more mature reincarnations of GRM and ARISTOTELES, respectively.

All three missions are linked with each other because each of them will make use of the same accelerometer technology, although for each mission tuned with respect to sensitivity and measurement bandwidth (see also Section 3). CHAMP may be considered as a proof of concept enabling improvement of current long-

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[1] Delft University of Technology, Delft Institute for Earth-Oriented Space Research, Delft, The Netherlands.

[2] R. Rummel, Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Munich, Germany.

[3] Centre National d'Etudes Spatiales, Toulouse, France.

[4] Technical University Graz, Institute of Theoretical Geodesy, Graz, Austria.

[5] Nansen Environmental & Remote Sensing Centre, Marine Monitoring and Remote Sensing Department, Bergen, Norway.

[6] European Space Research and Technolgy Centre, Noordwijk, The Netherlands.

[7] Proudman Oceanographic Laboratory, Bidston Observatory, Prenton, U.K.

[8] Laboratoire d'Etudes en Geophysique et Oceanographie Spatiales LEGOS/GRGS, Toulouse, France.

[9] University of Copenhagen, Department of Geophysics, Copenhagen, Denmark.

[10] University of Milan, Department of Earth Sciences, Milan, Italy.

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Table 1. Required gravity anomaly and geoid height accuracy (static field) for different applications (claimed EGM-96 global RMS accuracy between brackets for relevant resolution interval)

Application	Accuracy		Spatial resolution
	Geoid (cm)	Gravity (mgal)	(km)
SOLID EARTH			
Lithosphere and upper-mantle density		1-2 (4.8)	100
Continental lithosphere			
• sedimentary basins		1-2 (4.8-8.5)	50-100
• rifts		1-2 (4.8->8.5)	20-100
• tectonic motions		1-2 (0.4-4.8)	100-500
Seismic hazards		1 (4.8)	100
Ocean lithosphere and interaction with asthenosphere		0.5-1 (2.1-4.8)	100-200
OCEANOGRAPHY			
- short scale	1-2 (30)		100
	0.2 (23)		200
- basin scale	≈ 0.1 (4)		1000
ICE SHEETS			
- Rock basement		1-5 (4.8-8.5)	50-100
- Ice vertical movements	2 (4-30)		100-1000
GEODESY			
- Leveling by GPS	1 (4-30)		100-1000
- Unification of datums	1 (0-30)		100-20000
- Inertial Navigation		≈ 1-5 (0.1-4.8)	100-1000
- Orbits^a	1 (1-10)		100-1000

^{a}Radial orbit error

wavelength static gravity field modeling by an order of magnitude. GRACE will enhance the resolution of this modeling in addition to observing time variability of the long- to medium-wavelength part of the gravity field. The foreseen launch date for GRACE is in the fall of 2001 (status January 2001). GOCE aims at very high resolution mapping of the static gravity field, better than 100 km with an accuracy of 1 mgal and 1 cm in terms of gravity anomalies and geoid heights, respectively. GOCE, Gravity field and steady-state Ocean Circulation Explorer, will be the first Earth Explorer Mission in the Living Planet Programme [*ESA*,1998*b*; *ESA*,1999*c*] of the European Space Agency (ESA). The foreseen launch is in 2004 (status January 2001).

2. MISSION RATIONALE

Although in the last decade significant progress has been made in the field of global gravity field modeling, culminating in *e.g.* the EGM-96 [*Lemoine et al.*,1997] and recent GRIM models [*Perosanz et al.*,1997; *Biancale et al*,2000], such models are far from homogeneous in terms of accuracy and resolution. This is due to the accumulation of many data sources based on different observation techniques, in different reference frames, with different quality and aliasing problems, and different geographical coverage [*ESA*,1999*b*]. Although existing models perform very well in precise orbit determinations of *e.g.* TOPEX/POSEIDON and the ERS satellite with radial orbit error levels in the 2-5 cm range [*Tapley et al.*,1994; *Perosanz et al.*,1997; *Scharroo and Visser*,1998], their accuracy has to be improved by an order of magnitude for several applications in the geosciences. The latter is corroborated by a comparison of the required gravity field model accuracy for many applications with the globally averaged accuracy of the EGM-96 model (Table 1). Locally, the accuracy can be an order of magnitude worse. In addition, the global average is dominated by probably overly optimistic error estimates for the ocean parts, for which the gravity field model may be contaminated by ocean signals due to the incorporation of satellite radar altimeter data.

It will be obvious that existing gravity field models suffer from a lack of accuracy, homogeneity and contamination with non-gravitational phenomena. The only means of overcoming these deficiences in a reasonable time span and at acceptable costs is a dedicated gravity mission. However, the drawback of flying a satellite to this aim is the attenuation of gravity with altitude,

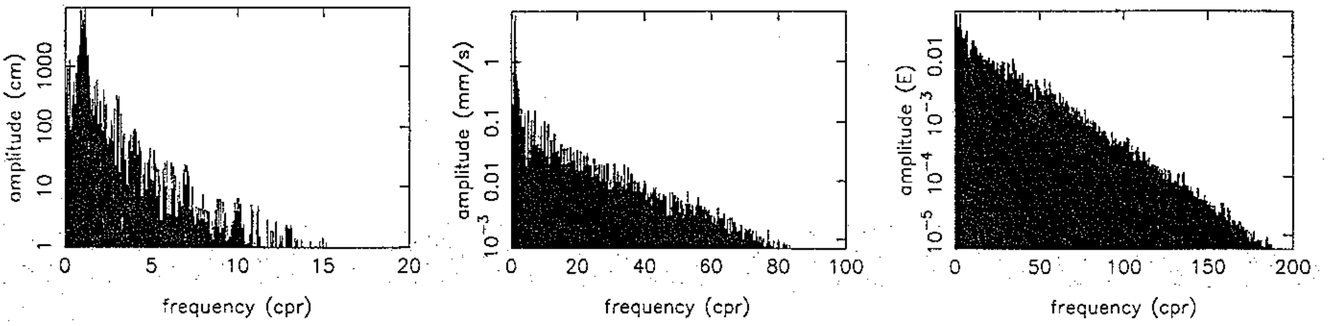

Figure 1. Predicted envelopes for CHAMP (left, altitude perturbations), GRACE (middle, low-low SST) and GOCE (right, Γ_{zz}) gravity field observations based on EGM-96 for a typical orbit altitude of 300 km

which becomes even more pronounced for the higher resolutions.

To ensure the production of a high-accuracy, high-resolution, homogeneous gravity field solution, a gravity mission has to satisfy the following criteria:

- uninterrupted tracking to achieve a more or less homogeneous data distribution and quality;
- the measurement or compensation of non-gravitational forces to prevent contamination;
- an orbit altitude as low as possible to counteract gravity field attenuation with altitude;
- enhance the high resolution part of the gravity field spectrum.

These criteria played a dominant role in the proposed design of the GOCE spacecraft (Section 3).

3. MISSION CONCEPT

The recently launched CHAMP satellite and currently planned GRACE and GOCE missions have different objectives in terms of gravity field sampling. CHAMP will focus on the static long wavelength part (in addition to measuring the geomagnetic field), GRACE on temporal variability and GOCE on the static long to short wavelength gravity field spectrum. This has resulted in three different satellite designs. CHAMP is equipped with a Global Positioning System (GPS) receiver enabling high-precision orbit determination by high-low Satellite-to-Satellite Tracking (SST) to the GPS satellites. Due to its low altitude ($\approx$ 450 km at Begin Of Life, BOL), the CHAMP orbit is perturbed significantly by long wavelength gravity field terms. The GPS receiver will thus provide indirectly the information for modeling the gravity field. However, the CHAMP orbit is perturbed also significantly by atmospheric drag, which can not be modeled with sufficient precision. To overcome this problem, accelerometers are measuring the non-conservative forces allowing a decoupling from gravity field induced perturbations. A typical spectrum of altitude variations that can be derived from the high-low SST observations based on only gravity is displayed in Figure 1 (left). It can be seen that the signal drops by more than three orders of magnitude from 1 cpr (cycles per orbital revolutions, 40,000 km wavelength) to 15 cpr (2700 km wavelength). It can be shown that similar drops occur for the flight and cross-track directions [*Visser*,1992]. CHAMP is also equipped with a Laser Retro-reflector Array (LRA) providing observations that can be combined with the GPS SST observations and/or used for validation purposes. First reports indicate that the GPS receiver and accelerometer are functioning properly, where the resolution of the latter appears to be better than 10^{-9} m/s^2 (priv. comm., G. Balmino, Centre National d'Etudes Spatiales, France). In addition, already a valuable data set of satellite laser tracking observations has been accumulated.

GRACE will basically consist of two CHAMP-type satellites trailing each other at a distance of a few hundreds of kms at about the same altitude ($\approx$ 480 km, BOL). To enhance sensitivity to higher-frequency gravity field perturbations, GRACE will be equipped with a low-low SST device. It can be seen in Figure 1 (middle), that the drop with three orders of magnitude occurs at 80 cpr, or at a wavelength of about 500 km.

The sensitivity to high frequency gravity field perturbations can be further enhanced by adopting a completely new space borne concept, namely Satellite Gravity Gradiometry (SGG). SGG is based on measuring the difference in acceleration of two adjacent proof masses, in this case on board of one and the same satellite. Such a difference measurement is in a very good approximation equal to the second derivative of the local gravity field potential, or the local gravity gradient (denoted by Γ). By taking multiple derivatives, high frequencies are magnified. In this case, the radial SGG component (Γ_{zz}) decays with three orders of magnitude at about 200 cpr (100 km wavelength, Figure 1, right). Conceptually, SGG is thus superior to both high-low and low-low SST when it comes to observing the fine structure of the earth's gravity field. GOCE will be equipped with an electrostatic gradiometer working at room temperature consisting of a triad of three pairs of three-axes accelerometers located on three orthogonal axes with a baseline of about 0.5 m [*ESA*,1999*b*]. The gradiometer instrument will be tuned to be particularly sensitive in the 1-100 mHz frequency range, referred to as the Measurement Bandwidth (MB), for which the measurement precision aimed at is 3 $\mathrm{mE}/\sqrt{\mathrm{Hz}}$ (1 E = 1 Eötvös Unit $= 10^{-12}\ \mathrm{s}^{-2}$) for the differential accelerometer measurements. This is equivalent to allocating an error budget of $10^{-12}\ \mathrm{m/s^2}$ per individual accelerometer for the differential mode where the range must be below 10^{-7} $\mathrm{m/s^2}$ [*ESA*,1999*b*]. A trade-off had to be made between sensitivity and dynamic range of the accelerometers, resulting in the specified MB and measurement precision. Outside this MB, the gradiometer will measure with reduced precision. The selected altitude will be 240-250 km, which means that the MB in the frequency domain is equivalent with 80-8000 km in the space domain (half-wavelength). Each accelerometer will have two sensitive and one less-sensitive axes due to the on ground testing in a 1-g environment. The three pairs are in principle able to provide the full SGG tensor. However, the requirement is to provide the three diagonal components only. The off-diagonal components will be used to reconstitute with very high precision the rotational motion of the satellite to eliminate centrifugal and angular acceleration terms from the SGG observations [*Aguirre-Martinez*,1999].

To take optimal advantage of the information content of the SGG measurements, the position of the instrument has to be known with high precision. For example, a misfit in position of 1 m can lead to an increase of the SGG error budget with about 1 mE due to the central term of the gravity field. Therefore, GOCE will be equipped with a high-quality, dual-frequency GPS receiver. As with CHAMP and GRACE, this will also allow a recovery of the long-wavelength part of the gravity field, *i.e.* the part for which the gradiometer is less sensitive. The GPS receiver thus has a dual role: provide the SST tracking measurements for a very precise geolocation of the gradiometer instrument (1) and for a precise long-wavelength, complementary, gravity field recovery (2). Both the gradiometer and GPS receiver are able to provide continuous measurements with 1 second time interval (1 Hz). Also GOCE will be equipped with a LRA that can be used for validation purposes and partial backup to the GPS receiver.

So far, three of the mission criteria have been met: uninterrupted tracking, low orbit altitude and enhancement of high frequencies. The fourth criterion, elimination or measurement of non-gravitational forces can also be met with the current design. The gradiometer will be able to provide measurements of the non-conservative forces by evaluating the common-mode of the accelerometers. In addition, the implementation of a Drag Free Control (DFC) system is foreseen in the current design in order to prevent saturation of the accelerometers. For example, atmospheric drag will be at a level of $8 \times 10^{-6}\ \mathrm{m/s^2}$ compared to a dynamic range of $10^{-7}\ \mathrm{m/s^2}$ for the accelerometers along the sensitive axes. The DFC system will consist of ion thrusters to eliminate the large, long-wavelength, components of non-conservative forces (predominantly atmospheric drag), and cold gas proportional thrusters to eliminate the larger part of these perturbations in the gradiometer MB.

The foreseen mission life time for GOCE is 20 months, consisting of a commissioning phase of 3 months and two 6-months measurement periods with a 5-months hibernation period in between during which the satellite experiences relatively large temperature fluctuations due to eclipses. The selected orbit will be a dawn-dusk or dusk-dawn sun-synchronous orbit, with is near-polar. The inclination of the orbit will be 96.6°, *i.e.* small polar caps will not be covered with observations amounting to less than 1% of the total earth's surface, referred to as the polar gaps. For comparison, CHAMP and GRACE will fly near-polar orbits with an inclination of 89°, filling the gaps left by GOCE for the larger part, although with reduced sensitivity to the high-frequency part of the polar gravity field. Although the satellites will not fly exactly over the poles, the instruments will provide information about the gravity field in the gaps as well, especially the gradiometer due to its 3-dimensional sensing capability [*Sünkel*,2000]. Finally, it is interesting to note that airborne gravimetry campaigns are planned over the Arctic region that will further complement the GOCE gravity data set (priv. comm., R. Forsberg, Geodynamics Dept., Kort & Matrikelstyrelsen, Denmark).

4. MISSION PERFORMANCE

The proposed GOCE satellite will contain an electrostatic gradiometer, a GPS receiver and a DFC system. An important role in the design was played by

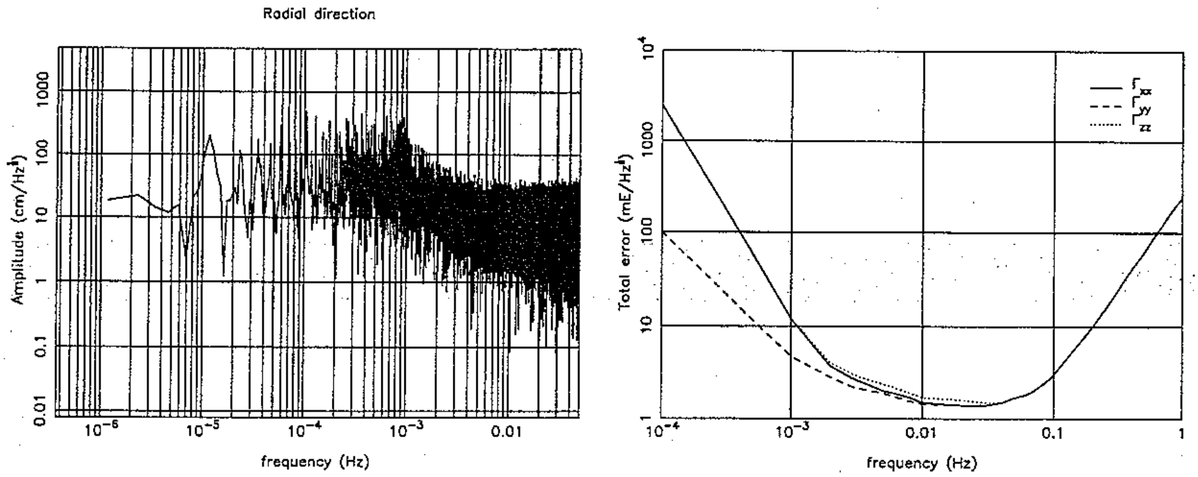

Figure 2. Power Spectral Densities for GOCE radial orbit error (left) and error budget for diagonal SGG components (right). The orbit error integrated over the entire spectrum is 2.5 cm (x, y and z denote the along-track, cross-track and radial direction, respectively)

several mission analysis and error propagation tools to check the mission performance both at the instrument level and in terms of achievable gravity field products [*Alenia*,1998; *ESA*,1998*a*; *SID*,2000; *CIGAR II*,1990; *CIGAR III*,1993; *CIGAR III*,1995].

The achievable gravity field recovery accuracy and resolution for GOCE depend on the quality of the GPS-based precise orbits and the error budget for the diagonal SGG components. Detailed studies have been conducted to predict the error budgets both for precise orbit determination and SGG measurements [*ESA*,1999*b*; *SID*,2000; *Visser and van den IJssel*,2000]. For example, estimates of the radial orbit error spectrum based on a kinematic orbit determination approach and the SGG error budget for the diagonal components are displayed in Figure 2. The expected orbit accuracy is at the few cm level, leading to effectively no increase of the SGG error budget due to position uncertainty (with respect to an earth-fixed reference frame) of the gradiometer instrument.

The expected orbit accuracy spectra and SGG error budgets were fed to an error propagation tool to assess the achievable gravity field accuracy. The gravity field is conveniently modeled as a spherical harmonic expansion:

$$U = \frac{\mu}{r}\left\{1+\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{a_e}{r}\right)^l(\bar{C}_{lm}\cos m\lambda\right. \\ \left. +\bar{S}_{lm}\sin m\lambda)\bar{P}_{lm}(\sin\phi)\right\} \qquad (1)$$

where μ is the gravity parameter of the earth (the product of the universal gravity constant G and the mass of the earth M), a_e the mean equatorial radius, $\bar{P}_{lm}$ is the fully normalized Legendre polynomial of degree l and order m, $\bar{C}_{lm}$ and $\bar{S}_{lm}$ denote the fully normalized gravity field harmonic or Stokes coefficients. This series is truncated at a certain maximum degree l_{max}. The resolution of such a model is $40,000/l_{max}$ km. With the error propagation tool, the accuracy of the spherical harmonic coefficients can be predicted as a function of the orbit and SGG error spectra [*Colombo*,1984; *Schrama*,1991; *Visser et al.*,1994].

The predicted performance is displayed in Figure 3. The prediction is valid for the area of the earth covered by the ground track of the satellite, *e.g.* for GOCE between -84° and +84° geographical latitude (two polar caps forming less than 1% of the earth's surface are not covered by observations). For comparison, predictions for GRACE and CHAMP are included plus the EGM-96 covariance and the degree variance according to Kaula's rule of thumb [*Kaula*,1966]:

$$\bar{C}_{lm}, \bar{S}_{lm} \div \frac{10^{-5}}{l^2} \qquad (2)$$

It is assumed that the orbit error spectra for all missions look similar, because in all cases use will be made of GPS receivers that are more or less developed in the same time frame for which it is fair to assume similar observation error characteristics. In addition, for all missions orbit determination uncertainty due to non-conservative forces is effectively minimized by the use of accelerometers [*SID*,2000; *Visser and van den IJssel*,2000]. For GRACE, it was also assumed that low-low SST Doppler measurements are available with a

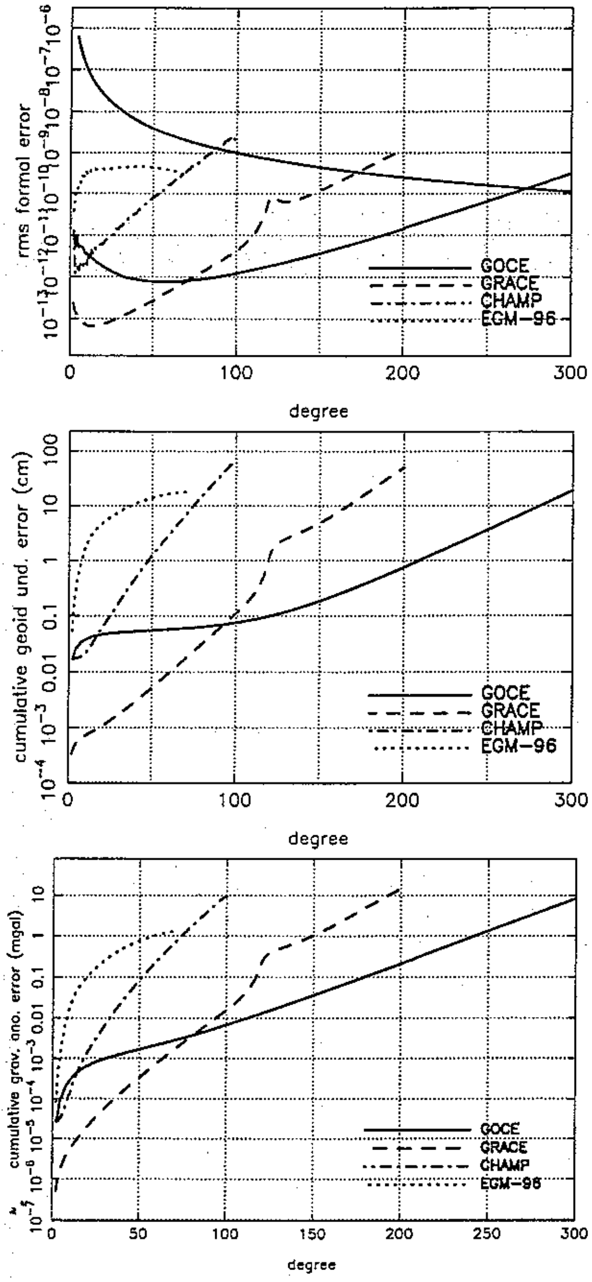

Figure 3. Predicted achievable gravity field recovery as a function of the spherical harmonic degree: degree Root-Mean-Square (RMS ,top), cumulative geoid error (middle) and cumulative gravity anomaly error (bottom). The decreasing line denotes gravity signal variance according to Kaula's rule of thumb

claimed precision of 1 μm/s over the entire MB (no degradation at low and very high frequencies as assumed for GOCE) with an inter-satellite distance of 300 km [*ESA*,1998*a*]. The foreseen mission life times for CHAMP and GRACE are 5 years compared to 1 year (measurement phase) for GOCE.

According to the predictions, all missions will lead to a significant improvement in gravity field modeling, at least a few orders of magnitude improvement over the state-of-the-art global model EGM-96. It can be seen that the error curve of the latter flattens around degree 20. At higher degrees the error level is reduced significantly by the inclusion of surface gravity and altimeter data [*Lemoine et al.*,1997]. No such data were used in the CHAMP, GRACE and GOCE predictions.

It can also be seen that the GOCE concept is superior at the medium to small wavelengths and GRACE at the long wavelengths: the intersection point is at degree 70 (half-wavelength 285 km). The exceptionally high accuracy predicted for GRACE at the low degrees opens the possibility to generate time series of gravity field solutions, *e.g.* per month with of course lesser accuracy than the 5-year static solution, and study the time variability of the gravity field at the long(er) wavelengths. For GOCE, the signal to noise ratio becomes one around degree 270 or a resolution of about 75 km. For CHAMP, also an improvement of at least an order of magnitude is expected at the long wavelengths. In addition, CHAMP may be considered to be a 'proof of concept', testing accelerometer technology that will also be used for GRACE and GOCE in combination with a high-quality GPS receiver. By comparing Figure 3 with Table 1, it can be seen that most science requirements can be met by GOCE.

5. MISSION PRODUCTS

The scientific instruments on board of GOCE will provide a continuous data stream of GPS SST and SGG observations. In addition, ancillary data are required from the Attitude and Orbit Control System (AOCS) including the DFC and external data from *e.g.* the International GPS Service (IGS) to allow a precise orbit determination. An estimated guess for the total amount of GOCE SST and SGG observations is more than 60 million (for the two 6-months observation intervals). A gravity field model with a resolution of 75 km requires the estimation of more than 270^2 or 72,900 unknowns. Reducing the scientific observations to the gravity field products is a real challenge from a computational point of view. However, sophisticated algorithms have been developed and implemented allowing to conduct this task in a reasonable time frame at acceptable (computing) costs [*CIGAR IV*,1996; *Sünkel*,2000].

It has to be stressed that the primary objective of GOCE is the generation of a high-resolution, high-

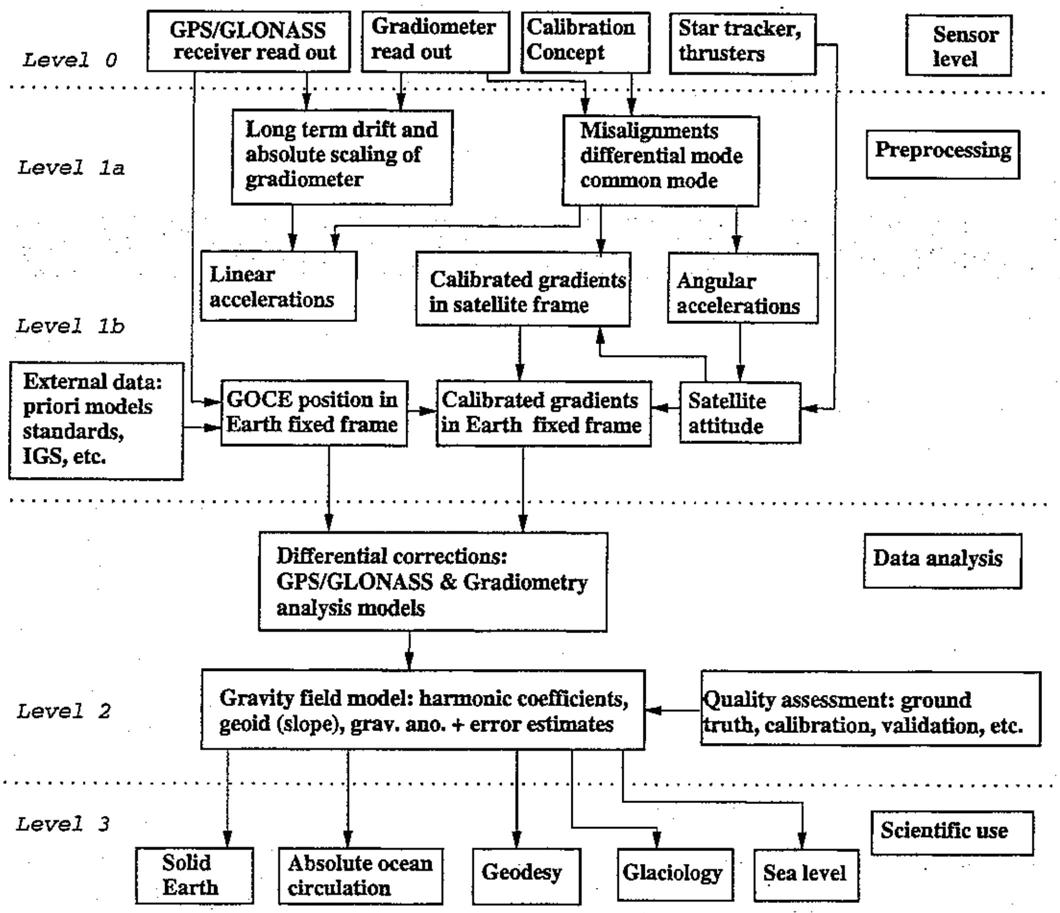

Figure 4. Scheme for GOCE data reduction

accuracy model of the static gravity field. Due to the specific mission scenario, *i.e.* a one-year observation period interrupted by 5 months of hibernation, the time variable gravity field will not average out, especially those signals with a dominant annual cycle. Correcting for time variable gravity field signals will form part of the processing chain [*Sünkel*,2000]. In relation to this issue, it is foreseen that the GOCE data processing will benefit strongly from the GRACE results.

Several stages can be distinguished in the processing of the GOCE observations to the final gravity field products (Figure 4, [*ESA*,1999*b*]). Raw sensor data (*level 0*) of the scientific instruments (GPS receiver and gradiometer) plus ancillary data from the AOCS/DFC (including star tracker and thruster activity data) will be converted to calibrated time series of SST and SGG observations (*level 1a*) and geolocated (*level 1b*) after a preliminary orbit determination making use of external IGS data. Finally, the data will be reduced to a gravity field model together with a quality estimate (*level 2*). Part of the latter process is the computation of the most precise GOCE orbit possible. The gravity field product may be in the form of a set of spherical harmonic coefficients, a local or global grid of geoid height or gravity anomaly values, a grid of geoid slopes, etc. A quality measure will be attached to the different products. It has to be noted that the calibrated SGG measurements may already be seen as an important geophysical product that can be used directly for certain applications. The production of the *level 0* to *level 1b* products will be taken care of by an assigned Processing and Archiving Facility (PAF). It is foreseen that the reduction to the final gravity field products (*level 2*) will be taken care of by a scientific data consortium that may consist of several participating groups.

The gravity field products will be provided to the scientific community to be used for and incorporated in many applications in *e.g.* the fields of solid-earth research, oceanography, geodesy, glaciology and sea level studies, referred to as *level 3* (Section 6).

6. SCIENTIFIC USE

Gravity plays a dual role in the geosciences. First, in the form of the geoid, which may be considered as the hypothetical ocean surface at rest and serves as a reference for ocean circulation studies and for linking local and global height systems into one common reference frame. Second, as a mirror of the mass structure of the earth's interior, which is the complement of many processes like sea-floor spreading, subduction of oceanic lithosphere, glacial isostatic readjustment, etc. The predicted performance of GOCE with respect to resolution and accuracy in gravity field modeling will allow meaningful applications in many research areas. An inventory was made of the possible impact in several scientific fields, which is highlighted below.

6.1. Solid Earth

In solid-earth research, a high-resolution, high-accuracy gravity field model can serve as an important boundary condition. Gravity field data will enhance images of the density structure of the lithosphere and upper mantle in combination with seismic tomography data, lithospheric magnetic-anomaly measurements and topography data, *e.g.* [*Achache*,1994].

Precise knowledge of the density structure will help in improved modeling of *e.g.* sedimentary basins, rifts, tectonic motions and sea/land vertical motions. Furthermore, high-precision knowledge of the density anomalies in the earth will improve the understanding of the tectonic processes and mechanisms behind earthquakes, *e.g.* [*Negredo et al.*,1999; *ESA*,1999*b*].

6.2. Ocean Circulation

Also in the case of ocean circulation studies, gravity plays at least a dual role. First and direct in the form of the geoid, the equipotential surface that serves as a reference for ocean dynamics. Second and indirect in the form of orbit perturbations that have to be modeled with high precision to allow the use of satellite radar altimeter data for many applications in the field of oceanography.

A high-precision geoid model will lead to significantly improved and more detailed modeling of ocean currents, leading to reduced uncertainties in volume transports, especially in the upper ocean layers [*LeGrand and Minster*,1999; *Woodworth et al.*,1998]. Ocean dynamic modeling plays an important role in modeling the earth's energy/heat budget, transport of nutrients (fishing) and weather prediction.

With CHAMP, GRACE and GOCE the so-called gravity field induced orbit error will become insignificant. Already a valuable altimeter data set consists covering a period of more than two decades, collected by the SEASAT, GEOSAT, TOPEX/POSEIDON and the ERS satellites. The orbits of these satellites can be recomputed using post-flight gravity field models enhancing the point to point accuracy of the altimeter measurements. At the same time, it may be expected that the recomputed orbits will be defined in a more consistent reference frame (Section 2). Also sea level change studies will benefit from improved orbit modeling (Section 6.5).

6.3. Ice Sheets

Although GOCE will cover the larger part of the Arctic and Antarctic ice sheets, the remaining polar gaps have to be filled in to guarantee high-precision gravity field modeling for these areas. However, the GOCE data will be complemented by CHAMP and GRACE observations and airborne gravimetry campaigns (Section 3). It is fair to assume that this complement of data sources will result in high-precision Arctic and Antarctic gravity field modeling.

A precise gravity field over the Arctic and Antarctic ice sheets will, in combination with information on ice thickness from *e.g.* in-situ surveys, result in better models of the underlying bedrock topography resulting in improved knowledge of ice sheet dynamic behavior, *e.g.* mass fluxes, especially in the 50-100 km resolution domain. Improved ice dynamics modeling also forms part of the sea level change equation (Section 6.5).

In addition, a precise geoid in the polar areas will enhance geodetic surveying of the ice sheets by *e.g.* GPS leveling [*Roman et al.*,1997]. Furthermore, precise gravity field knowledge in the polar areas will practically eliminate the relating orbit error of future altimetric missions facilitating to a larger extent the use of ice topographic data that are collected by such missions, of which two are currently foreseen: Ice, Cloud and land Elevation Satellite (ICESat) and CRYOSAT. ICESat, which will carry the Geoscience Laser Altimeter System (GLAS), forms part of NASA's Earth Science Enterprise (ESE) scheduled for launch in July 2001 [*Schutz*,1998]. CRYOSAT, which has been selected as the pioneering Earth Explorer opportunity mission in the ESA's new Living Planet program, is scheduled for launch in 2002 [*ESA*,1999*a*].

6.4. Geodesy

The field of geodesy encompasses many research and application areas where gravity plays a crucial role. A number of applications will benefit significantly from having a global gravity field model with 1 cm accuracy in terms of geoid heights and 1 mgal accuracy in terms of gravity anomalies at 100 km spatial resolution: leveling by GPS in addition to or replacement of traditional leveling techniques, unification of (local) height systems in order to define one globally consistent datum, orbit determination of satellites and inertial navigation.

Geometric heights determined by GPS can be converted to heights above sea level ('orthometric heights') with the aid of an accurate geoid model [*Rummel*,1992]. This is similar to the extraction of dynamic ocean topography from satellite altimetry in combination with a precise geoid.

In well surveyed areas, predominantly in Europe, North America, Japan and Australia, the GOCE geoid can be combined with very high frequency local terrestrial gravity data resulting in cm-precision local geoids down to a resolution of 5 km. In less surveyed areas, predominantly in developing countries, GPS converted orthometric heights can be obtained free of long-scale biases with sufficient accuracy to satisfy mostly less demanding local needs. Due to missing local gravity information, small scale omission errors of the order of 10-20 cm have to be added [*ESA*,1999*b*]. In general, it may be concluded that height determinations can be conducted faster and at lower cost.

The geoid precision aimed at with GOCE will enable connection of all height systems with cm-precision in one consistent global reference frame, provided that at least one location in each separate system can be positioned with high accuracy using a space based positioning technique such as GPS [*Arabelos and Tscherning*,1999]. Unification of heigh systems allows to bring all sea level recordings into one system (Section 6.5), eliminate height discontinuities between adjacent islands and remove existing biases in terrestrial gravity anomaly data sets.

In precise orbit determination of earth orbiting satellites, gravity field induced orbit errors will become negligible using post-flight GOCE models (the same will be true for post-flight GRACE and to a lesser extent CHAMP models). Precise orbit determinations will not only improve for altimetric satellites (Sections 6.2-6.3), but also for atmospheric profiling missions like the future METOP satellites of which the first will be launched in 2003 (ESA Press Release 06/99, 8 July 1999). The latter missions require (near) real time precise orbits for operational application in *e.g.* numerical wheather prediction models. Improved gravity field knowledge will result in more accurate near real time and predicted orbits to be included in operational applications. Finally, modeling of non gravitational orbit perturbations, such as induced by atmospheric drag or solar radiation, but also modeling of temporal gravity field induced orbit perturbations, *e.g.* caused by tides, will benefit from improved knowledge of the static gravity field.

Inertial navigation is based on single and double integration of measured accelerations to obtain position and velocity changes of a user, *e.g.* land vehicles, aircraft, missiles, submarines, etc. Attitude changes can be derived by making use of gyro's. The accelerometers and gyro's are either mounted on space-stable (or leveled) platforms or fixed to the vehicle to be navigated. The accelerometers measure the sum of the user vehicle and gravity acceleration and precise knowledge of the gravity field will improve overall navigation accuracy and allow an increase in time intervals between velocity and positioning updates [*Schwarz*,1981].

6.5. *Sea Level*

Sea level change is an aggregate of many different phenomena related to solid-earth dynamics (section 6.1), ocean current systems (section 6.2), ice sheet evolution (section 6.3) and height systems (section 6.4). Different mechanisms may play a role in *e.g.* local sea level change [*Di Donato et al.*,1999]. A proper understanding of the various components of and mechanisms behind sea level change plays a crucial role in climate (change) studies and modeling.

Globally averaged sea level is estimated to have risen by 10-25 cm in the past century and certain predictions indicate an additional rise of approximately another 50 cm in the next century [*Warrick et al.*,1996]. With two thirds of the world's population living in coastal zones, some of which will already have significant elevated risk of flooding with sea level rises of a few decimeters, understanding and being able to predict sea level change is of great importance.

In order to be able to improve and enhance the value of sea level change predictions, it is not sufficient to simply observe total sea level. It is required to understand the various distinct components if accurate predictions are to become available. Moreover, historical tide gauge records and currently available climate models suggest that sea level change has been and will be far from globally uniform [*Warrick et al.*,1996; *Peltier*,1998; *Di Donato et al.*,2000].

Improved gravity field knowledge will aid in improved understanding of (several components of) sea level changes. First, high accuracy geoid modeling will lead to

Table 2. Geographically correlated and anti-correlated radial orbit error for several altimeter satellites (cm)

Satellites	EGM-96		GOCE	
	Correlated	Anti-Corr.	Correlated	Anti-Corr.
ERS-1/2 and ENVISAT	2.24	1.89	0.08	0.08
GEOSAT and GFO	2.51	1.89	0.14	0.13
TOPEX and Jason	0.67	0.58	0.08	0.07
CRYOSAT	7.46	5.52	0.03	0.03

more reliable estimates of ocean and heat fluxes in General Circulation Models (GCMs) that are used in the modeling of sea level change due to thermal expansion. It is expected that thermal expansion is expected to contribute significantly to sea level change in the next century. Second, precise geoid models for the Arctic and Antarctic areas will lead to improved models of ice sheet dynamics. Third, improved gravity field knowledge will allow a better analysis of historical tide gauge records which basically are measures of local sea level with respect to local land level. Different phenomena define changes in local sea level, ranging from *e.g.* changes in ocean circulation to changes in local solid-earth processes. Interpretation of tide gauge records will benefit from improved ocean dynamics and solid-earth modeling. Fourth, unification of height systems will enable comparison of local sea level records in one consistent global reference frame. Fifth and finally, improved gravity field knowledge, especially of the larger wavelengths, will lead to a reduction of the radial orbit error for altimeter satellites. Although already much progress has been made in reducing this error for satellites like TOPEX/POSEIDON and ERS-1/2 [*Tapley et al.*,1994; *Scharroo and Visser*,1998], further reductions are required to improve sea level change estimates based on altimeter measurements and bring the uncertainty significantly below the signal level.

(Re)Computation of the orbits of previous (GEOSAT, ERS-1), current (ERS-2, TOPEX/POSEIDON, GFO) and future (Jason-1, ENVISAT) satellites will result in a multi-decadal record of sea level change estimates of high quality.

The radial orbit error based on the state-of-the-art EGM-96 gravity field model has been assessed for different altimeter missions and serves as an example to indicate the importance of its reduction (Table 2). For GEOSAT, the radial orbit error has an RMS of 2.5 cm. In order to be able to derive sea level change estimates at the mm/year accuracy level (10 cm per century) for a time span of a few decades (GEOSAT flew in the mid eighties), this error has to be reduced to the sub-cm level. With a post-flight GOCE gravity field model this accuracy level can be achieved. Also note the relatively large radial orbit error for CRYOSAT when using EGM-96. This is due to its almost polar orbit with an inclination of 92°. Gravity field induced orbit perturbations for inclinations close to 90° are very poorly represented in existing models.

As indicated before, sea level changes are expected to be far from globally uniform. This is also true for the gravity field induced radial orbit error. For example, variations in the geographically correlated (average of error on ascending and descending satellite tracks) and anti-correlated (error on ascending minus error on descending track) radial orbit error are of the order of a few cm for the ERS and ENVISAT satellites with EGM-96 (Figure 5). Such errors will result in sea level change estimates that have different errors for different local areas when for example linking altimeter data sets of different altimeter satellites with different radial orbit error spectra that flew in different periods. When comparing *e.g.* GEOSAT and ERS altimeter data, the error can be larger than 5 mm/year.

7. CONCLUSIONS

The first decade of the 21th century, a major step forward will be enabled in the field of geopotential research with the advent of three dedicated satellite gravity missions, GOCE, GRACE and CHAMP, where CHAMP will also measure the geomagnetic field. New technologies, from new generation high-precision GPS receivers to low-low microwave Doppler tracking instruments, ultra-sensitive (arrays of) accelerometers and high-resolution atmospheric drag compensation systems, have been developed that will enable measuring gravity in a space borne environment over a wide wavelength spectrum.

It is expected that CHAMP will provide observations that enable an improvement in gravity field modeling by an order of magnitude over existing models at the long wavelengths (down to ≈ 500 km). The mission can also be seen as a proof of concept of using high-sensitivity accelerometers in combination with GPS (and LRA)

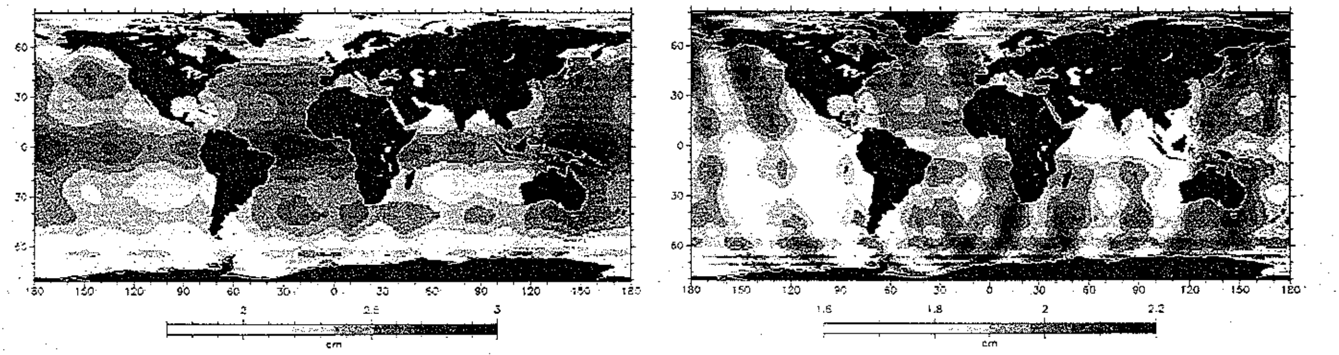

Figure 5. Geographically correlated (left) and anti-correlated (right) radial orbit error for the ERS and ENVISAT satellites based on the EGM-96 calibrated covariance

tracking. The expected performance of GRACE will allow the generation of very precise monthly long to medium wavelength gravity field solutions opening the possibility to study the time variability of the gravity field at these wavelengths. Moreover, GRACE will provide the information for high-precision modeling of the static gravity field as well with unprecedented resolution and accuracy: the gravity signal to noise ratio is expected to reach one at a spherical harmonic degree around 170 (half-wavelength 120 km). The focus of GOCE will be on achieving as high a resolution as possible in modeling the static gravity field. The expected gravity signal to noise ratio is expected to reach one at a degree around 270 (half-wavelength 75 km). The expected accuracy for a gravity field model complete to degree and order 200 (half-wavelength 100 km) is better than the 1 mgal and 1 cm for gravity anomalies and geoid heights aimed at.

The GOCE data products will consist of calibrated and validated gravity field models with associated quality estimates. The models will be provided in several forms: sets of spherical harmonic coefficients with associated (reduced) error/covariance matrices, or local/global grids of gravity anomalies, geoid heights, geoid slopes, etc., with associated error/covariance functions. The GOCE gravity field solutions will be used in a wide field of applications and scientific research.

Significant progress is anticipated in the fields of solid earth research, ocean circulation modeling, ice sheet dynamics, geodesy and the strongly multidisciplinary field of sea level change studies.

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M. Aguirre, European Space Research and Technolgy Centre, Postbus 299, NL-2200 AG, Noordwijk, The Netherlands, (maguirre@estec.esa.nl)

G. Balmino, Centre National d'Etudes Spatiales, GRGS - 18, Av. Edouard Belin, 31401 Toulouse Cedex 4, France, (georges.balmino@cnes.fr)

J. Johannessen, Nansen Environmental & Remote Sensing Centre, Marine Monitoring and Remote Sensing Department, University of Bergen, Norway, (johnny.johannessen@nrsc.no)

C. LeProvost, Laboratoire d'Etudes en Geophysique et Oceanographie Spatiales LEGOS/GRGS, Observatoire de Midi-Pyrenees 14, Avenue Edouard Belin, 31401 Toulouse Cedex 4, France, (Leprovos@pontos.cst.cnes.fr)

R. Rummel, Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstrasse 21 D-80290 Munich, Germany, (rummel@step.iapg.verm.tu-muenchen.de)

R. Sabadini, University of Milan, Department of Earth Sciences, Via L. Cicognara 7, I-20129, Milan, Italy, (roberto.sabadini@unimi.it)

H. Sünkel, Technical University Graz, Institute of Theoretical Geodesy, Steyrergasse 30/III, A-8010 Graz, Austria, (suenkel@geomatics.tu-graz.ac.at)

C.C. Tscherning, University of Copenhagen, Department of Geophysics, Juliane Maries Vej 30, Copenhagen, DK-2100, Denmark, (cct@osiris.gfy.ku.dk)

P.N.A.M. Visser, Delft University of Technology, Delft Institute for Earth-Oriented Space Research, Kluyverweg 1, 2629 HS, Delft, The Netherlands, (pieter.visser@lr.tudelft.nl)

P.L. Woodworth, Proudman Oceanographic Laboratory, Bidston Observatory, Bidston Hill, Prenton CH43 7RA, U.K., (plw@mail.nerc-bidston.ac.uk)