

Global Gravity Field Models and Their Use in Earth System Research

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Abstract The launch of dedicated gravity satellite missions such as CHAMP, GRACE and GOCE has revolutionized our knowledge of the Earth's gravity field. Since the gravity field reflects mass distribution and mass transport through the complex system Earth, a precise knowledge of the global gravity field and its temporal variations is important for many areas of Earth system research, such as solid Earth geophysics, oceanography, hydrology, glaciology, atmospheric and climate research. In this paper the progress of global gravity field modelling based on satellite data is reviewed, with special emphasis on first results of the ESA mission GOCE, where the new observation type of satellite gradiometry enables to derive high-resolution static gravity field models. Additionally, first combined satellite-only gravity field models based on GRACE and GOCE, making benefit of the individual strengths of these two missions, are addressed, and the application of these gradually improving gravity field models in several fields of geoscientific research is discussed.

1 Introduction

The Earth's gravity field reflects the mass distribution and its transport in the Earth's interior and on its surface. In 2000, the era of dedicated satellite gravity missions began with the launch of CHAMP (CHAllanging Minisatellite Payload; Reigber et al. 2002), followed by the launches of GRACE (Gravity Recovery And

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Climate Experiment; Tapley et al. 2007) in 2002, and GOCE (Gravity field and steady-state Ocean Circulation Explorer; Drinkwater et al. 2003) in 2009. Based on data of these missions, global Earth's gravity field models with homogeneous accuracy and increasingly high spatial resolution could be derived.

The Earth's gravitational potential V is usually parameterized in terms of coefficients of a spherical harmonic series expansion in spherical coordinates (with radius r , co-latitude ϑ , longitude λ):

$$V(r, \vartheta, \lambda) = \frac{GM}{R} \sum_{n=0}^{N_{\max}} \left(\frac{R}{r}\right)^{n+1} \sum_{m=0}^n \bar{P}_{nm}(\cos \vartheta) [\bar{C}_{nm} \cos(m\lambda) + \bar{S}_{nm} \sin(m\lambda)] \quad (1)$$

\bar{P}_{nm} where G is the gravitational constant, M the mass of the Earth, R the mean Earth radius, \bar{P}_{nm} the fully normalized Legendre polynomials of degree n and order m , and $\{\bar{C}_{nm}; \bar{S}_{nm}\}$ the corresponding coefficients to be estimated.

Satellite gravity missions measure derived quantities of the gravitational potential V , depending on their specific measurement concept. Since they are the only measurement technique which can directly observe mass changes on a global scale, they are a unique observational system for monitoring mass redistribution in the Earth system.

The high-resolution static gravity field, represented by the geoid, serves as a unique physical reference surface. It is not only used in geodesy to define height systems, but also in a variety of geoscientific disciplines. Since it represents the surface of an ideal ocean at rest, in oceanography it is compared with the actual ocean surface, which can be derived by satellite altimetry. Thus, the so-called mean dynamic topography (MDT) can be computed, from which geostrophic ocean surface currents can be derived. These ocean currents are, beside the atmosphere, the second largest mechanism for global heat transport through the Earth system. High-resolution static gravity field models also provide boundary values for geophysical models of lithospheric structures and dynamic processes in the Earth's mantle and crust.

Temporal gravity variations, as they can be derived from the GRACE mission, are a direct measure of mass variations and thus are able to monitor mass transport processes in land hydrology, cryosphere, ocean, and atmosphere. Thus, the determination of the gravity field can contribute to derive ice and water mass balance. Non-gravimetric methods are based on the observation of the individual contributors to mass balance. As an example, in the case of land hydrology these are precipitation P , evapo-transpiration ET and surface run-off R .

$$P - ET - R = \Delta S \quad (2)$$

These individual components are difficult to observe homogeneously on a global scale and therefore are only inaccurately known, leading to large error margins also for the resulting mass balance equation. The unique quality of gravity field measurements is the fact that they directly measure the right-hand side of the mass balance Eq. (2), i.e., storage changes ΔS representing the sum of all

contributors to mass balance. Of course, also global gravity field estimates suffer from several error sources, such as the separability of different sources composing the gravity field signal, errors in geophysical background models, and limitations in spatial and temporal resolution. In spite of this fact, gravimetric methods offer the possibility of closing the Earth mass budget comprising the effect of various interacting processes within the Earth system. With a global view of mass transport, they provide a unique framework in which the results from other Earth observation missions monitoring certain Earth's subsystems can be related to each other, and they are an important contributor to the monitoring of several Essential Climate Variables (ECVs; Liebig et al. 2007).

In the present paper, a brief review of important results of a decade of gravity field observation from space is given in Sect. 2, and the achievable performance is evaluated. Based on the continuously improving accuracy and spatial resolution of these models, in Sect. 3 the added value of combined global gravity field models derived from GRACE, GOCE and complementary gravity data is evaluated, and potential applications in Earth science are discussed in Sect. 4. Finally, Sect. 5 provides the main conclusions and an outlook to future research activities.

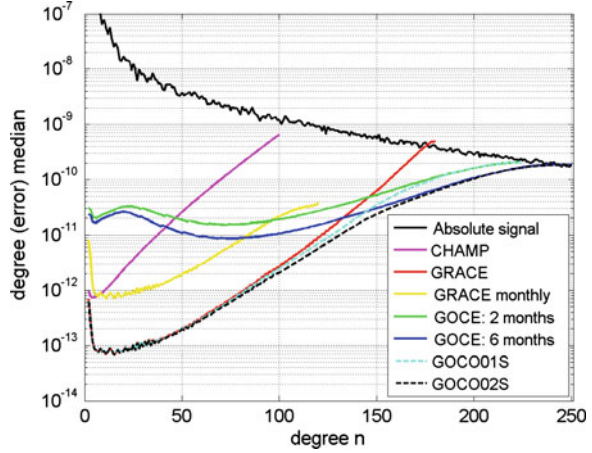
2 Satellite Gravity Missions: Status and Results

2.1 CHAMP

After a series of satellite laser ranging (SLR) missions, from which the very long-wavelength component of the Earth's gravity field could be and is still derived by orbit analysis, a new era of gravity field determination from space began with the launch of the first dedicated gravity field mission CHAMP in 2000 into a low Earth orbit (450 km altitude). CHAMP was equipped with a space-borne GPS receiver enabling continuous 3D tracking of the satellite using the GPS constellation. This so-called high-low satellite-to-satellite tracking constellation (SST-hl) provided a completely new opportunity to determine the long wavelength static gravity field with unprecedented accuracy. In addition, CHAMP was the first satellite being equipped with an accelerometer dedicated to observe the non-gravitational accelerations acting on the satellite, like air drag, solar radiation pressure and Earth albedo. For the first time a homogeneous global gravity field model could be derived from a single satellite. Several static models have been computed, which outperformed all previous satellite-only solutions in the long wavelengths (up to degree and order 70) at least by a factor of ten (e.g., Reigber et al. 2002; Gerlach et al. 2003). Today, CHAMP-only gravity field solutions up to degree 100 are available.

The magenta curve in Fig. 1 shows the performance of the model AIUB-CHAMP03S (Prange et al. 2011) in terms of the degree error median

Fig. 1 Degree error medians of several global gravity field models



$$\sigma_n = \text{median}_m \{ \sigma_{\bar{C}_{nm}} ; \sigma_{\bar{S}_{nm}} \}, \quad (3)$$

where $\{ \sigma_{\bar{C}_{nm}} ; \sigma_{\bar{S}_{nm}} \}$ denote the formal coefficient error estimates of the gravity field model. It represents the error per harmonic degree n and thus per spatial (half) wavelength λ , according to $\lambda = 20,000 \text{ km}/n$.

As a reference, the absolute gravity field signal is displayed as black curve. Evidently, a signal-to-noise ratio of one is reached at a degree of about $n = 100$.

After 10 years of successful operation and decreasing orbit altitude, the CHAMP mission passed away on 19 September 2010.

2.2 GRACE

In 2002 the along-track satellite formation mission GRACE was launched into a near polar low Earth orbit (500 km altitude). Apart from high-low satellite-to-satellite tracking by the GPS constellation for each individual satellite, the key element is a K-band microwave ranging system observing the distance variation between the two satellites with micrometer accuracy. This type of mission is called a low-low satellite-to-satellite tracking constellation (SST-II). In addition, for observing the non-gravitational accelerations again an accelerometer has been located in the centre of mass of each satellite. The GRACE mission has two main goals: (1) the determination of the static field up to medium wavelengths (degrees 100–150) with unprecedented accuracy, and (2) the determination of the long wavelength time variations of the gravity field. The most recent static models derived purely from GRACE data resolve the global gravity field up to degree 180, e.g., GGM03S (Tapley et al. 2007), EIGEN-5S (Förste et al. 2008), AIUB-GRACE02s (Jäggi et al. 2009), and ITG-Grace2010S (Mayer-Gürr et al. 2010). The red curve in Fig. 1 shows the performance of one of the best currently available

GRACE models ITG-Grace2010S, resolved up to degree/order 180. Compared to CHAMP, the superior measurement principle of SST-II results in a significantly better performance in the low to medium wavelength range as well as a higher spatial resolution.

The GRACE mission opened the possibility to derive the non-tidal, temporal variations in the gravity field from space by solving for monthly gravity field models. The analysis of monthly fields allows to monitor the continental water storage variations, and to estimate the mass balance of ice sheets. Monthly solutions are routinely provided by the research institutions GFZ, CSR, JPL, and ITG (University of Bonn). Additionally, GRGS provides 10 days interval solutions (Bruinsma et al. 2010a). Even daily solutions based on a Kalman filter approach are computed by ITG (Kurtenbach et al. 2009). Regional solutions, independent of spherical harmonic fields and obtained using alternative approaches, have been computed by the Ohio State University (Han et al. 2005) and the NASA Goddard Space Flight Center (Lemoine et al. 2007). The yellow curve in Fig. 1 shows the achieved accuracy of a typical monthly GRACE solution.

Spectacular science results have been achieved by the analysis of GRACE data. As an example for cryospheric applications, the mass loss of the Greenland ice sheet has been observed to be in the order of 100–200 gigatons per year (e.g., Wouters et al. 2008; Velicogna 2009), and a significant negative trend of the integral Antarctic ice mass since 2002 was observed by GRACE-based studies (Horwath and Dietrich 2009). Figure 2 shows mass balance estimates for Greenland and Antarctica applying different methods, as they have been collected by Allison et al. (2009). Although they almost unambiguously show ice mass loss, the absolute value differs considerably, and still large uncertainties persist. This is not only due to methodological differences. In the case of the GRACE results, the main error sources are the separability of the gravity signal of ice from other gravity field contributors, such as glacial isostatic adjustment (GIA) in reaction to ice load changes, errors of other geophysical background models (atmosphere, ocean) applied during the GRACE processing, as well as the restricted spatial and temporal resolution leading to aliasing effects.

GRACE is also able to monitor the global hydrological cycle, both, concerning inter-annual variations and emerging trends of continental water storage. As an example, based on GRACE data the ground water depletion in Northern India could be detected (Tiwari et al. 2009), thus monitoring the loss of non-renewable drinking water resources from space. Nowadays, GRACE data are already assimilated into hydrological models or are used for their calibration (Werth et al. 2009a).

Since GRACE takes measurements only in one direction (along-track), the resulting error structure is highly anisotropic, which is one reason for the typical striping pattern of monthly gravity field solutions. The necessary filtering applying different methods (Werth et al. 2009b) limits the achievable spatial resolution of these monthly temporal GRACE solutions to 400–500 km. With sophisticated filter strategies spatial resolutions even down to 300 km seem to be possible.

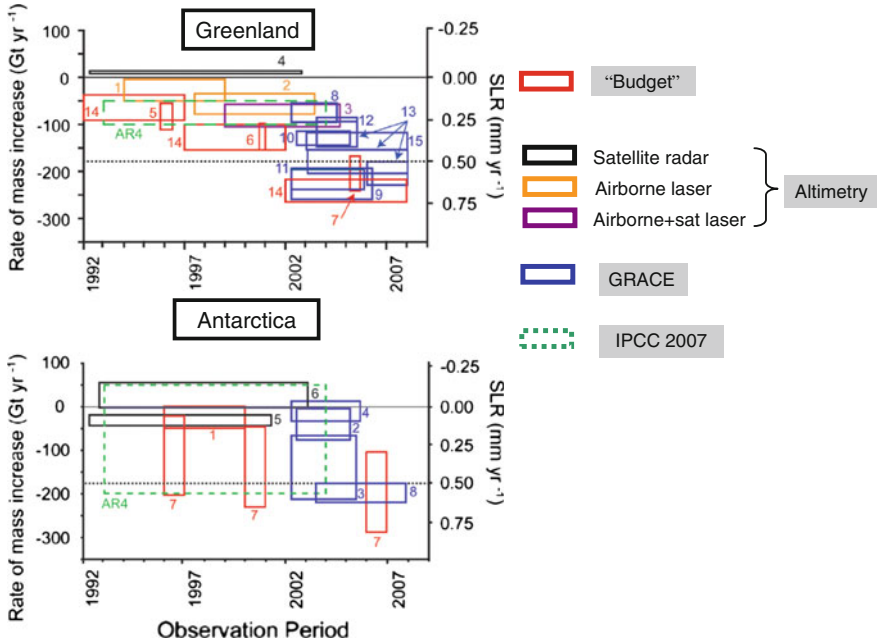


Fig. 2 Ice mass trends for Greenland (*top*) and Antarctica (*bottom*) derived by different methods indicated by colors; the graphics show the rate of mass increase/loss and the resulting sea level rise (SLR); from: Allison et al. (2009), modified

After 9 years of successful and almost continuous operation, battery problems might force the future mission scenario to hibernation phases, in order to monitor as a minimum mass variation trends until 2014/15. A GRACE follow-on mission is foreseen to be launched in August 2017.

2.3 GOCE

The GOCE satellite was successfully launched on 17 March 2009, and started its operational phase in September 2009. GOCE is based on a sensor fusion concept: SST-hl using GPS orbit information, as it is done for the CHAMP mission, plus on-board satellite gravity gradiometry (SGG). This completely new measurement concept is based on the observation of gravitational gradients (representing second order derivatives of the Earth's gravitational potential) in space with accelerometers over short baselines from a platform flying in drag-free mode, i.e. by in-situ compensating the non-gravitational forces. By measuring these gravity gradients, it is the first mission that observes direct functionals of the Earth gravity field from space, and not only the indirect influence of the gravity field on the spacecraft orbits. Further, whereas the GRACE observables (ranges and range rates between the two GRACE satellites) are sensitive in the along-track direction only, the full

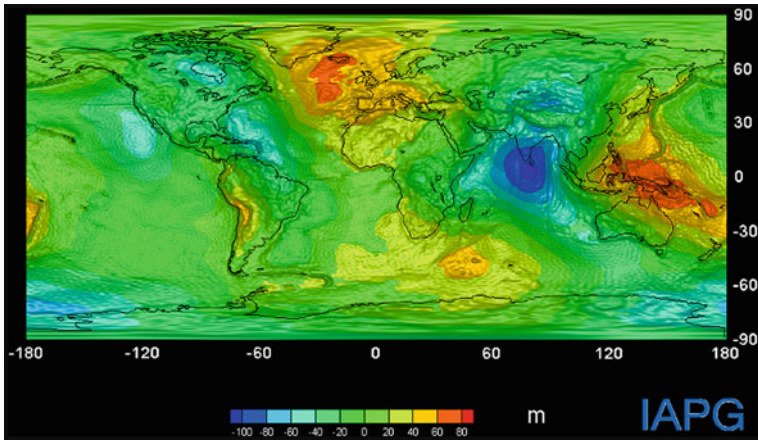


Fig. 3 Time-wise earth gravity field model GO_CONS_CGF_2_TIM_R1 derived from 71 days of GOCE data, expressed in geoid heights [m]

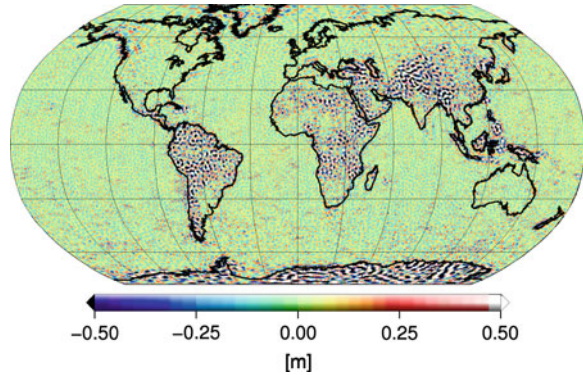
gravitational tensor is measured in-situ by the GOCE gradiometer, thus providing 3D information of the Earth’s gravity field with an isotropic error structure.

The GOCE mission is designed to resolve the medium to short wavelengths of the static gravity field (up to a maximum degree and order of 240–250). This higher resolution compared to GRACE is not only possible due to the different observation type of gravity gradients, which is more sensitive to detail structures of the gravity field, but also due to an extremely low satellite altitude of about 255 km, which is achievable only due to the active drag compensation. In contrast, the SST-II observation technique applied by GRACE is superior in the low to medium wavelengths of the gravity field spectrum.

First GOCE gravity field models based on about 71 days of GOCE data (November 2009 to January 2010) have been computed in the frame of the ESA project “High-Level Processing Facility” (Rummel et al. 2004) by applying 3 independent and complementary processing strategies, the direct (Bruinsma et al. 2010b), time-wise (Pail et al. 2010a), and space-wise (Migliaccio et al. 2010) method, and have been made publicly available in July 2010. An overview of the processing strategies and an evaluation and validation of the results can be found in Pail et al. (2011). Figure 3 shows the gravity field solution of the time-wise method GO_CONS_CGF_2_TIM_R1, which is a pure GOCE solution without any gravity field prior information, in terms of geoid heights.

The green curve in Fig. 1 shows the corresponding formal error estimates of this gravity field model, resolved up to degree/order 224, in terms of degree error medians. GOCE starts to become superior over GRACE approximately at degree $n = 150$. Below, GRACE shows a better performance due to its SST-II concept and the larger data volume. Generally, the independently obtained results of GRACE and GOCE show a striking consistency in the low to medium degrees,

Fig. 4 Geoid height differences between GOCE model GO_CONS_CGF_2_TIM_R1 and combined gravity field model EIGEN-5C up to degree/order 200



demonstrating that both missions are reasonably calibrated, and no major systematic errors are inherent in the gravity field models derived from them.

A comparison of this solution against the combined gravity field model EIGEN-5C (Förste et al. 2008), which includes GRACE, terrestrial gravity field and satellite altimetry data, reveals interesting and promising features. Figure 4 shows geoid height differences between GOCE and EIGEN-5C, resolved up to degree/order 200. They show a high consistency (small differences) for Europe, Northern Asia, North America, and the open ocean areas.

However, in regions where currently available terrestrial gravity field data are known to be poor, such as South America, Africa, Asia or Antarctica, significant differences show up, demonstrating the impact of only 2 months of GOCE data for the gravity field knowledge in these regions.

The release 2 of a time-wise GOCE-only gravity field solution GO_CONS_CGF_2_TIM_R2 based on the data period November 2009 to July 2010 (effectively 6 months after reduction of data gaps and calibration phases) has become publicly available in February 2011. The blue curve in Fig. 1 shows the significant improvement compared to the previous 2 months solution (green curve). As it has to be expected, due to the increase of the data amount by a factor of about 3, the improvement is in the order of $\sqrt{3}$ over a wide spectral range. The cross-over with the GRACE performance has now been decreased from 150 to about 135.

It can be shown that this factor of $\sqrt{3}$ is not only present in the formal errors, but is a real improvement of the gravity field accuracy. For this purpose, gravity anomaly deviations of the 2 months solution GO_CONS_CGF_2_TIM_R1 (top) and the release 2 model GO_CONS_CGF_2_TIM_R2 (bottom) from EIGEN-5C have been computed (Fig. 5), clearly showing the noise reduction over the open oceans and regions with high-quality terrestrial gravity field data incorporated in EIGEN-5C.

Originally, the nominal GOCE mission end was scheduled for April 2011. However, it was decided by ESA to extend the mission until December 2012. Recalling the improvement when including a larger data amount as shown in Figs. 1 and 5, this leaves a very promising perspective. In order to evaluate the impact of GOCE on the global knowledge of the Earth's gravity field and thus on

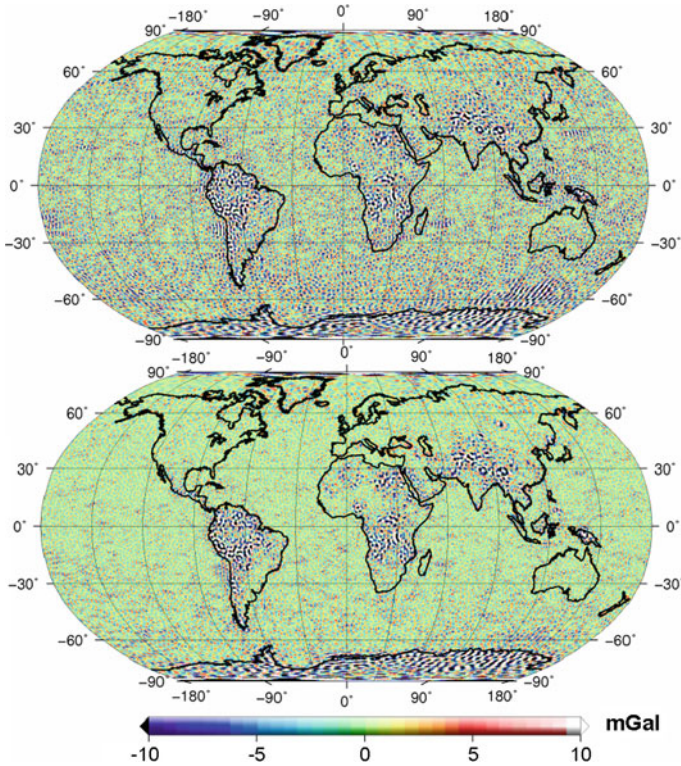


Fig. 5 Gravity anomaly deviations from EIGEN-5C up to degree/order 200: (*top*) GOCE 2 months solution GO_CONS_CGF_2_TIM_R1; (*bottom*) GOCE 6 months solution GO_CONS_CGF_2_TIM_R2

many applications in Earth sciences, Fig. 6 shows cumulative geoid height errors (left) and gravity anomaly errors (right) in dependence of the harmonic degree (spatial resolution). The red and blue curves show the performance of the 2 months and the 6 months solutions, respectively, while the black curve represents a performance prediction assuming a successful GOCE mission (at the present altitude) until end of 2012. The results are 3 cm geoid height error and 1 mGal gravity anomaly error at degree/order 200 (= 100 km half wavelength).

3 Combined Satellite-Only Gravity Field Models

It was discussed in Sect. 2 and shown in Fig. 1 that the GRACE mission shows a better performance than GOCE in the low to medium degrees up to 130–150 due to the SST-II concept, while beyond GOCE starts to become superior because of SGG. Thus, a consistent combination of these two missions makes optimal benefit of the individual strengths of these two satellite missions. A first satellite-only

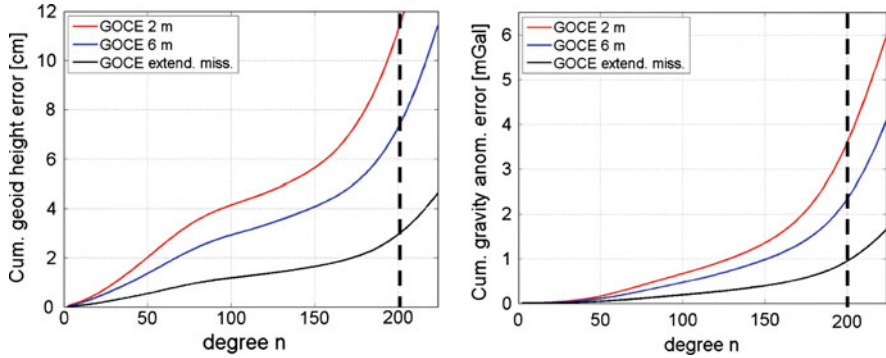


Fig. 6 Cumulative geoid height errors in [cm] (*left*) and cumulative gravity anomaly errors in [mGal] (*right*) for GOCE solutions based on a different amount of data

combined model GOCO01S (Pail et al. 2010b) was computed by addition of normal equations of these two satellite missions, plus some additional constraints to improve the signal-to-noise ratio in the high degrees.

GOCO stands for “Gravity observation combination” and is a joint project initiated by the Institute of Astronomical and Physical Geodesy, TU München, the Institute of Theoretical and Satellite Geodesy, Graz University of Technology, the Institute of Geodesy and Geoinformation, University of Bonn, the Astronomical Institute, University of Bern, and the Space Research Institute, Austrian Academy of Sciences (www.goco.eu). The main objective is to derive combined global gravity field models from complementary data sources such as the satellite gravity missions GOCE, GRACE and CHAMP, terrestrial gravity field and satellite altimetry data, and SLR.

For GOCO01S, concerning GOCE a slightly improved version of the GOCE normal equations of the time-wise solution based on approximately 2 months of data was used. The improvement is mainly related to a better treatment of some minor data problems of one of the gradiometer components in the South of Australia. Additionally, GRACE normal equations of ITG-Grace2010S (Mayer-Gürr et al. 2010) up to degree/order 180, which are based on GRACE data covering the time span from August 2002 to August 2009, have been used for the combination.

The processing methodology is described in Pail et al. (2010b). Since the lower degrees are well-determined by GRACE, no gravity field information derived from GOCE orbits was included. Figure 7 shows the performance of the individual components and the final model in terms of degree error medians.

The magenta curve represents an unregularized solution which is solely based on 2 months of GOCE gradiometry, while the red curve is related to the GRACE-only solution. The combination solution GOCO01S is displayed as blue dashed curve. As a reference, the GOCE-only model GO_CONS_GCF_2_TIM_R1 is displayed in green color. In addition to SGG, it is based on kinematic GOCE precise science orbits in the low degrees.

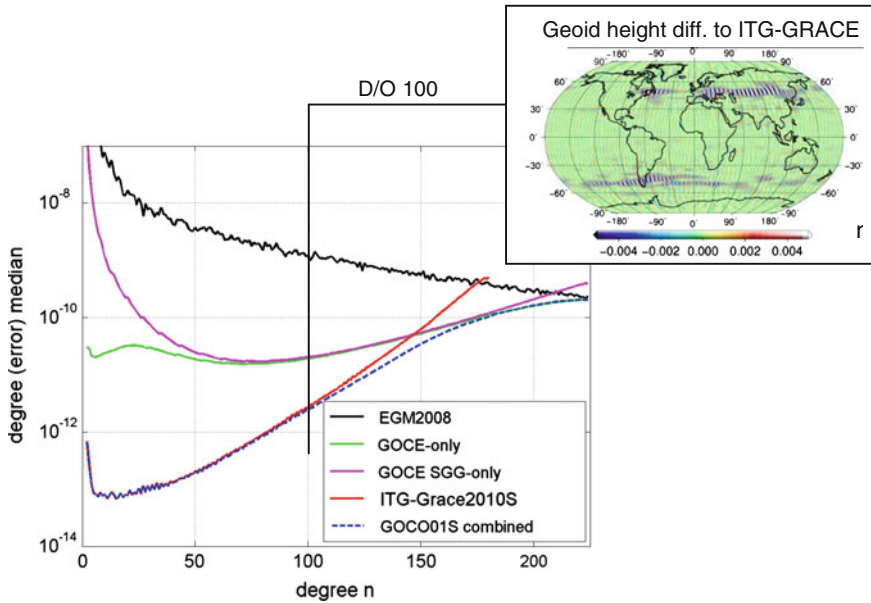


Fig. 7 Degree error medians of the GOCE component (*magenta*), the GRACE component (*red*), and the combined GOCO01S solution (*blue dashed*). As a reference, the GOCE-only SST + SGG solution GO_CONS_GCF_2_TIM_R1 (*green*), and the absolute gravity field signal based on EGM2008 (*black*) are displayed. *Upper right* geoid height differences between GOCO01S and ITG-Grace2010S up to degree/order 100

Analyzing the satellite-only combination model GOCO01S, evidently GOCE starts to contribute already below degree/order 100, shown by the divergent error curves (red vs. blue). In order to illustrate this contribution more lucidly, geoid height differences between GOCO01S and the pure GRACE component ITG-Grace2010S up to degree 100 are visualized in the upper right, revealing patterns which are typical for GRACE errors. Thus, it can be concluded that by inclusion of only 2 months of GOCE data the 7 years GRACE solution could be improved by a few millimetres already at degree/order 100.

In June 2011, also a second release of a combined satellite-only model, GOCO02S, was processed. It is based on 8 months of GOCE data (November 2009 to July 2010) and the ITG-Grace2010S model. Additionally, normal equations of 12 months of GOCE GPS-SST, 8 years of CHAMP GPS-SST and 5 years of SLR to 5 satellites have been included. Table 1 summarizes the main features and data used for GOCO01S and GOCO02S.

The performance of GOCO02S is shown as dashed black curve in Fig. 1. Still, the main contributors to this solution are GOCE (dark blue curve) and GRACE (red curve), while the contributions by the additional components included in this solution are only very minor. SLR has been adopted in order to stabilize the estimates of the very low degrees. The performance in the high degrees is

Table 1 Main features and data sets used for the combined gravity field models GOCO01S and GOCO02S. Also given is the maximum degree/order (*d/o*) of resolution and the number of observations contained in the individual normal equations

Data set	GOCO01S <i>d/o</i> 224	GOCO02S <i>d/o</i> 250	GOCO02S #obs. [mio.]
ITG-Grace2010S	<i>d/o</i> 180 7 years	<i>d/o</i> 180 7 years	85
GOCE gradiometry	<i>d/o</i> 224 2 months	<i>d/o</i> 250 8 months	57
GOCE GPS-SST (high-low tracking)	–	<i>d/o</i> 110 12 months	72
CHAMP GPS-SST (high-low tracking)	–	<i>d/o</i> 120 8 years	63
SLR	–	<i>d/o</i> 5 5 years/5 sats.	2
Constraints	<i>d/o</i> 170–224 (Kaula)	<i>d/o</i> 180–250 (Kaula)	–
SUM			280

dominated by the GOCE contributions, and thus is very similar as shown in Fig. 5 for the GOCE-only model.

4 Earth Science Applications

As discussed in Sect. 1, one of the main geoscientific applications of high-resolution static satellite gravity field solutions is oceanography. In order to show the impact of the new GOCE models in this field of application, the mean dynamic topography (MDT), which is defined as the difference of the mean sea surface h and the geoid N ,

$$H = h - N \quad (4)$$

has been computed for the region of the Antarctic Circumpolar Current (ACC) on a regular grid of $0.5^\circ \times 0.5^\circ$ using a mean sea surface (DGFI-2010) derived from 17.5 years of data of several altimeter missions (ERS-1, ERS-2, ENVISAT, TOPEX/Poseidon, Jason-1, and Jason-2), and a geoid model. The strategy of the MDT computation and the filtering of the mean sea surface is described in Albertella et al. (2010).

Figure 8 shows the resulting MDT using either the GRACE-only model ITG-Grace2010S or the combined model GOCO01S for computing the geoid. The top row shows the MDT for selected spectral ranges (degrees 90–120, 120–150, and 150–180) when using ITG-Grace2010S.

In addition to oceanographic signals, striping patterns related to GRACE errors are visible in all three spectral windows, but grow in amplitude with increasing degrees. In contrast, when using the GOCO01S model and thus additionally

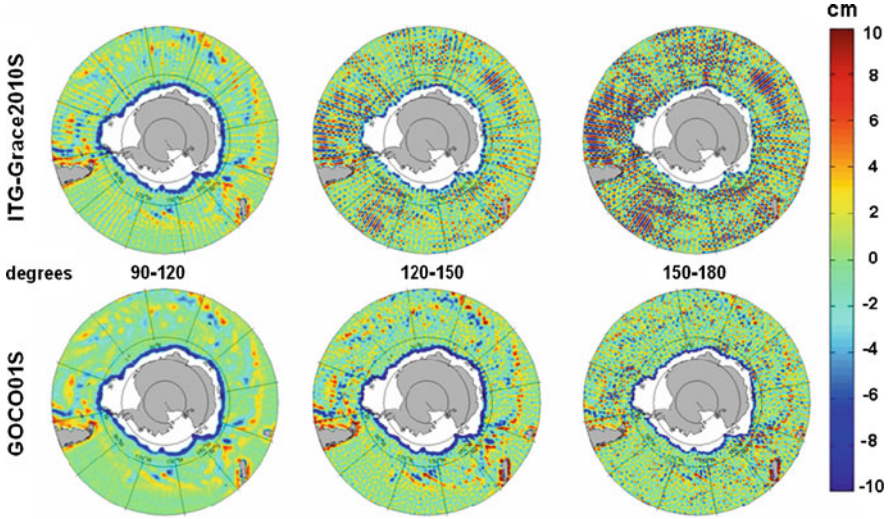


Fig. 8 Mean dynamic topography derived from multi-year and multi-mission satellite altimetry data, and two global geoid models (*top row* ITG-Grace2010S; *bottom row* GOCO01S), analyzed in different spectral windows: (*left*) degrees 90–120; (*centre*) degrees 120–150; (*right*) degrees 150–180

2 months of GOCE data, these error structures almost vanish, and the oceanographic signal becomes more prominently visible. Especially in the spectral window of degrees 150–180 the great contribution by the additional high-resolution information of GOCE is evident.

Applying a simplified form of the Navier-Stokes equation assuming geostrophic conditions, ocean surface velocities can be derived as horizontal derivatives of the mean dynamic topography H :

$$\begin{aligned}
 2 \omega \sin \varphi v &= -g \frac{\partial H}{\partial x} \\
 2 \omega \sin \varphi u &= g \frac{\partial H}{\partial y}
 \end{aligned}
 \tag{5}$$

u and v are the geostrophic velocities in North and East direction, respectively, ω is the Earth’s rotation rate, and g is mean gravity. Please note that the North component of the velocity u is obtained by the derivative of the dynamic topography in East direction, and the East component v by the derivative in North direction. Descriptively this means, that the surface currents flow along the isolines of the MDT.

Figure 9 shows the geostrophic surface velocities $\sqrt{u^2 + v^2}$ of the Antarctic Circumpolar Current (ACC) derived from the MDT (cf. Fig. 8), resolved up to degree/order 180, when using for the geoid either the GRACE-only model ITG-Grace2010S, GOCO01S, or GOCO02S. Since geostrophic velocities are first order

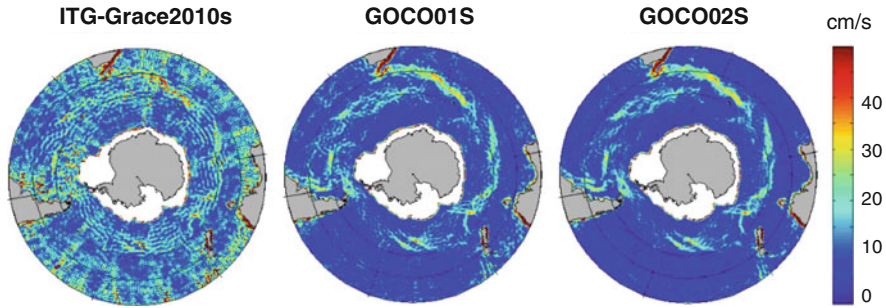


Fig. 9 Geostrophic ocean surface velocities [cm/s] of the Antarctic circumpolar current derived from geodetic MDT using different global geoid models, resolved up to degree/order 180

derivatives of the MDT, they are particularly sensitive to high degree signals. Similarly to Fig. 8, also here there are huge numerical artefacts in the solution of the GRACE-only model, while the actual ocean currents are already clearly visible in GOCO01S. The second release GOCO02S shows further improvement and reduction of noise. Consequently, for the first time it has become possible to derive ocean currents with high accuracy and spatial resolution from satellite data.

Another example where the impact of GOCE for the estimation of geostrophic velocities becomes also visible is the Gulf current (Fig. 10). Again, significant improvements when using GOCE data is evident. These results are compared to velocities which have been measured *in-situ* by drifters. The latter dataset has been compiled in the frame of the project Drifter Data Assembly Center (DAC), a segment of the Global Drifter program coordinated by NOAA and AOML (Lumpkin and Garraffo 2005). The total ocean velocity signal in this area has an rms amplitude of 17.10 cm/s. The differences of the velocities derived by using the ITG-Grace2010S model from this drifter measured velocities is 9.46 cm/s. This value could be significantly reduced to 5.86 cm/s when using the combined GOCO02S model.

It should be emphasized that for this type of studies it is crucial to use a pure satellite-only gravity model, which is independent of terrestrial gravity field and satellite altimetry data. Since the mean sea surface is derived from satellite altimetry data, it is important that the geoid model, which is subtracted from the mean sea surface in order to derive the MDT, does not include altimetry data as well.

As another field of application for high-resolution static gravity models, current studies investigate the impact on GOCE for modelling subduction zones and dynamic processes of the lithosphere. For this geophysical application, combination models from satellite gravity, terrestrial gravity data, and gravity anomalies derived from satellite altimetry, are computed (Fecher et al. 2011), in order to further extend the spatial resolution to substantially higher degrees than for satellite-only models.

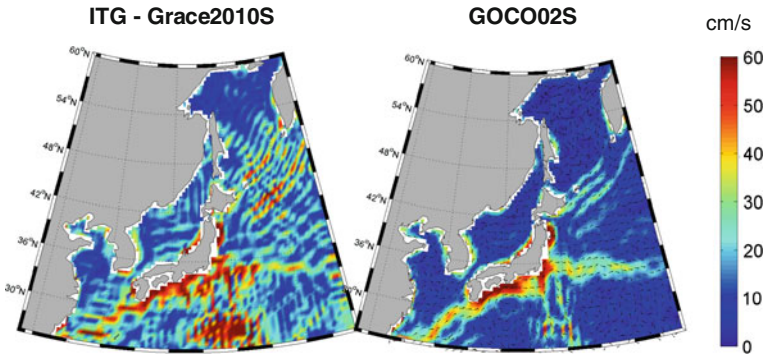


Fig. 10 Geostrophic ocean surface velocities [cm/s] of the Gulf current derived from geodetic MDT using ITG-Grace2010S (*left*) and GOCO02S (*right*), resolved up to degree/order 180

Therefore, as part of the GOCO project initiative several numerical studies to solve full normal equation systems up to degree/order 600 in a rigorous sense have been performed (Fecher et al. 2010). In the near future, rigorous combination solutions complete to degree/order 720 are envisaged. Since the storing and solution of a full equation system of degree/order 600 requires a working memory of about 1 Terabyte, tailored processing strategies on supercomputers have to be applied.

5 Conclusions and Outlook

In this paper an overview of the status of global gravity field modelling using data from dedicated satellite gravity field missions CHAMP, GRACE and GOCE is given, and exemplarily selected geoscientific applications and their impact on Earth system research are discussed.

Spectacular results could be obtained from static and, in particular, time-variable GRACE gravity fields, from which the long-wavelength component of global mass transport processes could be derived for the very first time in a consistent way. The new observation type of GOCE gradiometry allows to achieve a higher spatial resolution of the static gravity field, and thus a more refined picture of small scale processes in oceanography and solid Earth geophysics.

In this paper the progress of GOCE gravity field processing is reviewed, concentrating on those activities the author is responsible. Compared to the first GOCE-only solution GO_CONS_GCF_2_TIM_R1, recent GOCE solutions including a larger amount of GOCE data show improvements according to the statistical \sqrt{N} rule of uncorrelated observations. This is a strong indicator that there are no significant systematic errors in these solutions, and that the stochastic models, which are applied to form the metric of the normal equation systems of the individual components, are correct and meaningful.

Additionally, the first consistent combination models of satellite gravity field data, GOCO01S and GOCO02S, have been addressed, and their impact on an important oceanographic application, namely the derivation of the mean dynamic topography and ocean surface currents, is discussed.

It is important to emphasize that for the computation of the gravity field models discussed in this paper no external gravity field information is used, neither as reference model, nor for constraining the solution. Thus they are GOCE-only/satellite-only in a rigorous sense. Due to this independence of external gravity field information (especially terrestrial gravity field data and satellite altimetry) they can be used for an *independent* comparison and combination with terrestrial gravity data and altimetric gravity anomalies, and for assimilation into ocean models (using a high-resolution geoid which is independent of altimetry).

For geophysical applications GOCE gradiometry provides as a new observation type, which will enable an improved modelling of lithospheric structures (Hosse et al. 2011). A comparison of the new GOCE models with previously existing gravity field models shows, that substantial improvement of our gravity field knowledge could be achieved especially in regions with interesting geophysical features, such as the Andes and Himalaya area, or the East African rift zone.

Future activities of global gravity field modelling will include the incorporation of gradually increasing amounts of GOCE data for the computation of GOCE-only and satellite-only combined models. Recently, a new pre-processing method for GOCE gravity gradients related to an improved angular rate reconstruction could be derived (Stummer et al. 2011), which has been implemented in the official ESA Level 1b processor, so that reprocessed gradients with an improved performance particularly in the long to medium wavelengths will shortly be available, and thus will further improve satellite-only gravity field models.

In parallel, also the inclusion of terrestrial gravity anomalies and satellite altimetry by combination on normal equation level, and rigorously solving very large normal equations for 500,000 unknown gravity field parameters, is currently under investigation.

The application of these gradually improving static and time-variable gravity field models in several geoscientific fields will demonstrate their valuable contribution to Earth system research.

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