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GOCE data, models, and applications: A review

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ABSTRACT

With the launch of the Gravity field and Ocean Circulation Explorer (GOCE) in 2009 the science in gravity got another boost. After the time-lapse and long-wavelength studies from Gravity Recovery and Climate Experiment (GRACE) a new sensor was available for determination of the Earth's gravity field and geoid with high accuracy and spatial resolution. Equipped with a 6-component gradiometer and flying at an altitude of 260 km and less GOCE provides the most detailed measurements of Earth's gravity from space ever. On top, GOCE also provides gravity gradients, i.e., the three-dimensional second derivatives of the gravitational potential. This paper provides a review of the results presented at the 'GOCE solid Earth workshop' at the University of Twente, The Netherlands (2012), where an overview was given of the present status of the data models, and applications with GOCE which form the basis for this special issue and the review in this paper. An introduction will be given to the GOCE satellite followed by an overview of GOCE data and gravity models. The present state of GOCE related research in geodesy, oceanography and solid Earth sciences indicates the first steps taken to integrate GOCE in the different application fields. For all three fields an overview is given on the most recent scientific results and developments, and first results specifically focusing on these studies where GOCE data has made a unique contribution and provides insights that would not have been possible without GOCE.

1. Introduction

In 2009 the European Space Agency (ESA) launched their Gravity field and Ocean Circulation Explorer (GOCE). GOCE was selected as the first so-called Earth Explorer Core Mission of ESA's Living Planet Programme in 1999 (European Space Agency, 1999; Drinkwater et al., 2003). After nearly a decade of development and launch preparations the satellite was launched from Plesetsk Cosmodrome in northern Russia on 17 March, 2009; precisely seven years after the launch of GRACE. The mission objective of GOCE is the determination of the Earth's gravity field and geoid with high accuracy and spatial resolution. Equipped with a 6-component gradiometer and flying at an altitude of 260 km and less it provides the most detailed measurements of Earth's gravity from space ever. More specifically, geoid heights are being determined with cm-level accuracy and gravity variations to one part-per-million (1 ppm) of "g", in both cases with a spatial resolution of about 100 km on the Earth's surface. It should be noted that these mission objectives are complementary to those of the Gravity Recovery and Climate Experiment (GRACE) mission, see e.g. Tapley et al. (2004). 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 spatial resolution. The two types of gravity field information are complementary and vastly important for Earth system science. The GRACE time series reveal the path and to some extent the size of mass movements, related to and caused by processes such as melting ice sheets, the global water cycle, sea level variations, post glacial mass re-adjustments and others. GOCE, on the other hand, provides one global and detailed map of spatial gravity and geoid variations. On top, GOCE also provides gravity gradients, i.e., the three-dimensional second derivatives of the gravitational potential. A comprehensive description of the GOCE mission design and operations experience is provided in Floberghagen et al. (2011).

Although the mission is still continuing and further improvement of the quality of the data is to be expected, the scientific community has already started working with early releases of data. At the 'GOCE solid Earth workshop' at the University of Twente, The Netherlands (2012), an overview was given of the present status of the data models, and applications with GOCE which form the basis

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for this special issue and the review in this paper. An introduction will be given to the GOCE satellite followed by an overview of GOCE data and gravity models. The present state of GOCE related research in geodesy, oceanography and solid Earth sciences indicates the first steps taken to integrate GOCE in the different application fields. For all three fields an overview is given on research directions, and first results specifically focussing on these studies where GOCE data has made a unique contribution and provides insights that would not have been possible without GOCE.

2. The GOCE mission

2.1. Mission design

Mapping the gravity field at high accuracy and fine spatial scale requires the space-based observing platform to orbit at the lowest possible altitude. At such altitudes the near-Earth environment exerts significant aerodynamic forces and torques on the satellite. On the other hand, the environment in which the instrument acquires its measurements must be as “quiet” as possible, and ideally free of any disturbances from non-gravitational forces. These specific requirements applicable to the GOCE satellite could only be satisfied by embarking a number of novel technologies, including various ‘firsts’, making the GOCE mission a major technological challenge (and achievement). These technologies include: drag-free-control along the flight direction, modulated electric propulsion, electrostatic gravity gradiometry, triple-junction Gallium-Arsenide solar cells and the manufacturing of a larger than ever three-dimensional carbon-carbon honeycomb structure providing the extreme mechanical stability of the gradiometer instrument. The need for a low, quiet flight means the design must minimize air drag forces and torques, and eliminate mechanical disturbances. The result is a very slim satellite with a cross-sectional area of 1.1 m^2, 5.3 m in length and a launch mass of about 1050 kg. The satellite is symmetrical about its flight direction and two winglets provide additional passive aerodynamic stability. The same side of the satellite always faces the Sun. The spacecraft is thus kept both Sun- and nadir-pointing by means of magnetotorquer actuation. Precise attitude information is provided by three advanced stellar cameras (so-called star trackers) as well as the gradiometer instrument, which provides the function of a gyroscope measuring ultra-precise angular accelerations. The wing pointing towards zenith carries two GPS antennas.

Due to its unprecedented thermo-elastic stability requirements in the few milliKelvin range, the gradiometer is thermally decoupled from the satellite and has a specially designed thermal control concept. An outer, actively controlled thermal domain is kept at a very stable temperature by heaters and is separated by blankets from an inner passive domain that provides an extremely homogeneous environment for the accelerometers. The temperature must be stable to within 10 milli-degrees Kelvin for a period of 200 s.

2.2. Electrostatic gravity gradiometer (EGG)

The EGG consists of three orthogonal pairs of capacitive accelerometers mounted on the ultra-stable carbon–carbon honeycomb support structure. The principle of operation of these accelerometers is that a proof mass is kept levitated in the centre of a slightly larger cage by electrostatic forces, i.e. by applying so-called control voltages between the (eight) electrode pairs embedded in the cage and the different faces of the square cuboid proof mass. These voltages are representative of the accelerations seen by the proof mass and are the initial input to an elaborate chain of processing steps that, ultimately, lead to a full-fledged model of the gravity field. The requirements for the gradiometer are severe and stringent. The accelerations measured by each accelerometer within a band-limited frequency range of 5–100 mHz can be as small as one part in 10^{13} of the gravitational attraction experienced on Earth. The GOCE accelerometers are therefore about 100 times more sensitive than any accelerometers previously flown, such as SuperSTAR on GRACE (Touboul, 2003; Touboul et al., 2004). The distance between each sensor pair must not vary by more than 1% of an Ångstrom over a time interval of about three minutes. Realistically, this can only be achieved by using structural design technologies based on three-dimensional carbon–carbon panels and central stiffeners. Two accelerometers of the same pair are mounted at 50 cm distance to each other and form a gradiometric arm. Along the satellite orbit the two proof masses of any pair of accelerometers tend to gravitate under the influence of the Earth’s gravity field and its spatial variations. The gradiometer measures this tendency, expressed as a differential acceleration between accelerometer pairs, for all six accelerometers and each of them in six degrees of freedom (three linear accelerations, three rotational accelerations).

In order to measure gravity gradients, a differential observation technique is used. The measurements from two accelerometers along one arm are subtracted from each other, removing noise and disturbing forces that affect both accelerometers. This process is known as ‘common mode rejection’. What remains is the difference in acceleration due to Earth gravitation, measured at two locations separated by 50 cm. This difference is a very good approximation of the gravity gradient, the second derivative of the gravitational potential. The difference in the accelerations measured by the two accelerometers belonging to the same arm therefore represents the basic scientific product of the gradiometer.

In addition to the differential measurement, the average acceleration of two measurements in one arm is also exploited. This average is representative of external forces on the spacecraft like atmospheric drag and solar radiation pressure. The information is used (by the satellite platform application software) to command the electric propulsion (ion) engine to continuously counteract the atmospheric drag and keep the satellite flying undisturbed and drag-free along the flight direction, for details see e.g. Andreis and Canuto (2005). Indeed, if this common mode acceleration in flight direction is not null, the controller will respond by either increasing or decreasing the ion engine thrust to maintain the spacecraft and its sensors in near free-fall conditions. The result is twofold: (i) the satellite maintains its orbital altitude and therefore is able to perform a uniform global mapping of the gravity field, and (ii) the common-mode rejection in combination with the minuscule remaining common-mode accelerations as well as as well as remaining imperfections after calibration (in terms of orthogonality of the arms and alignment of the sensor heads) efficiently reduces the noise in the differential mode accelerations (and consequently in the gravity gradients) to the $2\text{–}5 * 10E^{-12}\ m/s^2/\sqrt{Hz}$ level which represents the accuracy requirement for this measurement.

The gradiometer thus provides very sensitive measurements of the three linear and the most important angular accelerations of the spacecraft and the four out of six components of the gravity gradient tensor. Further details on the gradiometric sensor system on GOCE can be found in Cesare (2008).

2.3. Satellite-to-Satellite Tracking Instrument (SSTI)

Although the gradiometer is highly accurate, it is not manufactured to map the gravity field at all spatial scales (frequencies) with the same quality. To overcome this limitation, and for precise positioning of the satellite, GOCE is equipped with a state-of-the-art geodetic GPS receiver, called the Satellite-to-Satellite Tracking Instrument. By exploiting the extremely precise orbit

Table 1
Main characteristics of GOCE gravity field models. Performance numbers are estimated from the TIM model.

Model	Max degree (DIR/TIM/SPW)	Gradients	Data period	nr epochs (in mio.)	σ_N [cm] (d/o 200)	$\sigma_{\Delta g}$ [mGal] (d/o 200)
R1	240/224/210	Original	01/11/2009–11/01/2010	6	10.0	3.0
R2	240/250/240	Original	01/11/2009–05/07/2010	20	6.1	1.8
R3	240/250/–	Original	01/11/2009–17/04/2011	31	4.6	1.3
R4	260/250/–	Reprocessed	01/11/2009–19/06/2012	70	3.2	0.9

determination based on SSTI data (i.e., cm-level accuracy in each of the three orthogonal directions is confirmed by independent orbit determination techniques as well as by validation against satellite laser ranging tracking data) the robust and accurate retrieval of gravity field constituents at all scales from global to about 80 km is achieved. As with the EGG, the SSTI also acts as a sensor for the orbit control system by providing an on-board real-time navigation solution, which defines the target frame (orientation) for the attitude control system. The SSTI simultaneously tracks 12 GPS satellites and works on L1/L2 frequencies. This eliminates errors caused by the ionosphere, which extends between the GOCE and the GPS satellite orbits.

2.4. Mapping orbit

Upon launch into a sun-synchronous near polar orbit on 17 March 2009 a nominal orbit injection delivered the satellite into its target orbit corresponding to a mean semi-major axis of 278.65 km and an inclination of 96.7°. For optimal sun illumination and in order to minimize thermal gradients a dusk-dawn orbit with ascending node at 18:00 local solar time was chosen. During the first three years of the mission, after an initial check-out phase, the satellite was mapping the gravity field at an altitude of 254.9 km – corresponding to a 61 days/979 revolutions repeat cycle. Owing to the slight tilt of 6.7° with respect to a perfectly polar orbit and the extremely low altitude, during the nominal mission the satellite experienced two eclipse periods per year: one of relatively short duration during early winter and a longer one during summer. Starting from August 2012 onwards, upon having achieved the nominal objectives of the mission, the GOCE team has gradually brought the altitude down by slightly more than 30 km, in order to further increase the precision and spatial resolution of the GOCE gravity field products. At the time of writing the equatorial altitude is an unprecedented 223.88 km, in an 143 days/2311 revolutions repeat cycle. The mission is expected to end in late 2013 when the Xenon gas used as propellant for the drag compensation system will be depleted.

3. GOCE data and gravity models

Up to now, four releases (R1–R4) of GOCE gravity field models have been computed in the frame of the ESA project "GOCE High-Level Processing Facility" (HPF), a consortium of 10 European university and research institutes, managed by TU München. They are based on the following GOCE data products:

- Orbits: SST_PSO_2 (sub-products: SST_PKI_2 [kinematic orbits], SST_PCV_2 [variance-covariance information of orbit positions], or alternatively SST_PRD_2 [reduced-dynamic orbits]).
- Gravity gradients in the gradiometer reference frame (GRF) and attitude: EGG_NOM_2.
- Non-gravitational ("common mode") accelerations: EGG_CCD_1B.
- Models for temporal gravity field reduction, such as ephemeris of Sun and Moon, ocean tide models, correction coefficients for non-tidal temporal variation signals (SST_AUX_2), and for Earth's rotation (AUX_IERS).

Details on standards and background models can be found in the GOCE Standards document (EGG-C 2010). In the frame of GOCE HPF, three different methods and processing philosophies are applied for gravity field modelling: the direct approach (DIR; Bruinsma et al., 2010), the time-wise approach (TIM; Pail et al., 2010), and the space-wise approach (SPW; Migliaccio et al., 2010). The DIR and the TIM method are based on the assembling and solving of large normal equation systems using the observations along the orbit to estimate the harmonic coefficients as parameters of a least squares adjustment problem. While the DIR models are combination models including also CHAMP (Challenging Minisatellite Payload Reigber et al., 2002), GRACE (Gravity Recovery and Climate Experiment; Tapley et al., 2007) and satellite laser ranging (SLR) data (R3 and R4), all four releases of the TIM models are based solely on GOCE data and are independent of any other gravity field prior information. In contrast, SPW works predominantly in the space domain, applying least squares collocation and exploiting spatial correlations of the gravity field. After R2, the SPW approach has been redefined to provide gravity gradient grids mainly for geophysical users. A detailed overview of the three approaches is provided in Pail et al. (2011).

Table 1 summarizes the main characteristics of the four releases of GOCE gravity models GOC_CONS_GCF_2_xxx_Ry (xxx standing for DIR, TIM or SPW, and y for the release number), which cover different data periods and correspondingly different data volumes. Realistic performance estimates in terms of geoid height σ_N and gravity anomalies $\sigma_{\Delta g}$ accuracies at degree/order (d/o) 200 (corresponding to 100 km spatial wavelength) are given in the last 2 columns exemplary for the TIM models. Formal error propagation of the DIR models results in significantly lower numbers, e.g., 1.3 cm geoid height error for DIR R4.

In addition to the successively increasing number of observations, a further gain in performance of GOCE gravity field models could be achieved by an improved method for gravity gradient preprocessing in the frame of the Level 0 to Level 1b processing hosted at ESA. After modifications of the Level 1b processors described in Stummer et al. (2012), the GOCE data of the full mission period have been reprocessed and have already been used for release 4 of the gravity field models. Further improvements of the accuracy and spatial resolution can be expected from the GOCE satellite's orbit lowering by up to 30 km in its final phase, which will be used for the final R5 models to be released by mid of 2014. The accuracy of the models has been thoroughly validated by external data sources and reference gravity field models, which do not contain GOCE information. Already the comparison of the R1 models with the combined model EGM2008 (Pavlis et al., 2012), which contains also terrestrial data, has revealed that GOCE can provide for the very first time high-resolution gravity field information in regions, where no or only low-accuracy terrestrial gravity field information exists such as South America, central Africa, the Himalaya region, or Antarctica (Pail et al., 2011). Correspondingly, it is expected that there will be a high impact on the geophysical modelling of the lithosphere, e.g., in the active continental margin of the Andes region, or in the East African rift zone.

Exemplary, Fig. 1 shows gravity anomaly differences to EGM2008 up to degree/order 200 for the regions of North America (top) and South America (bottom). The left column provides

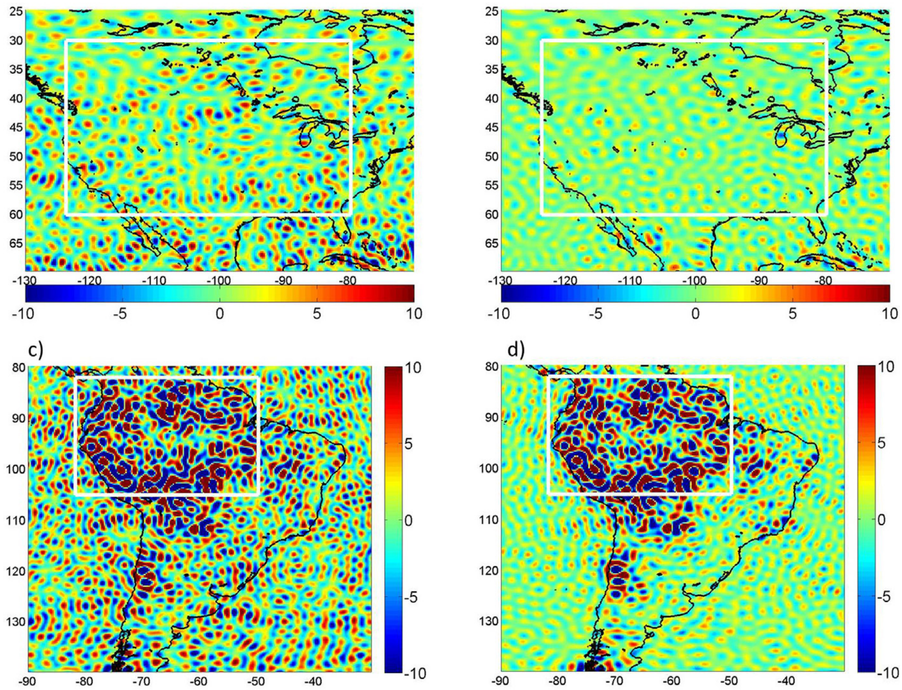

Fig. 1. Gravity anomaly differences (mGal) to EGM2008 in North America (top row) and South America (bottom row), for TIM_R1 (left column) and TIM_R4 (right column); from: Pail (2013).

difference fields of TIM_R1, and the right column of TIM_R4. In North America, where the EGM2008 is expected to have very good quality due to the availability of high-quality ground gravity data, the differences to the GOCE models are generally small, and the consistency steadily increases with increasing release number.

The standard deviations, computed in the sub-region marked by white rectangles in Fig. 1, are reduced from 2.6 mGal (R1) to 1.2 mGal (R4), showing the expected improvement due to the increase of the GOCE data volume. In contrast, in South America the large standard deviation of 10.3 mGal (R1) almost persists for R4 with 10.0 mGal, reflecting large systematic differences between GOCE models and EGM2008. The GOCE gravity field models have been externally validated applying different validation strategies (Gruber et al., 2011), such as the comparison with "direct" geoid height observations derived as a difference of geometrical heights obtained from long-term GPS observations and physical (orthometric) heights obtained by spirit levelling. As an example, Fig. 2 shows the rms of geoid height differences of R3 and R4 gravity field models and 675 GPS/levelling observations in Germany, and 873 stations in Japan. Considering that also the GPS/levelling observations are not free of errors, the differences of about 3.8 cm at d/o 200 in Germany for the TIM R4 model is in very good agreement with the error estimates given in Table 1. The validation in Japan shows that at d/o 200 GOCE models are superior to combined models such as EGM2008, even in regions where high-quality terrestrial data bases exist. Several studies have been performed to validate recent GOCE models in different regions, such as the Sudan (Godah and Krynski, 2015) or Norway (Mysen, 2015).

4. GOCE applications

4.1. Geodesy

In geodesy GOCE provides important contributions to at least three field of applications: combination of GOCE data with complementary gravity field information for global and regional gravity

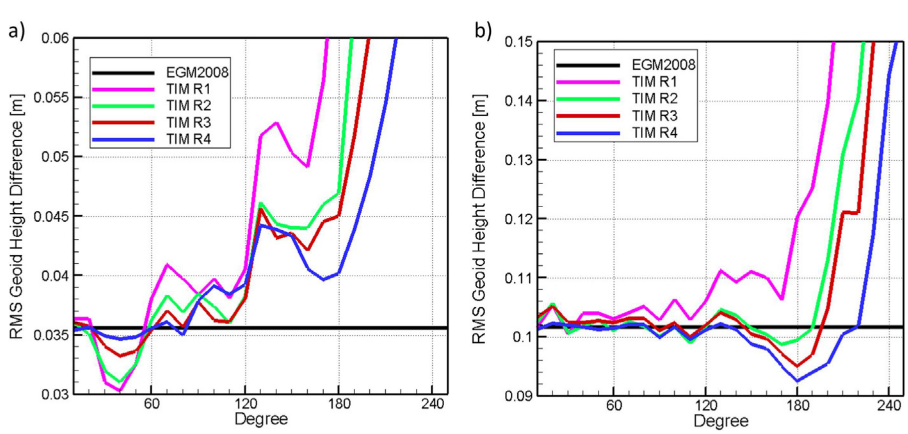

Fig. 2. Rms of geoid height differences [m] between gravity field models and GPS/levelling observations in Germany (675 points; left), and Japan (873 points; right), truncated at a certain maximum degree.

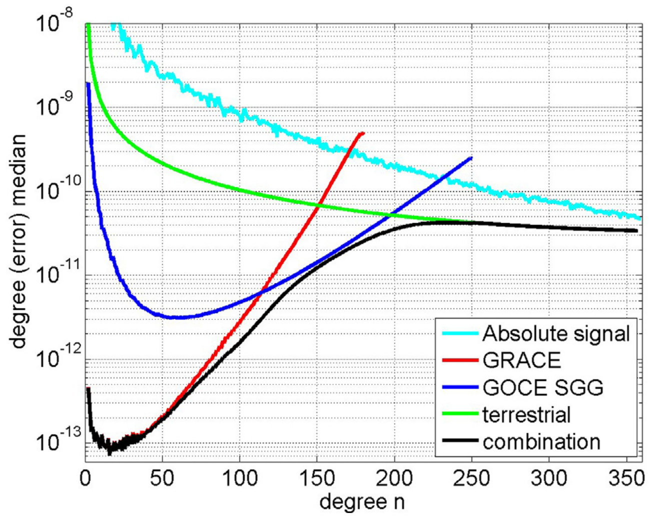

Fig. 3. Degree (error) medians of the gravity signal, the individual components and the combined solution.

field modelling, global unification of height systems, and improvement of satellite orbits.

4.1.1. Combined gravity models

Based on data of the GOCE mission, globally homogeneous gravity field models with high accuracy and a resolution down to 80 km spatial wavelength could be derived (cf. Section 3). However, due to the attenuation of the gravity field with orbit altitude, gravity field models derived only from satellite data will never be able to achieve very high spatial resolutions of only a few kilometres. However, precise knowledge of the Earth's gravity field structure with very high resolution is essential not only for a range of geoscience disciplines, such as solid Earth geophysics for lithospheric modelling and geological interpretation, exploration geophysics, and several climate research applications such as ocean circulation or sea level change research, but also for geodesy (e.g. surveying, inertial navigation) and civil engineering (e.g. construction, modelling of water flow for hydro-engineering). For this reason, satellite-only models are complemented by combined gravity field models, which contain very high-resolution or even point-wise gravity field information obtained by terrestrial gravity measurements over continents, and satellite altimetry over the oceans.

Additionally, also data from other satellite missions such as CHAMP, GRACE and SLR satellites can be used. In many respects, they are complementary to GOCE data. Due to its measurement concept of along-track satellite-to-satellite tracking applying a K-band microwave ranging system, GRACE is superior to GOCE in the low degrees up to about degree 100–120 (cf. Fig. 3). SLR data are used to determine the very low degree harmonic coefficients, which are also needed for defining the geodetic datum of global terrestrial reference frames. Within the GOCE era, several combined gravity field models including GOCE data have been derived. The first consistent combination solution of GRACE and GOCE has been performed with the model GOCO01S (Pail et al., 2010), where special emphasis has been given to a correct stochastic model of the individual components in the frame of the combination process. Meanwhile it has been followed by the models GOCO02S and GOCE03S (www.goco.eu), which include successively more GOCE data, and additionally also CHAMP and SLR data.

In principle, combined solutions have already been processed within GOCE HPF by applying the DIR approach (cf. Section 3). Additionally, further combined solutions including GOCE data have been processed by the CNES/GFZ group: EIGEN-6S (containing GOCE, GRACE, SLR), EIGEN-6C and EIGEN-6C2 (GOCE, GRACE, SLR, terrestrial data synthesized from EGM2008 (Pavlis et al., 2012), and satellite altimetry data (Förste et al., 2011)). EIGEN-6C2 is resolved up to d/o 1949, where the coefficients beyond d/o 370 have been solved based on a block-diagonal approximation of the normal equations. In Fecher et al. (2015) the combined gravity field model TUM2013C, containing GOCE gradiometry, GRACE, terrestrial and satellite altimetry data, based on the solution of full normal equations up to degree/order 720, is presented. It is the first high-resolution combined gravity field model which is completely independent of EGM2008.

Fig. 3 shows exemplarily a global average of the performance of the satellite missions GRACE and GOCE, and terrestrial gravity in dependence of the spherical harmonic degree (spatial wavelength), as well as of the resulting combined model. However, for local engineering applications, even the spatial resolution of these combined gravity field models of 10–20 km is too low. Hirt et al. (2013) present a solution by augmenting measured terrestrial and satellite data by high-resolution gravity field signals synthesized from a topographic model. This is justified by the fact, that about 60 to 80 % of the very high-resolution signal of the Earth's gravity field is caused by topography (the remaining part is related to shallow density anomalies in the Earth's interior). This model, named GGMplus has a spatial resolution of 200 m within $\pm 60^\circ$ geographic latitude, and is a combination of GRACE, GOCE, EGM2008 and synthetic gravity anomalies derived from the SRTM (Shuttle Radar Topography Mission; Farr et al., 2007) terrain model.

4.1.2. Global unification of height systems

Gravity defines the direction of the flow of water, and thus up and down, as well as the local horizontal plane and, orthogonally, the vertical direction (= plumbline). Since equipotential surfaces are geometrically not parallel (and, consequently, plumb lines are not straight lines), height cannot be measured purely by geometrical methods such as GNSS. Ideally, the zero height is defined by the physical equipotential reference surface of the geoid. One of the primary science objectives of GOCE is to provide a globally homogeneous high-resolution model of this reference surface, which can be used for global height unification.

Accurate and globally consistent height systems are needed for science and applications. Examples are ocean circulation studies and sea level research where a consistent and accurate height reference is needed along coastlines and across ocean basins and straits, or large civil constructions such as bridges and tunnels connecting mainland with adjacent islands. The current situation of national height system is quite heterogeneous. As an example, Fig. 4 shows the estimated offsets of European national height systems with respect to the European Vertical Reference Frame (EVRF) 2007, as well as in colour the different local tide gauges they refer to.

Until now, precise physical heights (= orthometric heights H) have been obtained by the classical geodetic method of spirit levelling, i.e., the observation of height differences together with gravity field measurements along profiles, which is a laborious and expensive task. This method can only be applied over connected land masses, while height transfer over oceans could not be achieved. In contrast, future national or continental height systems will be based on the technique of "GNSS-levelling". This method is based on precise long-term GNSS observations providing purely geometric heights H above the reference surface of a rotational ellipsoid (ellipsoidal heights h), and the accurate knowledge of the geoid N:

$$H = h - N \tag{1}$$

The main advantages of this method are the avoidance and elimination of large scale systematic distortions associated with spirit levelling, direct access to physical heights in the correct reference system by GNSS, applicability all over the world and also for height transfer over the oceans, and much higher cost efficiency.

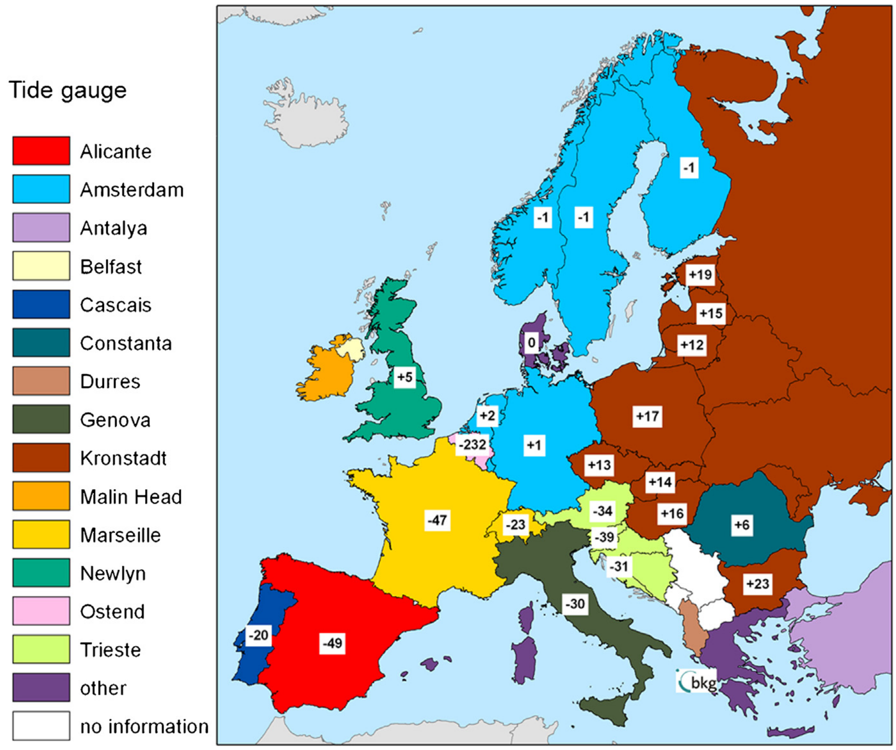

Fig. 4. Transformation parameters of national European height systems to EVRF2007 in cm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5 shows schematically the role of GOCE in global height system unification. Two national height systems (optionally on different continents), denoted as vertical reference systems (VRF) A and B, are defined by corresponding tide gauges measuring the local mean sea level. The local ocean surface can deviate from the ideal equipotential surface of the geoid by up to 2 m (cf. Section 4.2), leading to offsets of the national height systems ΔA and ΔB. If now the physical reference surface of the geoid is known, these offsets can be estimated very precisely, and the corresponding height systems can be connected.

There are several ways to unify vertical datum's, tide gauges and height systems, see, Heck and Rummel (1990). The main methods for height system unification are the geometric levelling and gravimetry approach, the geodetic boundary value problem approach, and the ocean levelling approach (Rummel, 2012a).

GOCE is expected to deliver the geoid with an accuracy of 2–3 cm and a spatial resolution of better than 100 km. Adding to it the short wavelength geoid part, geoid heights should become available in well surveyed regions with an accuracy of about 4 cm and in sparsely surveyed areas with about 20–30 cm. This is a quantum leap in global height determination, and it will permit to detect and eliminate systematic distortions of up to 1 m still present in our height systems. In a recent case study (Rummel, 2012b), the historical controversy between geodesists (“sea level is increasing towards higher latitudes”) and oceanographers (“sea level decreasing towards higher latitudes”) about the correct sea level slope along the coast line of North America could be settled, and the results obtained by traditional large-scale spirit levelling networks could be shown to be wrong. Fig. 6 shows the sea level slope at tide gauges along the east coast of North America from

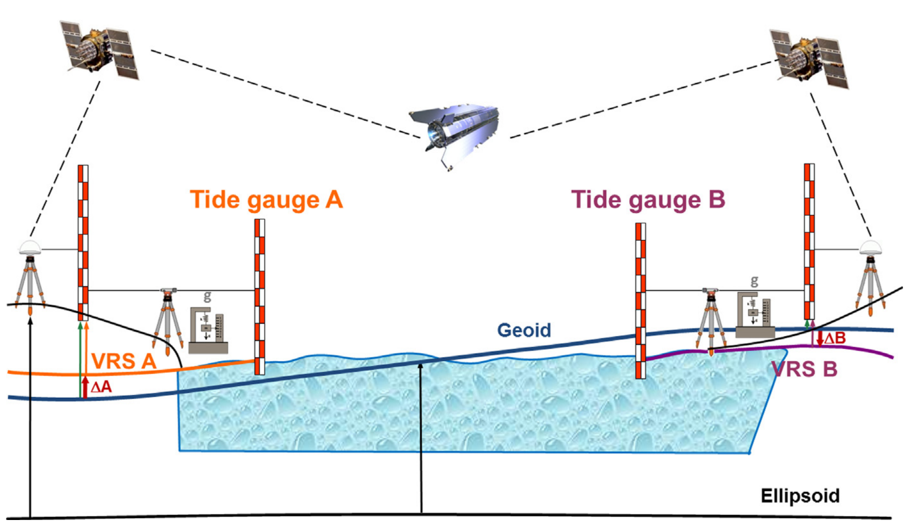

Fig. 5. Height system unification with GOCE.

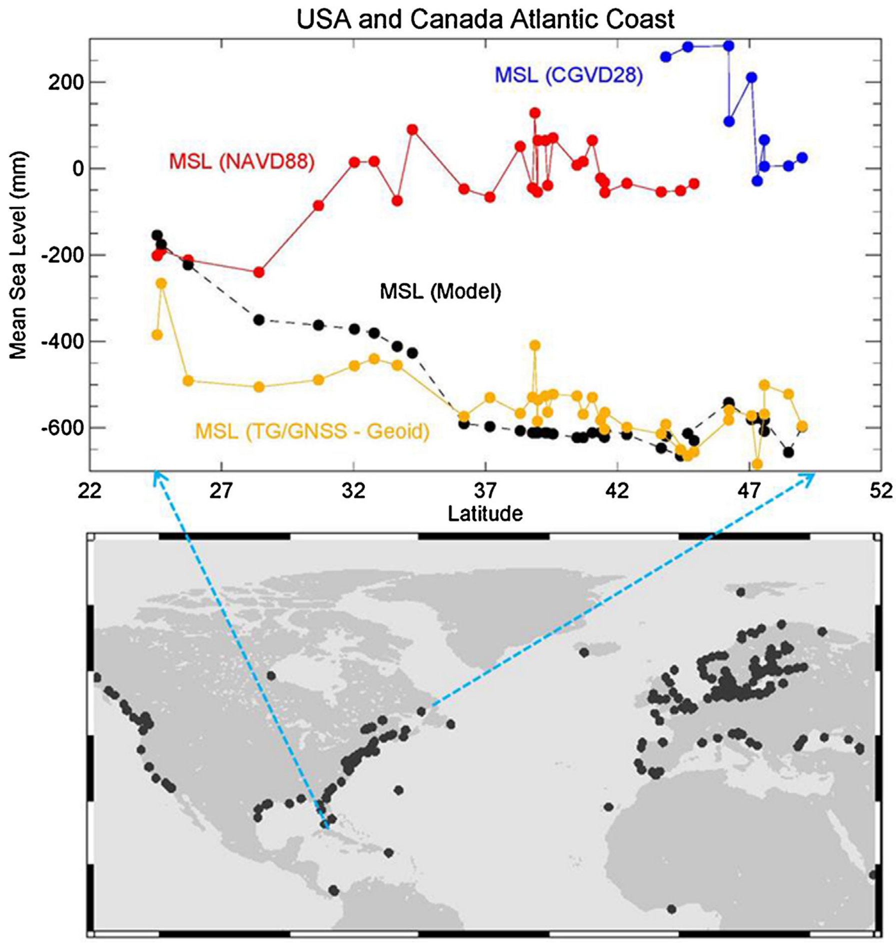

Fig. 6. Sea level slope at tide gauges along the east coast of North America from classical geodetic levelling (USA in red, Canada in blue), from an ocean circulation model (black) and from GNSS-levelling (yellow); from: Rummel (2012b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

classical geodetic levelling (USA in red, Canada in blue), from an ocean circulation model (black), and from GNSS-levelling based on the combination of GNSS observations and the global geoid model GOCO03S (yellow). Evidently the results from the ocean levelling approach and GNSS-levelling are consistent, and they show large differences to the former classing geodetic levelling in USA and Canada.

4.1.3. Improvement of satellite orbits

The main force acting on a satellite and keeping it in its orbit around the Earth is the Earth's gravity field, and gravity anomalies results in perturbations of the satellite orbit. Therefore, high-accuracy global gravity field models are a pre-requisite for the precise prediction of the orbit position of satellites. The attenuation of the gravity field with altitude is stronger for high-frequency gravity signals. Therefore, satellite orbits are mainly sensitive to low degree coefficients, and at a first glance it could be expected that the spectral range which is mainly covered by the GRACE mission has the dominant effect on satellite orbits. However, detailed analyses show that especially for Low Earth Orbiters (LEOs) the spectral range which is mainly covered by the GOCE mission, i.e. degrees 100 to 200, has a major impact on LEO orbits, not only concerning the orbital resonance frequencies.

4.2. Oceanography

As indicated by its name, measuring the ocean's steady-state circulation is a central objective of the GOCE mission. The link between GOCE and the ocean's circulation arises through the dominant role Earth's gravity plays in shaping the ocean's surface. In static equilibrium the ocean's surface would coincide exactly with the particular equipotential surface of Earth's gravity known as the geoid. However, small deviations from the geoid on the order of 1 m arise due to ocean dynamic processes driven by wind and buoyancy forcing. Thus the ellipsoidal height of the ocean's surface h can be written:

$$h = N + \eta \tag{2}$$

where N is the geoid height and η is the ocean's dynamic topography. The dynamic topography η plays the role of the orthometric height H.

It is common practice to consider the dynamic topography as consisting of a time-mean $\overline{\eta}$ and a time-dependent component η'. Through repeat track sampling, satellite altimetry alone can deliver the latter with an accuracy of less than 2 cm. The former, known as the mean dynamic topography (MDT), may be obtained by subtracting an estimate of the geoid from an altimetric mean sea surface (MSS):

$$\overline{\eta} = \overline{h} - N \tag{3}$$

One of the grand challenges of satellite geodesy has been to measure the geoid globally with sufficient accuracy that it can be subtracted from an altimetric MSS to reveal the MDT (Fig. 7, top) with sufficient accuracy and spatial resolution to be useful to oceanography.

The link between the MDT and ocean's steady-state (i.e. time-mean) circulation arises because the ocean is largely in geostrophic

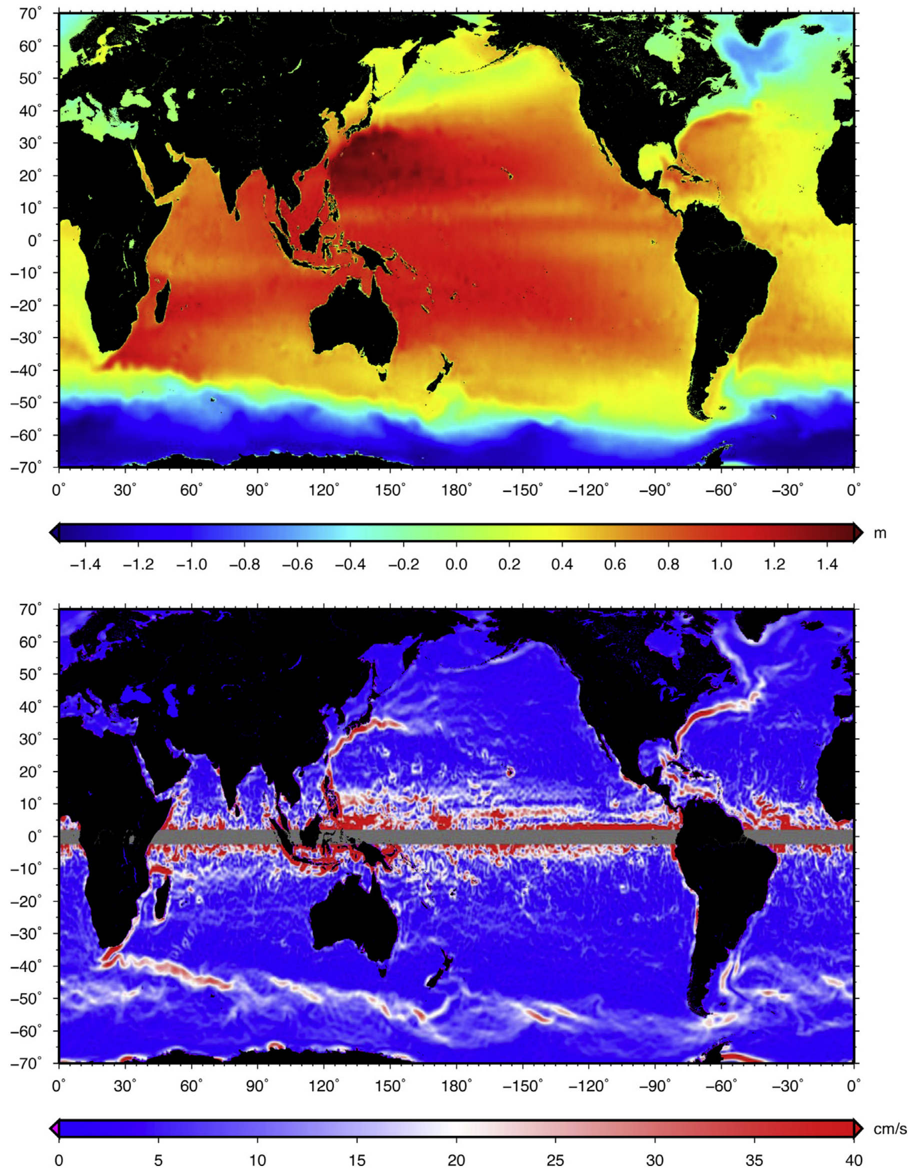

Fig. 7. (top) The ocean's mean dynamic topography calculated by subtracting a geoid obtained from the 4th generation timewise GOCE gravity model from the DTU10 mean sea surface. (bottom) The geostrophic surface current speeds associated with the GOCE mean dynamic topography.

balance. That is, for the open ocean, the dominant large-scale dynamical balance is between the Coriolis force and horizontal pressure gradients. Thus, if we know the MDT, the geostrophic surface currents may easily be determined according to:

$$u = -\frac{\gamma}{fR}\frac{\partial \overline{\eta}}{\partial \phi}, \quad v = \frac{\gamma}{fR\cos\phi}\frac{\partial \overline{\eta}}{\partial \lambda} \tag{4}$$

where $f = 2\omega_e sin\phi$ is the Coriolis force, ω_e is the angular velocity of the Earth, R is the mean radius of the Earth, ϕ is the latitude, λ is the longitude, and γ is the normal gravity.

To date, most of the oceanographic applications of the GOCE data have been focussed on obtaining the best possible surface currents (Fig. 7, bottom). Bingham et al. (2011) showed that, with only two months of data, GOCE delivered much better currents of the North Atlantic compared with an MDT based on 8 years of GRACE data, with current speeds in many important current systems now comparable, or even greater, than those obtained from in situ drifters. Knudsen et al. (2011) extended this analysis globally to four key, highly energetic regions: the Kuroshio and its extension, the Agulhas retroflection, the Brazil–Malvinas confluence and the Antarctic Circumpolar Current. In all regions it was found that ocean currents were stronger and better defined than pre-GOCE estimates. Similarly, Volkov and Zlotnicki (2012) found that the position of the fronts of the ACC – important diagnostic features of the climate system – were more clearly defined and consistent with non-geodetic estimates than was possible with GRACE. A number of further studies support the conclusion that GOCE has delivered measureable improvements in terms of resolution and current strength compared with what was obtained from GRACE (Albertella et al., 2012; Siegismund, 2013).

As carriers of vast quantities of heat and freshwater around the globe, ocean currents, such as those mentioned above, play a crucial role in regulating Earth's climate. Understanding and quantifying these transports is one of the key science drivers of the GOCE mission. To do this, however, we must go beyond the measurement of surface currents by combining the GOCE MDT with additional oceanographic data, particularly in situ measurements of density. To this end, Freiwald (2012) assimilated an MDT based on GOCE and GRACE data into an inverse model of the North Atlantic. They found that this led to an improved steady-state gyre circulation and increased meridional mass and heat transport relative to the unconstrained model. At a more sophisticated level, the data from GOCE offers the possibility of improving operational ocean models such as those used at the United Kingdom's Met Office (Drecourt et al., 2006; Lea et al., 2008). However, work in this area is still at an early stage (Haines et al., 2011).

Crucial to obtaining the best possible current estimates from the GOCE MDT and to optimally and rigorously combining the GOCE data with other data types, especially through data assimilation as described above, is an estimate of MDT error. A novel feature of the GOCE mission has been the provision of full error variance-covariance information with each of the gravity models released. However, because such information has not previously been widely available, and due to the large size of the error matrices, the tools and techniques to exploit this information are not well developed in the oceanographic community. In this issue, Bingham (2015) show how the formal errors associated with a GOCE gravity model may be used to determine the error characteristics of a GOCE MDT, and how this error characterization can then be used to determine the degree to which the MDT should be filtered to remove noise without excessively attenuating gradients associated with ocean currents.

4.3. Solid Earth

Variations in the Earth gravity field are a result of three main factors. The most significant variation is caused by the Earth's rotation which shapes the Earth into an ellipsoid resulting in a larger distance to the centre of the Earth at the equator than at the poles. The second variation is a result of Earth topography; high mountains and deep ocean trenches cause the value of gravity to vary. And the third variation is the inhomogeneous composition of the Earth's interior. Vertically there are several discontinuities at different depths (e.g. crust-mantle boundary) that are irregular, but also within the different layers the mass distribution is inhomogeneous. Superimposed on these static effects is a time-varying component of the gravity field. Reservoirs of natural resources (hydrocarbon and ground-water reservoirs or mineral deposits) can also subtly affect the gravity field, as can large scale mass movements due to earthquakes, a rise in sea level, or changes in topography such as ice-sheet movement or volcanic eruptions.

Recent work with GOCE gravity data can be divided into two main categories. The first category is using global or regional gravity models based on GOCE only data, satellite only data or combined models of satellite gravity data and terrestrial data in which GOCE data is incorporated. The combined models have generally a high resolution (down to 10 km or even less) but inhomogeneous data coverage due to local regions with high resolution ground based data (see Section 3 for details). GOCE and satellite only models have a much coarser resolution (around 100 km) but homogeneous coverage thereby showing strong spatial integrity of the data. A second category is the use (GOCE) gradient data, either calculated from gravity models or making optimal use of the newly added features available in satellite gravimetry which provides gradients directly.

4.3.1. Non-uniqueness

Inversions, or analysis, of gravity models are normally highly non-unique (Fig. 8, Fadel et al., 2013, 2015) and require *a priori* set parameters or physical constraints, either from observations or theoretical models. Major problems that need to be tackled are major errors in the definition of the *a priori* set density distribution, fixed objects boundaries (often based on data that cannot provide full boundary information either). Inversion processes in general do not allow for extreme thinning or high density structures, they tend to stay away from extreme models, do not consider petrology and thermodynamics, and have often problems with fuzzy boundaries between objects in the subsurface.

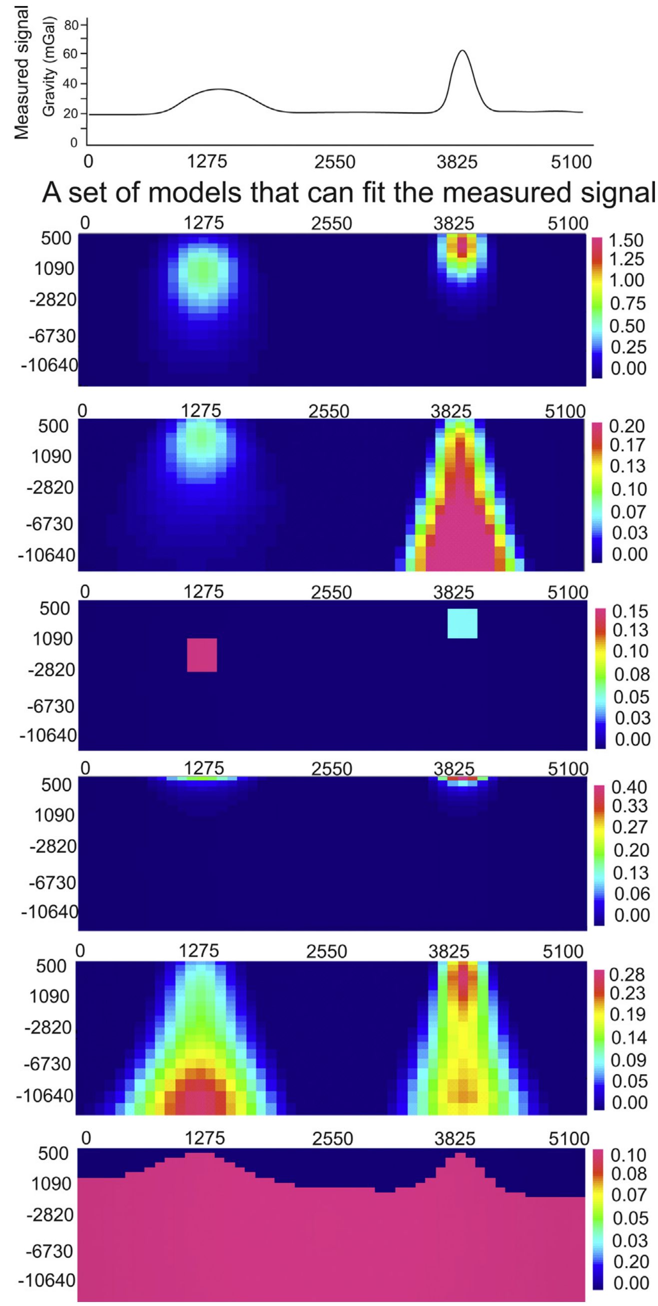

Fig. 8. Example of non-uniqueness for gravity data where different discontinuous structures will all give the same gravity signal. Small near-surface anomalies, larger single objects at greater depths or a bedrock undulation are not distinguishable from the measured gravity signal.

To overcome part of the non-uniqueness it is possible to do a joint inversion of gravity data with *a priori* information on crustal structure like seismic point observations or profiles and lateral density variations (e.g.Schmidt et al., 2011). This method works particularly well in areas of homogeneous data coverage where the constraints control the gravity inversion. This gives high accuracy for areas with point constraints but results in much higher variability for regions without constraints. This results in an uneven distribution of accuracy of the resulting output map. To overcome this spatial inhomogeneity approaches have been tested for inversion of a simple two-layer model with fixed density contrast over the studied interface, mostly the Moho (e.g. Oldenburg, 1974; van der Meijde et al., 2013; Tugume et al., 2013). This method is not relying on point constraint data and assumes that the entire signal is related to topography of the interface to be modelled. Recently this approach has also been applied using CRUST2.0 as a basis for spatially varying starting conditions (Bagherbandi, 2012). A 3D approach (Li and Oldenburg, 1998) is regularly used for shallow studies but not often for modelling of the Moho discontinuity (e.g.Welford et al., 2010). One way to overcome this is using a knowledge based approach. A first implementation of this approach is that Moho topography is directly linked to the causal physical process, or several processes. These processes then need to be known and well understood and the underlying assumptions, like isostatic equilibrium, need to be valid (Aitken, 2010). A second implementation would be numerical modelling in which multiple parameters are included and relations among them extensively explored. An example is the modelling by Fullea et al. (2009), who used a model with an internally consistent thermodynamic geophysical framework, where all relevant properties are functions of temperature, pressure, and composition. By simultaneously solving the heat transfer, thermodynamic, rheological, geopotential, and isostasy (local and flexural) equations, the programme outputs temperature, pressure, surface heat flow, density (bulk and single phase), seismic wave velocities, geoid and gravity anomalies, elevation, and lithospheric strength for any given model. This is only possible when extensive knowledge of an area is available.

4.3.2. Global and regional gravity models

A lot of the work so far has focussed on these regions where GOCE data is bringing additional knowledge; Africa, South-America and the Himalayas (see also Fig. 1). Focus fields are divers and vary from very local studies on shallow structure, like sediment basins, up to continent-wide and global crustal thickness and upper mantle models. Regional studies often focussed on specific structures like thickened crust or geological objects. Li et al. (2013) found from 2.5D gravity forward modelling that the Chad lineament in Africa contains high density bodies which were thrusted up into the mid-crust during the Neo-Proterozoic terrane collisions between the Saharan metacraton and the Arabian-Nubian shield and thereby delineates a first order geological boundary, missing on the geologic maps. A recent study (Pal and Majumdar, 2015) over the Singhbhum–Orissa craton in India using calculated 1st and 2nd derivatives they gathered additional insight on the geological setting of this area. Also Braitenberg (2015) studied craton, as well as rifts, but in Africa. Through a non-parametric regression method a consistent geological signal is isolated without contributions of crustal thickness and lithosphere. The residual field highlights density inhomogeneities related to linear geological structures delimiting cratons. It is shown through comparison of structures on the African and South American continent that these structures originate from Gondwana (Archaean and Proterozoic) times, and therefore their identification is of relevance for mineral exploration. Also on the South American continent, Mariani et al. (2013) showed a clear positive Bouguer residual anomaly in the Paraná basin in Brazil which suggests the presence of a hidden mass. Their interpretation is that this hidden mass is located in the mid to lower crust, probably gabbro and left behind by ascending basalts. A study on the sedimentary rock cover of the south-eastern Congo basin is based on calculated gradient data (Martinec and Fullea, 2015) of the GOCO3S model. Through a 5-parameter Helmert's transformation they improve significantly the fit of the gravity and vertical gravity gradient data over the basin. The remaining misfit is accounted due to density contrasts at the Moho, lithospheric density stratifications and mantle convection.

A first gravity based crustal thickness model for that same region as well as the whole continent of South-America was presented by van der Meijde et al. (2013). Their gravity data inversion is for a simple two-layer model with fixed density contrast over the interface, the Moho. The method is not relying on point constraint data and assumes that the entire signal is related to topography of the Moho. Model quality can therefore be assessed by a comparison with point observations on crustal thickness. They show that for the stable part of the continent 90% of their estimates are similar, within error bounds, to seismic observations. A comparison with seismological models shows a high correlation with the most recent model and a better fit than older models. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints the gravity based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America, in particular a continuous thinning of the crust behind the Andes mountains. A similar approach was applied to Africa (Tugume et al., 2013). Assessment of accuracy here was only made with respect to crustal thickness point observations and CRUST2.0 since no continent scale tomographic models were available for comparison. Regional crustal thickness models over two oceans (Indian and Atlantic) were based on a similar two-layer approach driven mainly by the definition and quality of the involved covariance functions (Arabelos and Tsoulis, 2013). The application leads to independent and much denser estimations of the crust-mantle interface over these regions, in comparison with the available Moho information provided by global databases such as CRUST2.0 (Arabelos and Tsoulis, 2013). Several global crustal thickness models have been published. Bagherbandi (2012), Bagherbandi et al. (2013) published a global crustal thickness model based on similar principles as van der Meijde et al. (2013) which shows large similarity but are additionally correcting for non-isostatic effects based on CRUST2.0 structural information. Their model is mathematically validated and is not compared to actual crustal thickness observations. Also Sampietro (2012), Negretti et al. (2013) presented a global crustal thickness model using CRUST2.0 as starting point. Using CRUST2.0 as a starting point is a good approach for areas where CRUST2.0 has homogeneous and dense data coverage. In data sparse regions, with strongly inhomogeneous data cover, some studies indicate large deviations from CRUST2.0 (van der Meijde et al., 2013; Tugume et al., 2013; Bagherbandi et al., 2013) whereas Tenzer et al. (2012) indicates that the gravity signal and the crust correlate very strongly (about 0.99). It needs further analysis on establishing the effect of the starting model towards the final inverted crustal thickness model.

Recently attempts have been done to combine (GOCE) satellite gravity data with seismology. Basuyau et al. (2013) show for the Himalayas that a joint inversion scheme will lead to lithospheric velocity-density models constrained in two complementary ways. A different approach is followed by Fadel et al. (2013, 2015) who are using object based analysis of seismic models to constrain the gravity inversion in 3D. They show that (fuzzy) boundaries of subsurface objects can be objectively derived, and these boundaries can lead to subsurface models that mimic the GOCE signal up to 96% without many parameters that need to be set in the process.

Including even more information is only possible in limited areas and generally spoken not in the data poor regions discussed above. Fullea et al. (2015) study upper mantle structure under the Atlantic–Mediterranean transition zone using calculated GOCE gravity gradients and other land-based geophysical data through lithospheric-scale geophysical-petrological modelling within a thermodynamically consistent framework. They investigate the perturbing effects of deep mass anomalies in potential field modelling and the potential contribution GOCE data, and model a positive seismic-velocity anomaly in the uppermost mantle under southern Spain and part of the western Mediterranean Sea. This type of work is probably the most detailed that is possible but requires setting of many parameters. Increasing complexity is thereby at the cost of increased subjectiveness in parameter settings compared to simplistic two-layer models studying a single discontinuous structure with only few parameters that can be set rather objectively.

4.3.3. GOCE gradients

So far all studies above have used total field data or gradients calculated from total fields. GOCE's unique feature is the direct measure of gravity gradients. Bouman et al. (2015) discuss for the first time the use of these gradients for solid Earth applications and evaluate the use of original measured GOCE gradient data versus the use of gravity gradient grids (calculated directly from the measured gravity gradients), either at satellite altitude or close to the Earth's surface. They conclude that the use of gridded data is easier so one avoids rotating frames at different altitudes and varying error characteristics. Applications are shown for the north-east Atlantic region, a well-studied region, and the underexplored Rub' al-Khali region on the Arabian Peninsula. It is concluded from these studies that interfaces with large density contrasts have a distinct signal in gravity gradients, contrary to intra-crustal density sources. The depth sensitivity is also well suited to be applied for upper mantle density structure studies, making it complementary to seismic tomography and gravity total field studies (Bouman et al., 2015).

These findings are in line with a spectral evaluation of gravitational gradients generated by upper Earth's mass components (Novák et al., 2013). Their spectral approach allows for numerical evaluation of global gravitational gradient fields that can be used to constrain gravitational gradients either synthesized from global gravitational models or directly measured by the space borne gradiometer on board of the GOCE satellite mission. The methodology could be used for improved modelling of the Earth's inner structure.

4.3.4. Where are we heading?

There have been a few initial attempts to map the deeper Earth with gravity data but mostly with GRACE data. Studies have so far looked into directional fabric of the mantle flows at depth, reflecting how the history of subduction influences the organization of lower mantle upwelling (Hayn et al., 2012), thermochemical oscillating domes in the lower mantle (Cadio et al., 2011), and recent variations in the core from a combined analysis of 2nd derivative magnetic and satellite gravity data (Mandea et al., 2012). New missions are also being proposed of which emotion (Earth system mass transport mission) is one of them (Panet et al., 2013). It is based on two tandem satellites in a pendulum orbit configuration at an altitude of about 370 km, carrying a laser interferometer inter-satellite ranging instrument and improved accelerometers. Such a setup is capable of measuring a wide range of mass signals related to the global water cycle and to solid Earth deformations.

An unexpected application was the use of GOCE as the first seismometer in space. Garcia et al. (2013) presented the first in situ sounding of a post-seismic infrasound wavefront, using data from the GOCE mission. The atmospheric infrasounds following the great Tohoku earthquake (on 11 March 2011) induce variations of air density and vertical acceleration of the GOCE platform. Clearly the use of gradient data is adding most of the new information. So far very few have worked with the actual measured gradients from GOCE (e.g. Bouman et al., 2015). It is foreseen that many studies that have used gradients calculated from total field data (e.g. Tedla et al., 2011; Fullea et al., 2015; Martinec and Fullea, 2015) will be redone using the measured GOCE gradients.

5. Conclusions

It is evident that GOCE made a unique contribution to different application fields. In geodesy, oceanography and solid Earth unique contributions have been made using GOCE data. The GOCE data clearly improved gravity models in spatial coverage and accuracy, and the gradient data is unique in itself. In oceanography major steps were made in understanding ocean surface currents at many places around the globe, e.g. the North Atlantic currents which have a major impact on weather conditions in the Europe and the USA. In solid Earth studies research has largely focussed on those areas where GOCE really made a difference because of the excellent spatial resolution and coverage, like Africa and South America. Studies have focussed on pre-dominantly on crustal studies (Moho or intra-crustal discontinuities) but progress in the deeper Earth studies is catching up fast, thereby also integrating other data sources to reduce non-uniqueness. A major step still to be made is the use of GOCE gradient data which is only slowly discovered but can open up a whole new field of studies from which many new insights can be expected.

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