Possibilities and challenges in the analysis and Interpretation of ESA's GOCE satellite gradiometric data

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Abstract

The realization of the satellite mission GOCE, dedicated to the direct measurement of the Earth's gravity field in terms of its second order derivatives at satellite altitude initiates a new era in gravity field modeling, analysis and interpretation. The present note briefly outlines the basic measurement principles of the mission and comments on some of the possibilities regarding the scientific exploitation of its final as well as intermediate products. Emphasis is given on the interpretation strategy emerging from the availability of an increasing number of global digital databases describing the Earth's upper structure. A distinct number of itemized points for future study towards the understanding and band-limited analysis of the observed gravity field are identified.

1. Introduction

Since the realization of the first dedicated satellite gravity field missions and the release of the respective gravity models, great effort has been put on devising means of identifying known or reproducible features of the Earth's gravity field. The standard approach in the process of assessing and interpreting the new models is to distinguish between the static and the temporal components of the observed gravity field. The availability over the last years of global digital databases with information regarding the geometry and density distribution of distinct layers of the Earth's crust permits a rigorous modeling of the implied gravity signal and thus enables the numerical investigation of correlations that might exist between these contributions and the respective quantities that may be obtained from limited bandwidths of the new gravity field models. Due to problems related mainly with the sampling of the data both in space and time and the existent exponential attenuation of the observed gravity field signal with increasing satellite altitude, satellite-only global geopotential models can be recovered only up to a certain resolution. Moreover, they also represent time-wise averaged values of the geopotential. Although assessed for internal accuracy, the actual performance of the derived models in terms of interpreting the static part of the gravity field remains largely unknown. Thus, besides some general remarks of the type '…*they capture the medium-to-long wavelength part of the observed gravity field*…', a detailed and justified interpretation of the information content of the new models regarding the static gravity field component is an open challenge in current gravity field research.

On Tuesday 17 March 2009 ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) was launched successfully into orbit. The GOCE satellite materializes one of the six missions currently under the umbrella of the Agency's Living Planet Program, an action dedicated to observing the Earth from space. The Living Planet Program comprises a science and research element and an Earth Watch Element. The former includes at the time being the following six Earth Explorer missions with a further three undergoing feasibility study: GOCE, SMOS (Soil Moisture and Ocean Salinity), Cryosat-2 (Sea Ice thickness and Ice sheet topography), Swarm (Geomagnetic field survey), ADM-Aeolus (Atmospheric Dynamics Mission) and EarthCARE (Earth, Clouds, Aerosols and Radiation Explorer), while the latter is designed to facilitate the delivery of Earth Observation Data captured from the satellites in space. The spacecraft was launched into a Sun-synchronous, near-circular orbit with an inclination of 96.7º. GOCE was placed into orbit at an altitude of about 290 km (283 km on 17 March), from where the satellite was left to gradually descend at a rate of 150 to 200 m per day to its operational altitude of around 273 km. During this process of decaying orbit, which was scheduled to be of the order of 45 days, many crucial initialization procedures in the spacecraft were due to take place. Thus, on 6 April 2009 the electric ion propulsion engine was switched on successfully. This sophisticated system which produces a gentle, stable and smooth thrust on the opposite direction to the satellite's movement (along track) is the most essential element of the satellite. Its normal operation, which has been now confirmed, should compensate for any non-gravitational effect on the motion of the satellite (for such a low altitude mainly atmospheric drag) and will permit the further exploitation of the gradiometer readings, which in a state of drag-free movement – *and only then* – can be used as direct measurements of the elements of the Earth's gradiometric tensor at satellite altitude. Following the utilization of the ion propulsion engine on 8 April 2009 the main instrument of the GOCE satellite, its 3-axes gradiometer started working. It is important to mention that switching on the gradiometer was by far a 'single-button' procedure, as the success of its utilization depended entirely on the state of the release mechanism of the individual proof masses, which consisted of single 5 μm thick golden wires, which were exposed to the whole mechanical stress during the taking off procedure. With the successful completion of the aforementioned commission procedures the satellite is now flying according to schedule at a velocity of about 8 km/s producing the desired gradiometric data.

2. The satellite

The choice for the low orbital altitude of the GOCE satellite was made deliberately in order to observe the strongest possible gravity signal from space. However, with the strong signal attenuation with increasing altitude being one of the driving factors for the design of the GOCE mission, the spacecraft itself has to manage a second more dominant disturbing factor. With the satellite altitude being that low the shuttle has to deal and somehow compensate the profound non-gravitational effects acting at those altitudes, with the atmospheric drag being the most important one. The disturbing effect of the atmosphere, which at altitudes around 270 km can be significant, is dealt with the operation of an electric propulsion system. This system, which is integrated in the back rear of the very slim and almost cylindrically-shaped GOCE satellite (5.3 m in length with a cross-sectional area of 1.1 m^2 and weighing 1000 kg) counteracts continuously with the atmospheric drag acing on the satellite producing a drag-free-control in the in-flight or along-track direction.

The Electrostatic Gravity Gradiometer (EGG) is the fundamental measurement device on-board the GOCE satellite (Figure 1). It consists of three pairs of accelerometers mounted on a stable carbon-carbon support structure. The operation principle of each of these capacitive accelerometers is the same as the one met at the single accelerometers mounted on the CHAMP and GRACE satellites: a prismatic proof mass is kept ‘floating’ in the centre of a cage by applying voltages at the different sides of the parallelipedic shaped mass. The accelerometer is then measuring the departure of the proof mass from this initial state in terms of the induced voltages measured by the system when this departure takes place. The GOCE accelerometers are about 100 times more sensitive than the ones previously used in the CHAMP and GRACE satellites, sensing as small as one part in 10^{12} of the gravity experienced on the Earth’s surface. In order to exploit this tremendous sensitivity in the realization of the gradiometric principle the distance between each sensor pair defining the 3 EGG axes must not vary by more than 1% of 1 Ångstrom. Thus, the single gradiometric arm of the EGG device is built by mounting two accelerometers of the same pair at a distance of 50 cm (± 0.01 Å) to each other on an ultra stable carbon-carbon structure (Fehringer et al. 2008).

Several reference frames related to the GOCE satellite exist, either referring to its instruments (accelerometry and gradiometry), to its relation to some Earth-linked frames, or to the definition of the GOCE Time System (Gruber et al. 2008). Two are the major reference frames for gradiometry: the Gradiometer Reference Frame (GRF) and the Accelerometer Reference Frame (ARF). GRF is the coordinate system in which the gravity gradients are actually measured. The GRF origin coincides with the origin of the $OAGRF_3$, with $OAGRF_3$ being the so-called One Axis Gradiometer Reference Frame, in this case defined for accelerometers A_3 and A_6. The origin in question is located at the midpoint of the straight line joining the

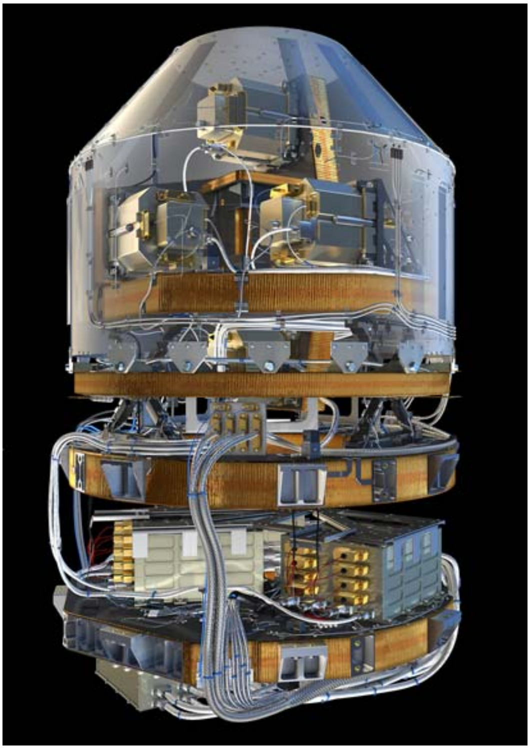

Figure 1. *The GOCE gradiometer consists of three pairs of identical ultra-sensitive accelerometers, mounted on three mutually orthogonal arms. One of the arms is aligned with the satellite's trajectory, one pointing towards the centre of the Earth, and the third is perpendicular to the other two. This allows the simultaneous measurement of six independent but complementary components of the gravity field. (Credit: ESA - AOES Medialab)*

origins of the Accelerometer Reference Frames ARF_3 and ARF_6 defined for the gradiometry pair consisting of accelerometers A_3 and A_6. The three axes X_{GRF}, Y_{GRF} and Z_{GRF} are defined as parallel to the corresponding axes of $OAGRF_3$ having also the same sign. In the nominal configuration, the following three conditions are met: (1) the origins of all OAGRF's coincide in one intersection point, the GRF origin, (2) the corresponding axes of each of the three OAGRF's are parallel and point in the same directions with the corresponding GRF axes and (3) the corresponding axes of all 6 ARF's are parallel and point in the same directions with the corresponding GRF axes.

The ARF is the reference frame in which the acceleration components of the proof mass relative to the cage are measured by the sensor. Contrary to the uniform definition of the other instrument-related gradiometer reference frames the ARF is defined differently for each of the three accelerometer pairs belonging to the three

One Axis Gradiometers (OAG's). The origin of each ARF is located in the center of the corresponding accelerometer. The direction and sign of the individual ARF axes on the other hand are defined differently for the three groups of accelerometers building the three OAG's (accelerometers A1 and A4 for OAG1, accelerometers A2 and A5 for OAG2, A3 and A6 for OAG3). The corresponding definitions are been made in such a way that there is a nominal alignment between the ARF axes and either an OAG baseline and/or the ground plate of the accelerometer (Figure 2).

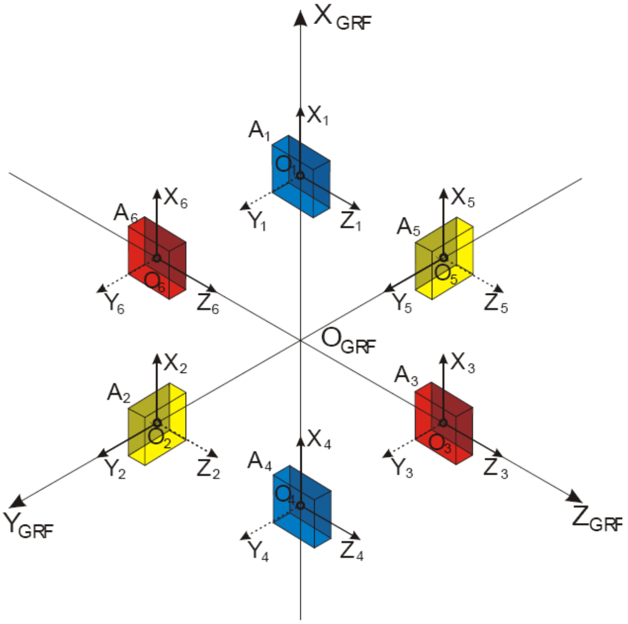

Figure 2. *Gradiometer Reference Frame (GRF) and Accelerometer Reference Frame (ARF) definitions. The axes of the ARF shown in solid lines represent the ultra sensitive axes of the accelerometer. Dashed arrows represent the less sensitive axes. (Credit: Gruber et al. 2008).*

3. The data

Different levels of GOCE data exist, depending on the level of pre-processing applied to the raw observed gravity gradients. The corresponding definitions are (Floberghagen et al 2008):

Level 0 data. These are raw time-series data as captured directly by the GOCE gradiometer. They refer to the Gradiometer Reference Frame (GRF) and are the raw source of information that is being downlinked continuously from the satellite to the dedicated ground receiving station.

Level 1b data. These are time series of calibrated and corrected instrument data along the GOCE orbit. These data include the fundamental instrument data: the complete set of the observed gravity gradients, the satellite-to-satellite tracking observations and the GOCE satellite position. Level 1b data include also some complementary data, which are the satellite linear and angular accelerations and the satellite attitude.

Level 2 data. These data express the final GOCE deliverables to the scientific community: gravity field models (sets of potential harmonic coefficients complete up to a certain maximum degree and order) and precise science orbits. Level 2 data products are regarded as the main source for further scientific analysis and will be used for the derivation of certain GOCE-only gravity field solutions, which are referred to as Level 3 products. This kind of products will be developed in the frame of studies in solid-earth physics, ocean circulation, sea-level rise, geodesy and others and will occasionally require combinations with other surface or satellite data.

3. Interpretation strategies

One of the main objectives and at the same time challenges for the scientific community, which will be engaged with the scientific exploitation of the GOCE data, is the underlying ansatz for the interpretation of the GOCE deliverables in the frame of gravity field modeling and analysis. A gradiometric mission was conceived and implemented in the first place with the fundamental goal to attempt a more sophisticated medium-to-short wavelength gravity field analysis, at least compared to its ancestors CHAMP and GRACE, with the even more ambitious goal to manage and isolate, i.e. identify, certain hidden sources in the Earth's upper crust, an effect that should be identifiable per definition in the GOCE Level 1b data. Taking the overall mission design and concept into account (a Sun synchronous orbit at an altitude of 270 km, gradiometry as measurement principle) it is expected that the GOCE observables will capture directly the medium-to-short wavelength part of the observed gravity field, which in the case of these orbit characteristics and satellite principles relates directly to the underlying sources present at the upper lithosphere and the crust.

The above mission facts provide a first impression towards the rigorous and systematic interpretation of the scientific end-products of the GOCE satellite. Different approaches can be applied depending on the kind of Earth data one wants to incorporate or are available for this purpose and – most importantly – the final objective of the interpretation procedure. Here we will refer only to two of the possibilities that can be taken into consideration, stressing the fact that many other interpretation strategies can be developed as well, that will not be considered here, such as a spectral assessment approach which would identify spectral bandwidths with measurable correlation with other available models, or the exploitation of certain compensation mechanisms describing the mass balance between crust and mantle (classical (rigid) or flexural isostatic models) for the fabrication of so-called topographic/isostatic gravity field models and their further assessment against the GOCE gravity models.

The first interpretation ansatz to be presented here deals with the spherical harmonic representation of the gravity signal of a known mass distribution and the possibilities that emerge from utilizing this technique in the analysis of GOCE deliverables. Given a mass distribution of a known geometrical shape one can always express the gravitational potential of the mass into an infinite series of spherical harmonics. In the case of a spherical distribution this analysis provides non-zero contributions only for the zeroth and first order spherical harmonic terms, while for other distributions one obtains the corresponding so-called multipole expressions with non-zero contributions also for higher orders (Tsoulis 1999). Recently, a method has been developed that computes even for degree 360 *numerically stable* spherical harmonic coefficients describing the gravitational potential of a generally shaped polyhedral body with constant density. Given such a mass distribution, i.e. a prismatic body consisting of an arbitrary number of planes, each built by a variable number of faces, the expression for the normalized spherical harmonic coefficients of the induced polyhedral gravitational potential reads (Tsoulis et al. 2009a)

$$\begin{aligned}\begin{bmatrix}\overline{C}_{lm}\\ \overline{S}_{lm}\end{bmatrix} &= \iiint_{Q\in simplex} \overline{h_{lm}}(Q)\,du(Q) = \\ &= \frac{1}{Ma^l}\sqrt{\frac{(2-\delta_{0m})(l-m)!}{(2l+1)(l+m)!}}\iiint_{Q\in simplex} r_Q^l P_{lm}\left(\cos\vartheta_Q\right)\begin{bmatrix}\cos(m\lambda_Q)\\ \sin(m\lambda_Q)\end{bmatrix}\end{aligned} \qquad (1)$$

This equation indicates the fact that the approach leading to it is based on the division of the total volume U of the polyhedron into a collection of simplices (tetrahedra), each having one vertex at the origin and the opposite face taken from one of the polyhedral faces, thus the integration over Q runs over each of these simplices. After inserting the actual limits of the simplex geometry the procedure of computing numerically equation (1) leads to a recurrent scheme which proves to be very stable even for maximum degree $L_{max} = 360$. Definitions of all parameters entering equation (1) as well as a detailed description of the algorithmic procedure and the obtained results can be found in Tsoulis et al. (2009a).

Having the spherical harmonic expansion of a polyhedral source available one can go and compute the spherical harmonic coefficients of known polyhedral sources lying inside the Earth, especially at those regions where we expect GOCE to be especially sensitive. If the geometry of the corresponding distribution is given, then the present methodology offers a very advanced mathematical tool for the representation and reconstruction of the observed gravity field signal (in terms of spherical harmonics) from distinct mass anomalies in the Earth's interior and at varying altitudes, thus also at GOCE altitude. In this manner one is equipped with an additional tool for the demanding task of geophysical interpretation of the GOCE gradiometric data and related gravity field models. Although the polyhedral modeling is a very flexible modeling tool that can be applied to arbitrary distributions, in the frame of GOCE data analysis and interpretation it should be expected that the method will be most valuable when applied to mass anomalies located at the middle-to-upper lithosphere and crust.

The exact crustal geometry, which enables the realization of the previous approach, is the keyword leading to the next interpretation strategy to be presented at this point. This approach is related to the amount of information that is currently available in digital form for the global representation of the Earth's topography, bathymetry and stratification of its crust up to the crust-mantle boundary. This information permits the computation both globally and locally/regionally of selected gravity field functionals that are related with the exploitation of Level 1b and Level 2 GOCE data. One example is the incorporation of the available high-resolution DEMs for precise geoid modeling studies over larger regions. Many studies have dealt with the practical application of this information to gravity field modeling. The increased spatial resolution of these data, which are delivered in terms of the increased resolution of the corresponding databases that are becoming continuously available from the relevant dedicated satellite missions, permits an investigation of the high-frequency part of the observed gravity signal, i.e. the one corresponding to the topographic and crustal masses. Thus, these dense topographic grids, due to their high resolution and their large geographic coverage can be used to compute very accurate topographic effects that refer to large regions, where the sphericity or equally ellipticity of the Earth's surface can be taken properly into account (Tsoulis et al. 2009b). Such computations are crucial in the scientific exploitation of the GOCE models in the frame of regional geoid modeling, gravity anomalies and other GOCE-related data.

On the other hand, the availability of crustal digital databases, which offer in a global unified resolution the structure (geometry) and the consistency (density) of a distinct number of layers from the variations of the visible topography and bathymetry (outermost crust) down to the crust-mantle boundary, enables the utilization of this information in a straightforward manner: to compute the crustal-induced gravity signal at satellite altitude through the established forward gravity field modeling techniques and relate the computed signal with the observed signal at GOCE altitude, as this is captured by the gradiometer Level 1b readings. This will permit the band-limited investigation of the observed GOCE signal and hopefully the identification of selected spectral ranges with a distinct geophysical relation. Two issues emerge in this methodological approach as the basic challenges from the algorithmic and computational point of view. The first one is the rigorous geometrical modeling of the given crustal masses. Using the available global topographic and crustal shape data a detailed topological information regarding the shape of the individual crustal layers should be provided, taking into account possible discrepancies and irregularities that might exist locally or regionally in the crustal databases. Using this topology information and applying the analytical algorithm for the computation of the gravity signal induced from a generally shaped polyhedral source the crustal induced gravity signal over individual points and grids of points due to the separately hidden crustal layers may be produced at GOCE altitude. The critical parameter in the further interpretation of this information will be the appropriate along-track filtering of the Level 1b GOCE data in order to isolate the bandwidth of the measured gradiometric signal where the computed crustal contributions of the same elements of the gradiometric tensor could be identified.

4. Concluding remarks

The global mapping of the Earth's gravity field provides an advanced tool for the investigation and understanding of the physical components and processes associated with the dynamic system 'Earth'. The first two satellite missions dedicated to gravity field analysis (CHAMP and GRACE) initiated a new era in Earth monitoring. However, based on the processing of range and position measurements, these approaches offer an indirect means of observing the actual gravity signal, rather than tracking it directly. The gradiometry principle of the GOCE satellite on the other hand will provide for the first time *direct* measurements of the observed gravity field homogeneously distributed over the globe and performed at satellite altitude, sufficiently remote from local disturbing field sources. The new data will enhance our knowledge of the gravity field both in terms of the retrieved spatial resolution as well as in terms of accuracy of the related final products (geoid undulations, gravity anomalies, second order derivatives etc). Furthermore, the increased resolution of global databases for the Earth's topography and crustal structure in conjunction with the available analytical methodologies for spherical harmonic analysis of the potential field of known mass anomalies permit a rigorous interpretation of the GOCE gradiometric measurements both in the spatial and spectral domains.

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