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GOCE gravity gradient data for lithospheric modeling

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ABSTRACT

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) is the European Space Agency's (ESA) satellite gravity mission to determine the Earth's mean gravity field. GOCE delivers gravity gradients, a new type of satellite data. We study how these data can improve modeling of the Earth's lithosphere. We discuss the use of the original GOCE gravity gradients versus the use of gravity gradients in grids at satellite altitude or close the Earth's surface and conclude that grids are easier to handle than the original data because one does not have to deal with very different error characteristics of the different gradients, given in a rotating frame at varying heights. The downward continuation to the surface enhances signal and better reflects the near-surface geology. But this does not outweigh the amplification of noise and omission errors, which is why we recommend using the field at mean satellite altitude for lithospheric modeling. The North-East Atlantic region is ideal to analyze the additional value of GOCE gravity gradients because it is a well-studied region in terms of regional geophysics. We calculated the gradient sensitivity for crustal depth slices using a 3D lithospheric model. This reveals that especially interfaces with large density contrasts have a distinct signal in the gravity gradients, but that they are quite insensitive to intra-crustal density sources, which can have quite a large effect on surface gravity data. We also show that the satellite gradients have a depth sensitivity well suited to study the upper mantle density structure, making them complementary to gravity and seismic tomography. In the underexplored Rub'al-Khali area the GOCE vertical gradient was used to invert for crustal thickness. The updated Moho model gives a good fit to four of the six gradients and independent depths from seismic stations. The Moho model was used to update the heat flow model and source rock maturity maps, which are generally consistent with known source rock maturity trends in the surrounding regions. GOCE gradients are therefore useful to map crustal thickness and deep regional structures for frontier areas. In combination with other data, heat flow can be modeled which is essential for basin maturity evaluation.

1. Introduction

GOCE is ESA's satellite mission that combines gravity gradiometry and GPS tracking to determine the Earth's mean gravity field with unprecedented, global accuracy and a spatial resolution up to 80 km (ESA, 1999). We explore how GOCE gravity gradient[1] data can improve modeling of the Earth's lithosphere and thereby contribute to a better understanding of Earth's dynamic processes. To this end, we study the sensitivity of this new type of satellite data to lithospheric density structure in the well explored and understood North-East Atlantic Margin. We assess the sensitivity of the GOCE gravity gradient data to geological structures with respect to their depth and relative density contrast. This analysis provides improved information about the lithosphere compared with results obtained by other more common sources like terrestrial gravity data, and seismic.

The obtained knowledge is transferred to a second study area, which is an underexplored region: the Rub'al-Khali desert on the Arabian Peninsula. Here gravity gradient data will be used to update a presumably less accurate geological model of the basin thickness, with the goal to improve the modeling for hydrocarbon exploration

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[1] Strictly speaking GOCE delivers gravitational gradients as there is only gravitation acting on the satellite but no force caused by Earth rotation. We stick here to the commonly used term gravity gradients.

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purposes. An updated Moho model – based on GOCE gradients – is validated with measured depths at a few available seismic stations. In addition, we discuss the updated heat flow model that was created with the new Moho model as input.

The use of GOCE gravity gradient data, however, is not straightforward for a number of reasons. First of all, the gradients are given in a rotating instrument frame. Secondly, four of the six measured gradients are much more accurate than the remaining two. In addition, the gradients have their highest accuracy in the measurement bandwidth (MBW) between 5 mHz and 100 mHz, with increasing errors above and below the MBW. These error characteristics hinder the rotation of the gradients from the instrument frame to reference frames directly related to the Earth. We will therefore address the direct use of the gradients and compare this with using gradient grids at mean satellite altitude as well as grids close to the Earth's surface.

Our paper is organized as follows. In Section 2 we discuss in some detail the error characteristics of the GOCE gradients and review the different options to use the contained gravity field information. The case study for the North-East Atlantic margin is presented in Section 3 and the transfer to Rub'al-Khali in Section 4. Finally, Section 5 contains the conclusions.

2. GOCE data and their preparation for geophysical studies

2.1. Characteristics of GOCE gravity gradient data

The GOCE gravity gradient data are delivered by the on-board gradiometer. The gradients are not directly measured, but derived from the differences between the accelerations of three pairs of accelerometers (Frommknecht et al., 2011). The gradiometer configuration is such that the V_{XX}, V_{YY}, V_{ZZ} and V_{XZ} gradients are determined with high accuracy, whereas the V_{XY} and V_{YZ} gradients are less accurate. Here (X, Y, Z) forms the gradiometer reference frame (GRF), which co-rotates with the satellite. The drag free and attitude control system (DFACS) keeps the X-axis as good as possible aligned with the velocity vector of the satellite minimizing drag, the Y-axis is perpendicular to the orbital plane and the Z-axis points in almost radial direction. The gradients obtain their highest accuracy in the MBW, which roughly corresponds to an along-track spatial resolution of 750–40 km. The current effective spatial resolution of GOCE data is around 90 km at the Earth's surface as we will see below.

Although GOCE has a near circular orbit, the height above the Earth's surface varies because of orbit resonances and because the Earth is not a sphere. This is demonstrated in Fig. 1, which displays the height of the satellite as a function of latitude for one repeat cycle of the nominal mission (61 days). One sees that the perigee height is 255 km, but for high latitudes the height above the Earth's surface increases. The mean height above the ellipsoid is 270 km.

2.2. Derived gravity field products

The GOCE gravity gradients in the GRF are used to compute GOCE-based global gravity field models (e.g. Pail et al., 2011). Commonly these global models use a spherical harmonic expansion up to degree and order 250. EGM2008 is a high-resolution global gravity field model up to degree 2190, which combines information from the satellite gravity mission GRACE, terrestrial gravity data and satellite altimeter data (Pavlis et al., 2012). The added value of GOCE becomes clear when comparing GOCE-based models with existing models that include terrestrial gravity data. The latter data may be of poor quality or absent in certain regions of the world, and models such as EGM2008 may suffer. This is shown in Fig. 2 displaying the gravity anomaly differences between GOCO03S

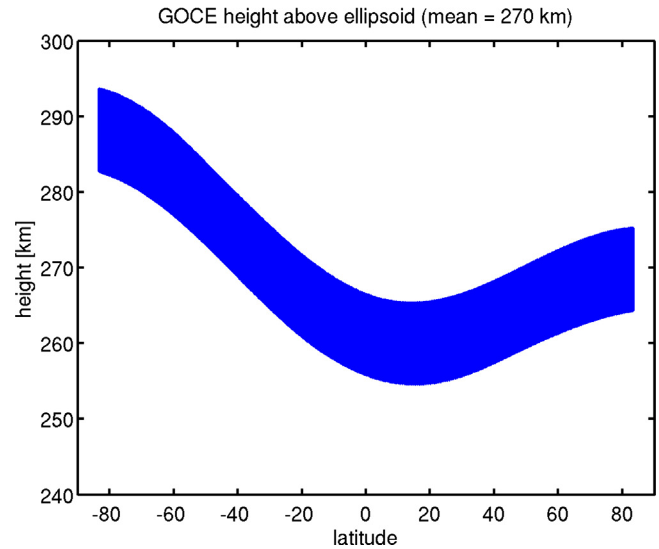

Fig. 1. Height of the GOCE satellite above the ellipsoid as a function of latitude.

(Mayer-Gürr et al., 2012) and EGM2008 up to spherical harmonic degree and order 200. For our North-East Atlantic study area with high quality terrestrial data the differences are smaller than for the study area in Saudi Arabia where the quality of the terrestrial gravity data in EGM2008 may be less. For global comparisons see Bouman et al. (2011) and Bouman and Fuchs (2012).

The latest GOCE global gravity field models represent the original gravity gradient data well (Bouman and Fuchs, 2012). These models also allow synthesizing arbitrary functionals of the gravitational potential everywhere on or above the Earth's surface. Nevertheless, there are a number of reasons why one may not like to use these global models. First of all, it may be more convenient to use gravity gradients instead of a set of spherical harmonic coefficients. Secondly, the global gravity field models are regularized and/or use a priori information. Because the models are global, the regularization is global as well. This may, however, not be optimal for all regions and dedicated regional gravity field solutions seem to be able to extract more signal from the GOCE data (Schall et al., 2012). One may therefore prefer to directly use the gradients.

The original GOCE gradients, however, are given in the GRF, which is a rotating instrument frame. In addition, 4 of the 6 gradients are accurate in the MBW. Above and below the MBW the gradients are less accurate and may contain systematic errors. The two less accurate gradients V_{XY} and V_{YZ} have errors that are about two orders worse than the accurate gradients V_{XX}, V_{YY}, V_{ZZ} and V_{XZ}. Thus it is not straightforward to use the gradients in the GRF. Alternatively, gradients in the Local North-Oriented Frame (LNOF) are given (Bouman et al., 2009, 2011; Fuchs and Bouman, 2011). These gradients are rotated to the LNOF after replacement of the long wavelength signal below the MBW with gradients from a global gravity field model. Also V_{XY} and V_{YZ} are computed from such a model. The LNOF gradients are a compromise between easier to use and keeping as much as possible the original GOCE data.

The GRF and LNOF gradients are given along the orbit, with varying height. An alternative representation therefore is in grids at a mean altitude. On the one hand the computation of grids averages out noise and on the other hand a regular grid at one altitude is more straightforward to handle than the gradients along the orbit. One could use grids at mean orbit altitude or one could downward continue to, for example, 10 km above the Earth's surface (Fig. 3). Downward continuation amplifies signal, but also amplifies noise (see Table 1). It also has to be noted that the spatial resolution at which the noise becomes larger than the signal does not change