



Introduction to the special issue on GOCE Earth science applications and models



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ABSTRACT

With the launch of the Gravity field and Ocean Circulation Explorer (GOCE) in 2009 the study of Earth's gravity field received another boost. After the time-dependent and long-wavelength information from the Gravity Recovery and Climate Experiment (GRACE) mission a new sensor with high accuracy and spatial resolution was available for determination of the Earth's gravity field and geoid. 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 to date. Additionally, GOCE provides gravity gradients, i.e., the three-dimensional second derivatives of the gravitational potential. This special issue provides a review of the results presented at the 'GOCE solid Earth workshop' at the University of Twente, The Netherlands (2012). The goal of this 2-day workshop was to provide training on the usage of GOCE data as well as to present the latest scientific results. The main workshop components were: to show the latest results on GOCE data in relation to solid Earth, provide new users with tips and tricks on which models and software to use, discuss quality and reliability of gravity data and models, and how to integrate GOCE data with own (local) gravity data. The workshop specifically focussed on where GOCE data has made a unique contribution and provides insights that would not have been possible without GOCE.

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Introduction

The Gravity field and Ocean Circulation Explorer (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 the satellite was launched from Plesetsk Cosmodrome in northern Russia on 17th March, 2009. 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 has provided unprecedented detailed measurements of Earth's gravity from space, with a spatial resolution of less than 100 km on the Earth's surface. The goal of GOCE is maximum spatial resolution, providing one global and detailed map of spatial gravity and geoid variations. Additionally, GOCE 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 van der Meijde et al. (2015) and Floberghagen et al. (2011).

The GOCE operational mission ended on November 11, 2013. Although the final data and models will be released in July/August 2014, the scientific community has already started working with early releases of data. At the 2-day 'GOCE solid Earth workshop' at the University of Twente, The Netherlands (2012), an overview was

given on the usage of GOCE data as well as to present the latest scientific results. The main workshop components were: to show the latest results on GOCE data in relation to solid Earth, provide new users with tips and tricks on which models and software to use, discuss quality and reliability of gravity data and models, and how to integrate GOCE with own (local) gravity data. The workshop specifically focussed on where GOCE data has made a unique contribution and provides insights that would not have been possible without GOCE. These contributions form the basis for this special issue.

GOCE solid Earth special issue

This special issue of JAG compiles a selection of papers presented at the 1st International GOCE Solid Earth workshop in Enschede, The Netherlands. The organization of this conference was a joint effort of the University of Twente (ITC) and the European Space Agency (ESA). It was the first GOCE related conference on a specific topic and attracted a broad range of scientists from all over the world. With 84 participants, 17 oral presentations and 39 posters the workshop exceeded expectations. All conference participants were invited to submit a paper to this special issue of JAG. The collected papers present results and new ideas on the quality of GOCE, applications in various fields ranging from surface to deep, and using different aspects of the GOCE data including the first results on GOCE gradient analysis for solid Earth applications.

van der Meijde et al. (2015) presents a comprehensive overview of GOCE, its data and its applications. They provide an introduction 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 those studies where GOCE data has made a unique contribution and provides insights that would not have been possible without GOCE.

The first work on GOCE gradients is done by Bouman et al. (2015). They study how these gradients can improve modeling of the Earth's lithosphere. They 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 data is applied to lithospheric modelling in the north Atlantic and crustal thickness modelling in the southern part of the Arabian Peninsula. Their main conclusion is that interfaces with large density contrasts have a particularly distinct signal in the gravity gradients, but that the gravity gradients are quite insensitive to intra-crustal density sources, which can have quite a large effect on surface gravity data. Of perhaps broader interest they also show that the satellite gradients have a depth sensitivity well suited to studying the upper mantle density structure, thereby making them complementary to gravity and seismic tomography.

An alternative approach for modelling Earth's crust is provided by Reguzzoni and Sampietro (2015). They present a new approach which allows the mean Moho depth to be estimated even when the normal gravitational field is removed if at least one seismic observation is available. They take into account the dependency of the crust density on the radial direction (usually neglected in Moho depth determination from gravity), and correct the a-priori density model of the crystalline crust for scale factors again using seismic information. Finally they consider a Moho with a non-constant depth as reference surface in the inversion, thus reducing the linearization error. The new crustal model has an Moho depth error standard deviation of 3.4 km globally and its gravitational effect differs from GOCE observations of 49 mE.

The upper mantle plays a major role analysis of satellite gravity data as also indicated by the previously described contributions. Fadel et al. (2015) provides a unique approach to modelling this contribution and retrieving crustal thickness reducing the number of free parameters in the inversion process. They introduced a 3D object-oriented image analysis approach to extract the 3D subsurface structures from geophysical data. The approach was applied to a 3D shear wave seismic tomography model of the central part of the East African Rift System. Subsequently, the objects extracted from the tomography model were reconstructed in a 3D model. Their density contrast values were then calculated using an object-based inversion technique and their final gravity contribution determined. They thereby show that upper mantle composition and crustal thickness can be modelled with very high accuracy.

Whereas the previous approach is very much data driven, Fullea et al. (2015) provide a more knowledge driven approach. They explore the potential of the gravity gradients and global gravity field models to image sub-lithospheric thermal and compositional anomalies. They assess the perturbing effects of deep, sub-lithospheric density anomalies in GOCE gravity gradients and other land-based geophysical data for the Atlantic-Mediterranean Transition Region. They find that gradients computed at the satellite altitude are rather sensitive to the presence of even a relatively small sublithospheric cold slab, like the one observed in their study

area AMTR, showing the potential of the new GOCE data to map upper mantle anomalies.

Also focussing on gradients is the contribution by Martinec and Fullea (2015) but their emphasize is on refinement of a sedimentary rock cover model for the Congo basin. The refinement of the sedimentary model is carried out for the vertical gravity gradient over the basin. They apply a 5-parameter Helmert's transformation, defined by 2 translations, 1 rotation and 2 scale parameters that are searched for by the steepest descent method. This resulted in a refined sedimentary model that is only slightly changed with respect to the original map, but which significantly improves the fit of the vertical gravity and vertical gravity gradient over the basin.

Because of the spatial continuity and integrity of the GOCE data it allows for across continents studies such as that of Braitenberg (2015). Regression analysis between gravity and topography shows coefficients that are consistently positive for the free air gravity anomaly and negative for the Bouguer gravity anomaly. The regression analysis allows the large gradient in the Bouguer anomaly signal across continental margins to be removed. A reconstruction of the pre-break up position of Africa and South America (the plates forming West Gondwana) is made from the residual GOCE gravity field. The reconstruction allows the positive and negative anomalies to be compared across the continental fragments, and so helps identify common geologic units that extend across both the now-separate continents.

Regional analysis of GOCE data for Asia, complemented with other gravity data, is performed for the Singhbhum-Orissa Craton in India by Majumdar and Pal (2015). The GOCE only field gravity data and in-situ gravity data of the same area have been utilized for comparative assessment to validate the results derived by EIGEN-6C2 gravity data. The GOCE field compares well to the terrestrial derivative fields in the long-wavelength part of the signal. Furthermore, published geological and structural maps of the area have been overlapped over different derivative maps and the analytical signal map to analyze the correlation with the subsurface geology and geological structures of the area. Major distinct geological signatures, on different derivative maps and the analytical signal map, correlate well with the existing geological map.

The special issue is not only focussed on specific solid Earth applications but also providing information on the quality and added value of the GOCE data. Three papers contribute to this specific topic. Fecher et al. (2015) provides a combined high-resolution global gravity field model up to degree/order (d/o) 720, including error estimates in terms of a full variance-covariance matrix, determined from GOCE and complementary gravity field data. The quality of the resulting gravity field solution is analyzed by comparison with independent gravity field models and GPS/leveling observations, and also in the frame of the computation of a mean dynamic topography. The validation shows that the new combined model TUM2013C achieves the quality level of established high-resolution models. Compared to EGM2008, the improvements due to the inclusion of GOCE are clearly visible.

A local analysis of the quality of the GOCE data for Sudan has been done by Godah and Krynski (2015). In their study, global geopotential models based on approximately 12 months of GOCE satellite gravity gradiometry (SGG) data have been compared over the area of Sudan with EGM08 and terrestrial data. The results reveal that geoid heights and free-air gravity anomalies obtained from the GOCE-based GGMs agree with the corresponding ones from the EGM08 truncated to d/o 200 with standard deviation of 18–20 cm, and 3.4–4.2 mGal, respectively.

Mysen (2015) analysed the GOCE quasigeoid performance over Norway. They found that the inclusion of the GOCE gravity potential can improve the quasi-geoid fit with the GPS/levelling network by 1.3 cm, and that this improvement takes place on spatial scales

larger than 80 km. They therefore expect that GOCE will improve our knowledge of the marine geoid.

The possible impact on marine geosciences is not necessarily solid Earth but provides a view into the interdisciplinary science for which GOCE data can be used. Such an example is provided by Bingham et al. (2015). They use GOCE to measure surface current speeds in the North Atlantic and find that GOCE can recover 70% of the Gulf Stream strength relative to the best drifter-based estimates. Crucial to this result is careful filtering which is required to remove small-scale errors, or noise, in the computed surface. At a resolution of 100 km the North Atlantic mean GOCE MDT error before filtering is 5 cm with almost all of this coming from the GOCE gravity model. Their filtering approach and use of co-variance data for estimation of errors is still under utilized in the solid Earth sciences.

It is evident from this special issue that GOCE is making unique and important contributions to a range of fields, including geodesy, oceanography and solid Earth science. The GOCE data have clearly improved gravity models in spatial coverage and accuracy, and the gradient data is unique in itself. In solid Earth studies research has largely focussed on those areas, such as Africa and South America, where GOCE has really made a difference because of its excellent spatial resolution and coverage. 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. Exploitation of the GOCE gradient data is in its infancy but has the potential to open up fresh avenues of exploration from which many new insights can be expected.

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