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Real Data Analysis GOCE (REAL GOCE): a retrospective overview

W.-D. Schuh and B. Kargoll

1 Introduction

Many years of intensive research led to the realization of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite mission (cf. [1]), which was launched on 17 March 2009. The primary goal of this mission is the determination of the static component of the Earth's gravity field with the unprecedented global accuracy and resolution of at least 1 mGal for gravity anomalies and 1-2 cm for the geoid at a global scale of at least 100 km. With the availability of this model other geoscientific core goals can be realized: the Earth system with all its interacting geophysical and oceanographic processes may be modeled with much higher reliability by means of a high-precision GOCE gravity field, while a high-precision geoid will finally enable geodesists to unify and connect the heterogeneous national height reference systems.

This outstanding leap in both accuracy and resolution of Earth gravity field determination has been made possible by the innovations in sensor and satellite technology. With the GOCE mission the measurement principle of satellite gravity gradiometry (SGG, cf. [4]) was applied for the first time in history. Another innovation in this mission was the first European satellite-borne GPS receiver, mounted on board the GOCE satellite to determine its orbital positions via satellite-to-satellite tracking (SST).

The electrostatic gravity gradiometer consists of mutually orthogonal arranged accelerometers, designed to measure, in differential mode, the second derivatives of the Earths gravity field potential and, in common mode, rotational accelerations and the non-conservative forces acting on the satellite. Based on these input signals a drag-free control regulates the thrusters to keep the satellite in free fall at a low altitude of approximately 260 km.

W.-D. Schuh and B. Kargoll
Institute of Geodesy and Geoinformation, University of Bonn, Nussallee 17, 53115 Bonn
e-mail: schuh@uni-bonn.de

In the first six month after launch all of the system components have been switched on and calibrated successively. Then the first measurement period (1 November 2009 - 11 January 2010) was carried out and resulted in the recording of approximately 6.1 million observations, which were used to compute *Release01* gravity field models. Subsequently, the *Release02* models were determined from the approximately 19.5 million observations collected until 5 July 2010. Finally, the *Release03* models were derived from the ca. 31.1 million observations obtained until 13 April 2011. Meanwhile, a better understanding of the actual measurement characteristics implied some modifications in the angular rate reconstruction and the calibration approach, and required a reprocessing of the all data.

The GOCE data processing has been performed on several levels. Firstly, the processing of Level 0 to Level 1b data has been carried out by ESA's Payload Data Segment (PDS); its main output are the gravity gradients and the corresponding attitude and GPS orbit data with a sampling rate of 1 Hz. The Level 1b to Level 2 data processing is supported by ESA and performed by the High-level Processing Facility (HPF, cf. [5]). The HPF, which is a consortium of eight universities and two research institutions, determines precise orbits and GOCE gravity field models and orbital gravity gradients.

The research produced by this consortium, which includes three German research institutions, has been enabled by the long-standing co-sponsorship of the Federal Ministry of Education and Research (BMBF) through the Geotechnologien Programme (which was initially also co-funded by the German Research Foundation (DFG)). Since its initiation in 2001 this support programme sponsored scientists specifically of up to ten German research institutions. In the course of their research acitivities (which included the development of tailored theoretical methods, algorithms and software, as well as technical, operational and collaborative skills), German research institutions were thus enabled to build up a sufficiently high level of know-how enabling them to carry out the intricate GOCE data-processing chain from GOCE measurements up to the final gravity field products independently and in its entirety.

The focus of the first collaborative Geotechnologien project "GOCE-Gravitationsfeldanalyse Deutschland I" (GOCE GRAND I, 2001-2004, cf. Part III in [3]) was on the implementation of standard procedures for the analysis, processing, calibration and validation of GOCE data, as well as on their combination with GRACE data. During GOCE GRAND II (2005-2008, cf. Part III in [2]), research was chiefly concerned with adaptations of the methods, algorithms and software modules to the final configuration of the GOCE satellite and its instruments. The goals of the subsequent third research project "REal data AnaLysis GOCE" (REAL GOCE, 2009-2012) were the complete implementation of the GOCE data processing chain and its application to the GOCE real data and contribute in particular to the fields of GOCE data analysis, gravity field modeling, validation, and combination with other geoscientific data and models (see Fig. 1). The REAL GOCE team consisted of seven university departments: the Departments of Theoretical Geodesy and of Astronomical, Mathematical and Physical Geodesy of the Institute of Geodesy and Geoinformation (IGG-TG and IGG-APMG) at the University of Bonn, the Institute of

Oceanography (IFM) at the University of Hamburg, the Institute of Geodesy (IFE) at the Leibniz University Hannover, the Geodetic Institute (GIK) at the Karlsruhe Institute of Technology, the Institute of Astronomical and Physical Geodesy (IAPG) at the Technical University Munich, and the Institute of Geodesy (GIS) at the University of Stuttgart; two research centers: the German Geodetic Research Institute (DGFI) and the GFZ German Research Centre for Geosciences at the Helmholtz Centre Potsdam; and one federal agency: the Federal Agency for Cartography and Geodesy (BKG). The individual contributions of these institutions to the achievement of the scientific goals of REAL GOCE are summarized in the following section (see also Fig. 1).

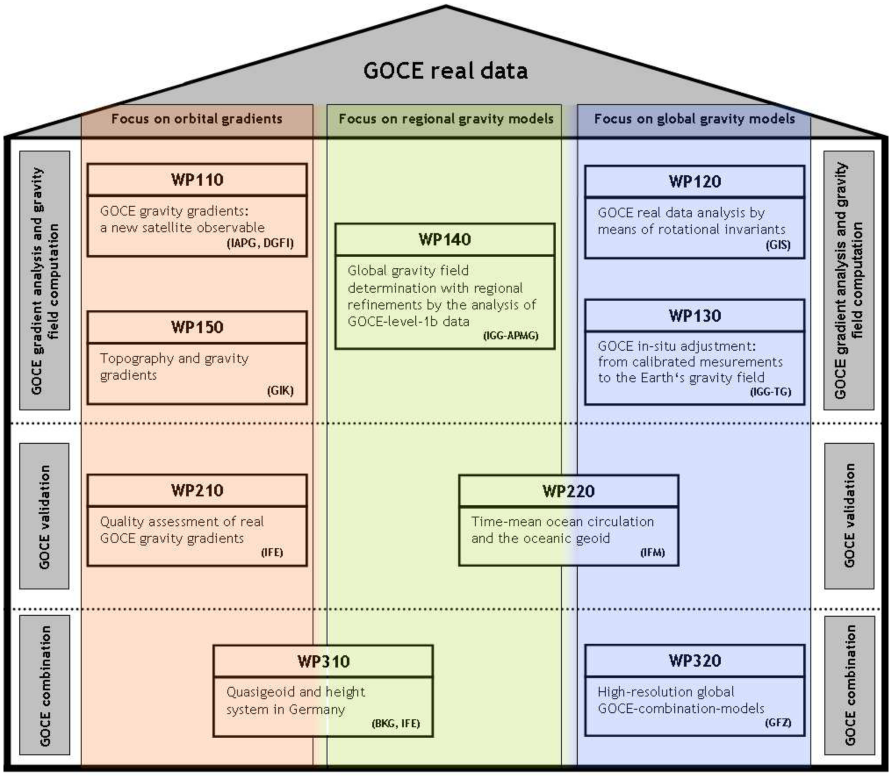

Fig. 1 REAL GOCE comprised nine work packages (WP) with different spatial (orbital, regional, global) and thematic focuses (GOCE gradient analysis and gravity field computation, GOCE validation, GOCE combination).

2 Contributions

Based on the general structure of REAL GOCE (as shown in Fig. 1), we will now introduce the reader into the specific contributions to REAL GOCE as described by the individual project partners in the subsequent, peer-reviewed papers.

Three contributions deal specifically with analyses of the orbital gravity gradients and their processing into gravity fields models. To begin with, Murböck et al. (”GOCE gravity gradients: reprocessed gradients and spherical harmonic analyses”, WP110) demonstrate the improvements of GOCE-only as well as GOCE-GRACE-combined gravity field models obtained by using re-processed (Level 1b) GOCE data. Furthermore, they analyze the formal errors of GOCE-only models in terms of spherical harmonics (based on, respectively, the *time-wise*, *space-wise* and the *direct approach*) via validating comparisons with Quick-Look models (based on the *semi-analytic approach*). Bouman et al. (”GOCE gravity gradients: combination with GRACE and satellite altimetry”, WP110) describe a strategy for avoiding the problem that relatively inaccurate gravity tensor components deteriorate the accuracy of the entire tensor when it is rotated from the *gradiometer reference system* into a geographical reference frame. They also investigate a regional method for comparing (thus validating) and combining GOCE gravity gradients with satellite altimetry data. The contribution of Grombein et al. (”Incorporating topographic-isostatic information into GOCE gravity gradient processing”, WP150) propose a *remove-restore* approach based on the *Rock-Water-Ice topographic-isostatic gravity field model* as part of the processing GOCE gravity gradients in order to avoid potential numerical instabilities due to the presence of high- and mid-frequency topographic-isostatic signal content in the gradients. As the result of their studies concerning regional gravity field determination, Shabanloui et al. (”Global gravity field models from different GOCE orbit products”, WP140) evaluate the solution of their *geometrical precise orbit determination* approach as an alternative to the ESA’s official *precise science orbits* by comparing the GOCE gravity field models determined from the respective orbit products. Two articles address GOCE gradient analysis and global gravity field computation. In Krasbutter et al. (”Adjustment of digital filters for decorrelation of GOCE SGG data”, WP130), we find an exposition of various *cascaded autoregressive moving-average* filtering strategies for taking the autocovariance patterns of the gravity gradients into account in the *in-situ* estimation of global gravity field models. As an alternative to this *in-situ* approach, Cai et al. (2012, ”GOCE real data analysis by means of rotational invariants”, WP120) describe a method for computing global gravity field models, which avoids the use of potentially inaccurate rotation measurements by adjusting certain (decorrelated) functionals of the gravity tensor. This contribution also addresses the problem of decorrelation-filtering of the various invariants.

Addressing GOCE validation (with a subsidiary focus on the combination of GOCE data with other sources) as the second thematic cornerstone of REAL GOCE, Brieden and Müller (”Cross-overs assess quality of GOCE gradients”, WP210) present the results of their work on assessing the quality of gravity gradients by analyzing their differences at the locations of *satellite track cross-overs*. A different kind of GOCE validation method, which is based on gravity field models instead of gradients, is described in Siegismund et al. (”Consistency of GOCE geoid information with in-situ ocean and atmospheric data, tested by ocean state estimation”, WP220); in this approach, a gravity field model based on GOCE data is used alongside *mean sea surface* and further ocean data to determine an *ocean general circulation model*, whose consistency is then checked by mean of the *German part of Estimating the Circulation and Climate of the Ocean* model.

The third major topic of REAL GOCE, GOCE combination (with applications also to the validation of GOCE data), is covered by three contributions. Voigt and Denker (”Regional validation and combination of GOCE gravity field models and terrestrial data”, WP310) present a *remove-compute-restore* approach to combining GOCE gravity field models with terrestrial gravity datasets, astrogeodetic vertical deflections, GPS/leveling data, and gravimetric quasigeoid models. In the second article dedicated to combination issues, Rülke et al. (”Height system unification based on GOCE gravity field models – benefits and challenges”, WP310) present results from validating GOCE gravity field models by means of GNSS/leveling data. Then they discuss an approach to combining global and regional gravity field models based on *low-pass* filtering of the former and *high-pass* filtering of the latter. Finally, they address the problem of unifying the various height systems in Europe by using GOCE gravity field models in combination with GNSS/leveling data. Other sources of gravity field related data combinable with GOCE data include Gravity Recovery and Climate Experiment (GRACE), Laser Geodynamics Satellites (LAGEOS), and surface gravity data. Shako et al. (”EIGEN-6C – a high-resolution global gravity combination model including GOCE data”, WP320) describe their procedure for computing such a GOCE combination gravity field model and evaluate its characteristics via comparison with the Earth Gravitational Model (EGM) 2008.

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