GOCE: ITS PRINCIPLES AND SCIENCE

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ABSTRACT. GOCE is the first satellite mission with a gravity gradiometer. It is very successful in delivering the global geoid and gravity anomaly field with rather high spatial resolution. The gradiometer measurements are based on the principle of differential accelerometry. It is the centre piece of a sensor system comprising in addition GPS, star tracking, angular control by magnetic torquing, drag free control in flight direction by ion thrusting and calibration via shaking with cold gas thrusters. Gravity field sensitivity is enhanced by the satellite's extremely low orbit altitude of only 265 km. GOCE science and application is primarily about "dynamic topography". In geophysics dynamic topography is referred to as that part of surface deformation which is not in isostatic balance but supported by vertical stresses at the base of the lithosphere. Gravity and geoid anomalies reflect the gravitational effect of dynamic topography. In oceanography dynamic topography is the deviation of the actual mean ocean surface, as measured by satellite altimetry, from the geoid which is the hypothetical ocean surface at rest. The uses of mean dynamic ocean topography range from ocean circulation studies via mass and heat transport in the oceans to the unification of height systems and levelling by GPS. Full exploitation of GOCE requires its combination with GRACE and with satellite laser ranging and GPS. The considered measurements and techniques must all refer consistently to the same set of geodetic standards such as those defined by the IERS.

1. INTRODUCTION

GOCE (Gravity and steady-state Ocean Circulation Explorer), the first mission of ESA's living planet programme, has been launched on March 17, 2009 (Journal of Geodesy, 2011). Its mission objectives are the determination of the geoid with an accuracy of 1-2 cm and gravity anomalies with 1 mGal, both with a spatial resolution of 100 km half-wavelength, which corresponds to a spherical harmonic expansion up to degree and order (d/o) 200. GOCE is the first satellite equipped with a gravity gradiometer instrument. Here we will summarize the principles of the gradiometer and of the entire sensor system. This description is followed by a short report about GOCE's performance. We will then talk about GOCE and GRACE and about IERS-standards. Finally a short account will be given of the state-of-the-art of science and application and some conclusions will be drawn.

2. PRINCIPLES

The core instrument of GOCE is a three axis gravity gradiometer, consisting of six accelerometers with very high sensitivity. The measurement principle is differential accelerometry. The measurements are taken in the gradiometer instrument reference frame with x pointing approximately in flight direction, z pointing towards the Earth and y completing a right-handed coordinate triad. Each accelerometer measures the sum of gravitational gradients, centrifugal accelerations (containing squares of angular velocities) and Euler angular accelerations. The contribution due to angular accelerations is isolated by separating the 3×3 matrix of acceleration differences into its symmetric and skew-symmetric part. Integration over time of the angular accelerations, and combination with the angular measurements of the star trackers on board, yields the angular velocities about the axes of the instrument. The GOCE gradiometer measures the gradient components V_{xx}, V_{yy}, V_{zz}, and V_{xz} with high precision and the components V_{xy} and V_{yz} with much lower precision. The gradiometer instrument is made to measure the medium to short spatial scales of the gravity field very well. At long wavelengths the accelerometers of the gradiometer instrument exhibit rather complex coloured noise behaviour. This part is therefore derived from the orbit as determined by high-low tracking using GPS. The sensor system comprises star

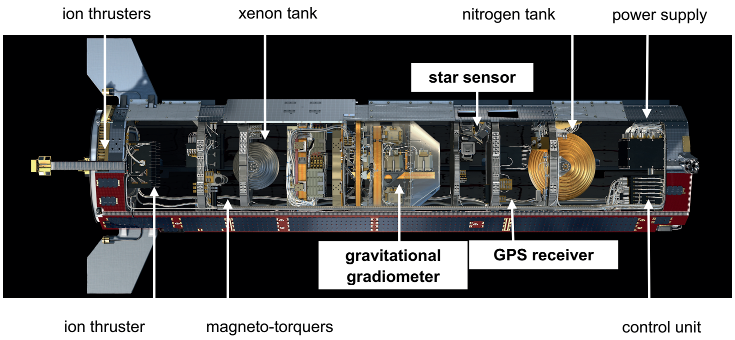


Figure 1: Gravitational field sensor system of GOCE, (source: ESA).

tracking, angular control by magnetic torquers and drag free control in flight direction, cf. Figure 1. The star tracking provides the orientation of the spacecraft with a precision of a few arc seconds relative to the celestial reference frame. In addition, it is combined with accelerometer data for angular rate reconstruction. The common mode accelerations along the three axes of the accelerometers serve as control signal for the drag free control in flight direction. The latter allows maintaining an orbit altitude as low as 265 km. The extremely low orbit altitude was chosen in order to enhance the gradiometric signal as well as the gravity related orbit perturbations. The mean orbit is almost circular and sun-synchronous with an inclination of 96.5°. This implies that the two polar areas with an opening angle of 6.5° are left without data. For more details it is referred to Rummel & Gruber (2010), Rummel et al., (2011) or to the GOCE special issue of Journal of Geodesy (vol. 85, no.11, 2011).

3. PERFORMANCE

On November 1, 2009 the first measurement cycle started. Since then the mission is in continuous operation with so far three major interruptions, from February 12 to March 2 and from July 2 to September 25, 2010 due to problems with the processor units and from January 1 to January 21, 2011 because of a software problem of the GPS receiver. Data flow and level-1 and level-2 processing are nominal. Currently, i.e. as of spring 2012, 1.5 years of mission data have been processed. All instruments work well. Only the noise level of the measured gradients in z-direction is somewhat higher than specified. More specifically, while the noise level of the components V_{xx} and V_{yy} is close to the predefined requirement, it is almost twice as high for V_{zz} and V_{xz} for reasons still not understood. A very powerful test of the gradiometer performance is the Laplace condition, i.e. the condition that the sum of the three diagonal gradient components V_{xx}, V_{yy} and V_{zz} has to be zero, in theory. In reality it gives the combined noise level of these three components. Power spectral densities of the gradiometer performance based on the Laplace condition show that the noise behaviour is essentially white in the measurement band from $5 \cdot 10^{-3}$ Hz to 0.1 Hz. The noise level is increasing proportionally to 1/frequency below the measurement band. Currently a first re-processing of all level-1B data is underway, with improved processing of the orientation quaternions from star tracking and of the angular rate reconstruction (Stummer et al, 2011). This will primarily improve the determination of the long spatial scales of the gravity field.

One measurement cycle takes about 61 days, usually followed by a calibration. The calibration signal is generated by a set of cold gas thrusters. So far, the High level Processing Facility (HPF), responsible for the level-2 processing (orbits and gravity field models), has produced three releases of GOCE gravity models (two months, six months and 12 months) together with their variance-covariance information. Three alternative processing concepts have been pursued; compare (Pail et al., 2011). All models have maximum d/o between 210 and 250. They are listed in Table 1. Also two combined GRACE/GOCE models GOCO01s and GOCE02s have been published (Pail et al., 2010).

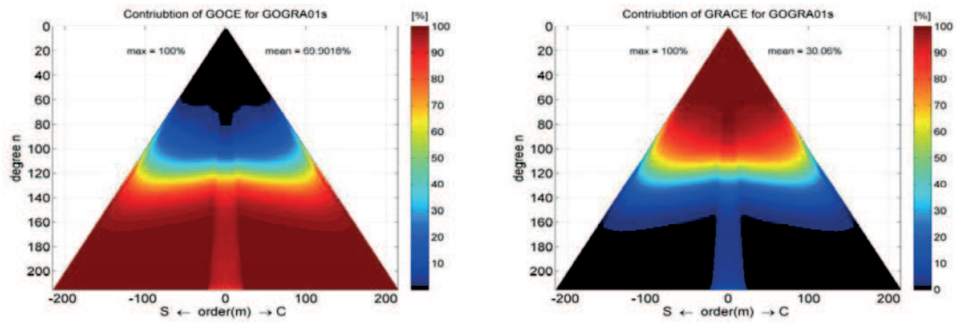
4. GOCE, GRACE AND IERS-STANDARDS

It should be understood that intrinsically GRACE models are superior to GOCE models at low degrees and orders, say below d/o 100, at d/o between 100 and 140 the fields are of comparable quality

Model	Data	D/O	Characteristics
DIR1	2 Months	240	Direct Approach: Prior model (combined) plus GOCE orbits & gradiometry
DIR2	6 Months	240	Direct Approach: Prior model (GRACE-only) plus GOCE orbits & gradiometry
DIR3	1 Year	240	Direct Approach: Prior model (GRACE-only normals) plus GOCE gradiometry
TIM1	2 Months	224	Time-Wise Approach: Pure GOCE (kin. orbits & gradiometry)
TIM2	6 Months	250	Time-Wise Approach: Pure GOCE (kin. orbits & gradiometry)
TIM3	1 Year	250	Time-Wise Approach: Pure GOCE (kin. orbits & gradiometry)
SPW1	2 Months	210	Space-Wise Approach: GRACE low d/o plus GOCE gradiometry
SPW2	6 Months	240	Space-Wise Approach: Pure GOCE (kin. orbits & gradiometry)

Table 1: GOCE gravity models produced by HPF and released by ESA (Nov. 2011). D/O is the highest degree of the series of spherical harmonic coefficients (source: Th. Gruber)

and above d/o 140 GOCE is more accurate than GRACE. This can also be seen from a contribution analysis as shown in Figure 2. The great sensitivity of GRACE at lower degrees and orders is the reason for its capability to measure the small temporal gravity variations due to mass changes of ice, ocean and continental hydrology; it will be rather difficult to recover temporal variations from GOCE data. The cumulative geoid error of release-3 models is about 4-5 cm. It will go down to 2 to 3 cm by the end of 2012, the extended mission period.



(a) GOCE SGG (b) GRACE

Figure 2: Percentage of the contribution of (a) GOCE (70%) being superior to GRACE from d/o 120 upwards and (b) GRACE (30%) dominating up to d/o 120 and) in a combined field. The relative weights are derived from variance component estimation, (source: W. Yi, 2012).

However, also gravity field models based solely on GRACE exhibit some weakness at very low degree and orders. Therefore it is advisable to combine GRACE measurements with time series of satellite laser tracking to satellites, such as LAGEOS 1 and 2, Stella, Starlette etc. Thus, the issue of the consistent use of standards and of compatibility of the included techniques has to be addressed. A geoid accuracy of 1 to 2 cm corresponds to about 1 ppb relative to the Earth's radius; a gravity accuracy of 1 mGal corresponds to 1 ppm w.r.t. gravity itself. Thus, GOCE, GRACE and satellite laser tracking and GPS have to be consistent at this level of relative precision. Furthermore, the combined use of geometric information (positions of individual points or the shape of the ocean's surface) and gravity/geoid information will require a global consistency of these two independent "worlds" at the level of a few ppb. GOCE gravity field analysis is based on GOCE standards, Gruber et al. (2009). They are almost but not exactly identical to the IERS-standards 2003, McCarthy & Petit (2004). The same is true for GRACE. Thus, combination of GOCE, GRACE, satellite laser ranging and GPS require adaptation in order to achieve perfect agreement of these data in terms of the applied fundamental constants and reductions, tide models and models of geophysical fluids. Combination of geometry with gravity and geoid goes one step further. It requires, in addition, full consistency in terms of permanent tides, GIA models, loading models etc. Also the question of how to deal with the three "degree equal one"-terms is of concern, as discussed e.g. in Wahr et al. (1998). This is a field that still needs intensive consideration, also before the background of the objectives of the Global Geodetic Observing System, compare Plag & Pearlman (2009).

5. SCIENCE AND APPLICATIONS

The main fields of GOCE application are geodesy, solid Earth physics and oceanography. The common denominator of the science objectives of GOCE is "dynamic topography".

Discovering the connection between processes observed on the Earth or in space and their internal dynamics is an essential goal in **solid Earth physics**. In good approximation the Earth is in isostatic balance. Dynamic topography in geophysics means the deformation of the surface of the Earth, not in isostatic balance but supported by the vertical stresses at the base of the lithosphere that are generated by flow in the mantle below. Comparison of the geoid or gravity anomaly signal as measured by GOCE with an Earth model in hydrostatic equilibrium predominantly reflects dynamic topography. The geoid or gravity anomaly signal generated by topographic masses in isostatic balance is generally much smaller. Research activities in solid Earth physics related to GOCE are just starting now.

At the end of 2012 approximately 16 measurement cycles will be completed, leading to an improvement by a factor of four compared with the first two-month models. EGM2008 combines ITG-GRACE03s (up to d/o 120) with gravity anomalies based satellite altimetry in all ocean areas and terrestrial Δg on land. Comparison with the GOCE models shows significant differences in those areas of the Earth where our expectation is, that in EGM2008 terrestrial gravity anomalies are either missing or sparse or inaccurate. These are Antarctica and parts of South America, Africa, Himalaya and SE-Asia. While the RMS-differences at d/o 180 between the GOCE release-3 fields and EGM2008 in terms of geoid height are between 3.5 cm and 5 cm in regions with good terrestrial gravity data (Australia, Europe and USA) they vary between 25 cm and 35 cm in South America, Africa and Himalaya and are about 11 cm in Antarctica (no terrestrial data are included there in EGM2008).

In **oceanography**, dynamic topography is defined as the deviation of the actual mean ocean surface from the geoid. Here the GOCE geoid serves as equilibrium surface, an idealization of the world's oceans at complete rest. The actual ocean surface is measured from space by radar altimetry. It is the first time that dynamic ocean topography is available from space with great detail and precision and without the use of oceanographic in-situ data.

For ocean studies the point of departure is geodetic dynamic ocean topography (DOT) with high spatial resolution, as derived from satellite altimetry and a GOCE geoid model. Taking the difference between the altimetric mean sea surface height h and geoid height N from GOCE implies the recovery of a rather small quantity, i.e. of dynamic ocean topography, from two much larger quantities. Furthermore, each the two quantities is delivered by its own satellite platform and measurement system. Also, their mathematical representation is fundamentally different: while altimetric heights are sampled along the ground tracks of the satellite as a densely spaced series of individual measurements, geoid heights are computed from a spherical harmonic representation of a gravity model which is derived by least squares adjustment from a large global data set of gradiometer measurements. Thus, consistency between altimetric sea surface heights h and geoid heights N is of utmost importance. A precondition is that h and N refer to the same coordinate system, reference ellipsoid and permanent tide system, see e.g. Hughes & Bingham (2008), Bingham et al. (2008). This is straightforward, in principle. However, it is less trivial to get the two quantities also spectrally consistent due to their completely different mathematical representation, as explained above. Various strategies exist, see e.g. Bingham et al. (2008), Albertella & Rummel (2009), Bosch & Savcenko (2010). In particular in coastal zones spectral consistency is difficult to achieve. Various models of altimetric mean sea surfaces exist, e.g. Hernandez & Schaeffer (2000), Andersen & Knudsen (2009) or Dettmering & Bosch (2010). They may differ in terms of the used time period, starting epoch, orbits, processing strategy, reduction models, treatment of sea ice and coastal zones, repeat cycles and selection of altimetric satellites. Criteria are needed as a guideline for sensible intercomparison, validation experiments with in-situ data, and for various oceanographic applications.

In Figure 3 a DOT is shown for the area of the Antarctic Circumpolar Current (ACC) with three spatial resolutions, up to d/o 60, 120, and 180. The DOT is thereby filtered with a Gauss-filter. There is the possibility to compare geodetic DOT-models with available ocean data and oceanic DOT models

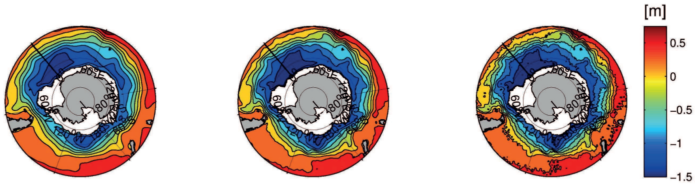


Figure 3: Mean dynamic ocean topography (DOT) of the Antarctic Circumpolar Current from a multi-year and multi-mission altimetric mean sea surface and the geoid computed using a GOCE-only gravity model based on six months of data up to d/o=60, 120 and 180 applying a Gauss-filter (from left to right). Units are meters.

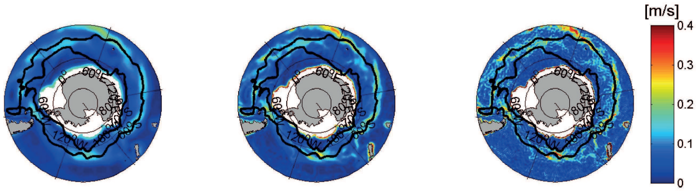


Figure 4: Geostrophic velocities as derived from the DOT of Figure 3 and also for d/o=60, D/O=120 and D/O180 (from left to right). Also shown are the fronts derived from oceanographic in-situ data. Units are meters per second.

such as Rio et al. (2007), Maximenko et al. (2009). GOCE based DOT-models with high spatial resolution are getting available just now, e.g. Le Traon et al. (2011) or Bingham et al. (2011). Geodetic mean topography is the point of departure for studies of surface ocean circulation, geostrophic velocities, assimilation into numerical ocean models, mass and heat transport. In geodesy it is the key to a global unification of height systems.

The effect of the high spatial resolution of GOCE will be especially important when computing geostrophic velocities and consequently in investigations of ocean mass and heat transport. Geostrophic velocities are a vector field on the Earth sphere, essentially the curl of the surface gradient field of the mean dynamic topography, or in other words a first spatial derivative. This leads to an amplification of smaller scales relative to the longer scales. In other words smaller spatial scales get a higher weight relative to the long spatial scales, cf. Janjic et al. (2012). Figure 4 shows the geostrophic velocities computed from the DOT model of Figure 3 for the area of the ACC, again up to d/o= 60, 120, and 180. The figure includes the fronts as derived from oceanographic in-situ data.

6. CONCLUSIONS

GOCE is a geodetic satellite mission. It demonstrates the value of gradiometry for global gravity field and geoid determination. More specifically, spatial scales typically between 80 km and 200 km will become much more consistent and accurate. Applications of gravity and geoid models in geophysics, oceanography and geodesy require an extremely high level of consistency and accuracy over the entire spectrum of spatial scales, or degrees and orders of a corresponding spherical harmonic series expansion. This will only be attainable if GOCE is combined with GRACE and with satellite laser ranging and GPS. It will require joint processing based on one common set of geodetic standards. Earth-fixed and celestial reference system, normal gravity, the attraction of sun, moon and planets, the effect of geophysical fluids, loading, tectonic motion and post-glacial re-adjustment must be dealt with consistently. Modern space geodesy is delivering essential Earth and climate variables. Geodesy will reach its full potential in Earth system science if Earth rotation, geometry and gravity/geoid can be analyzed in one unified system.

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