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# GOCE High Level Processing Facility Technical Note

# Product Acceptance Review (PAR)- Level 2 Product Report

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Prepared by: The European GOCE Gravity Consortium EGG-C





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# 1. INTRODUCTION

This technical note summarizes the status of the GOCE Level 2 products obtained at the end of the nominal operational phase of GOCE. It shall give an overview about product content and quality as well as a first assessment about what has been reached by the mission with respect to its objectives.

The document is structured as follow. Chapter 2 provides an overall summary of the status of level 2 products as well as an initial assessment of their impact on science applications. Chapters 3 and 4 describe the status of gravity gradient and orbit products as main intermediate level 2 products needed for gravity field determination. Chapter 5 to 7 summarizes processing techniques applied for gravity field modeling and the results obtained. Specifically, processing characteristics for each individual model are pointed out in these chapters. The rationale for having implemented three strategies for GOCE gravity field determination is provided further below in this introduction. Finally, chapter 8 shows results of quality assessment for the most recent GOCE gravity field models compared to other state-of-the-art global models.

### **Rationale for 3 Gravity Field Modeling Approaches**

One of the key elements of the gravity field modelling activities inside HPF was the development of three alternative strategies. These are:

- the direct approach (DIR) of WP5000 as a joint activity of GFZ and CNES,
- the time wise approach (TIM) of WP6000, jointly performed by TUG, ITG and IAPG, and
- the space wise approach (SPW) of WP7000 of POLIMI and UCPH.

The main reasons for the implementation of three methods in parallel were: (1) the three methods are representative for the existing philosophies of gravity field modelling, where it was impossible to say beforehand which of the three approaches would perform best and (2) the development of the methods in parallel would lead to a mutual control and to cross-fertilization.

Now, after the processing of 12 months of mission data, the decision taken in 2004 can be regarded as very successful. Three very competitive and comprehensive methods of GOCE gravity modelling have been developed and all three perform well. Even though rather basic differences exist in their methodology, all three are able to produce gravity models and associated error variance/co-variance methods of comparable quality. There exist small differences in their outcomes, but it is difficult to judge whether the differences are due to the applied method or due to the details of their implementation.

In summary three methods are now available for the recovery of a high resolution and high precision global gravity field model based on GOCE gravity gradiometry. And one should not forget: no method was available for this new type of measurement and sensor concept before this project started.

In order to optimize the GOCE science return, for the extended mission phase the following modification of the distribution of work is proposed:



- Direct approach (DIR) of WP5000: GOCE gravity field, employing prior information from other satellite missions such as GRACE (with their long and very successful work in the field of satellite gravity modelling, GFZ/CNES is highly qualified to produce such "GOCE + prior" gravity field models; this was also demonstrated with their result of the second release).
- Time wise approach (TIM) of WP6000: GOCE "pure", i.e. the recovery of a gravity field model based on GOCE data only (the three groups have already invested a lot of new ideas in the production of GOCE-only fields; their models of releases 1 to 3 are of this kind)
- Space wise approach (SPW) of WP7000: core element of the space wise approach is the use of (a fast version of) least-squares collocation (LSC). LSC is ideally suited for the production of global or regional grids with gravity functionals, such as radial vertical gravity gradients, gravity anomalies or geoid heights at satellite altitude or at a constant altitude close to the Earth's surface. Dense and high precision data grids are of great interest to several applications in geodesy and Earth sciences. It is proposed here to replace the standard gravity field model provided in terms of spherical harmonics by such grids.

With this slight change in philosophy we are able to (1) optimally exploit the specific strengths of the three groups and/or of their methods and (2) get three (instead of one) very useful types of GOCE HPF gravity field products.





# 2. FROM GOCE L2 PRODUCTS TO SCIENCE

In February 2012 GOCE is almost three years in orbit. After completion of the commissioning phase and calibration, delivery of science data started in October 2009. HPF began its operation without delay. Only minor adaptations of the processing algorithms were necessary. Important analyses took place concerning GPS and GPS-antenna performance, kinematic orbits, behaviour of the calibration parameters, STR quaternions, characteristics of common mode accelerations, performance of angular velocities and angular accelerations, and gravity gradients, cf. the following sections. Since November 2009 the data flow is almost continuous with only three interruptions. Two outages occurred due to problems with the onboard processor units and lead to interruptions of mission operation in 2010 from February 12 to March 2 and from July 2 to September 25. A GPS related software problem caused data loss from January 1 to 21, 2011. In September 2011 the third release of gravity models took place, based on approximately 1.5 years of data. An overview is given in Table 1.

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. D/O is the highest degree of the series of spherical harmonic coefficients

In parallel to the routine HPF processing, important feedback could be given about the data characteristics and quality of the Level 1b products. Several improvements of the level 1b processing were proposed and tested concerning the simultaneous operation of all three STR's, the quaternion algorithm and angular rate reconstruction, cf. Stummer et al., 2011 and Stummer et al, 2012. Currently a complete data reprocessing of Level 1b-products is conducted. In a special issue of Journal of Geodesy (volume 85, number 11, 2011) a detailed overview of the state-of-the art as of September 2010 of GOCE data analysis and science application is given.

What can we conclude about the mission performance? One should keep in mind that GOCE is a rather complex gravitational field sensor system. It is not comparable to a typical remote sensing mission. The sensor system comprises the gradiometer instrument with its three pairs



of orthogonally mounted single axis gradiometers, the GPS-receiver with two helix antennae, three star trackers, two ion thrusters for drag-free control in flight direction, angular control by magnetic torquing and cold gas thrusters for gradiometer calibration. It is a truly great achievement that all sensors work very well and according to expectation.

There is one exception. The noise level in the measurement band of the  $\{zz\}$ -component and  $\{xz\}$ -component of the gradiometer is approximately twice that of the components  $\{xx\}$  and  $\{yy\}$  and above the requirement. So far the cause of this degradation is not understood. Several investigations could not explain the behaviour. The degradation is unfortunate, because also the signal size of the  $\{zz\}$ -gradient component is approximately twice as high as that of the other diagonal components. It would therefore be the dominant component in gravity field analysis, while currently the contribution of  $\{zz\}$  is comparable to that of  $\{xx\}$  and  $\{yy\}$ . Analysis of the common mode accelerometer results suggests that all accelerometers perform equally well along all three axes.

A full measurement cycle of GOCE takes 61 days, or about two months. Before launch the prospect was that the mission would have to be interrupted by so-called hibernation periods. These are periods with long eclipses during each orbit revolution. The expectation was that the energy budget and the disturbance level would make it necessary to interrupt data collection during these hibernation phases, or even, that the satellite orbit altitude would have to be raised. Actually GOCE is operated without interruption – also during orbit eclipses. This leads to a significant increase of mission data. The GOCE mission objectives are to attain a geoid accuracy of 1 - 2 cm and a gravity anomaly accuracy of 1 mGal with a spatial resolution of D/O equal to 200 of the spherical harmonic expansion. It is our expectation that by the end of the extended mission phase these mission objectives can almost be met, despite the unexpected degradation of  $\{zz\}$  and  $\{xz\}$ .

As a rule-of-thumb (under the assumption of a normally distributed error behaviour) the accuracy of the derived geoid and gravity anomalies improves with the square-root of the number of measurement cycles. A recent analysis by R. Pail, based on pure GOCE information and on 1<sup>st</sup> release L1B gravity gradients, comes to the following projected performance at the end of the extended mission, i.e. at the end of 2012, see also Figure 36,

- geoid accuracy < 3 cm
- gravity anomaly accuracy < 1 mGal,
- both as commission error of a SH-expansion up to D/O 200.

The geoid accuracy of the gravity models of release 3 is approximately 4.5 to 5 cm at D/O 200.

Very informative are comparisons of the derived GOCE results with the best available static GRACE models and with the combined gravity field model EGM2008. Comparison with the seven-year GRACE model ITG-GRACE2010s of the University of Bonn (Mayer-Gürr et al, 2011) shows that:

- GRACE is more accurate than GOCE at D/O < 100
- GRACE is comparable in accuracy with GOCE between D/O 100 and 140
- GOCE is more accurate than GRACE at D/O > 140

These estimates follow from (1) a comparison per degree of the formal errors, (2) combination trials of GRACE and GOCE, and (3) validation experiments. The latter were conducted with GPS-levelling data (see below), regional gravity anomalies and with geostrophic velocities as derived from geodetic mean dynamic topography. The performance

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confirms pre-launch analyses. Any extension of the GOCE mission length works in its advantage. 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 (Mayer-Gürr, 2007) (a precursor GRACE model of ITG-GRACE 2010s based on 4.5 years data) up to degree and order 120 with gravity anomalies based satellite altimetry in all ocean areas and terrestrial gravity anomalies on land. Comparison with the GOCE models shows significant differences in those areas of the Earth where, as expected, 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 degree and order 180 between the GOCE release-3 fields and EGM2008 in terms of geoid heights are between 3.5cm and 5cm in regions with good terrestrial gravity data (Australia, Europe and USA) they vary between 25cm and 35cm in South America, Africa and Himalaya and are about 11cm in Antarctica (no terrestrial data included in EGM2008).

In summary, we conclude that GOCE-HPF proves to be successful for several reasons:

- It lead to the development of a very comprehensive processing chain
- The actual level-2 processing could be started without any delay. Only minor adaptations were found necessary
- A detailed and comprehensive performance analysis was and is done covering all processing steps. Important feedback could be given to CMF and PDS
- High level data product became available for immediate and convenient use in science. The products are widely used.
- The HPF processing rationale (logic, methods, algorithms) can now be used as baseline for any other gravity modelling activities outside of HPF

It is our conviction the for future satellite missions of comparable complexity (1) end-to-end simulation and (2) a high level processing facility are almost a "must".

**Science and Applications.** The science objectives of GOCE were analyzed in detail in 1998 as part of the mission proposal, cf. (ESA, 1999, chapter 3). Figure 1, taken from the 1999 Granada-presentation, summarizes their essence.

In order to facilitate the use of GOCE products, as provided by GOCE-HPF and in order to stimulate their use, the ESA initiated the development of a GOCE User Toolbox (GUT); see (Knudsen et al, 2011). Also this proved to be very beneficial for science applications. Currently we observe the main science activities in the areas of physical oceanography, geodesy and solid Earth physics.

The common denominator of the science objectives of GOCE is "dynamic topography".





**Figure 1:** Scheme showing the GOCE science applications, as discussed in 1999. The GOCE gravity field products are shown in blue, complementary data sets from solid earth physics, oceanography and geodesy are shown in green and the science products in brown. The applications in the field of sea level research are based on a synthesis of the four other areas. For a detailed discussion it is referred to ESA, 1999.

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. Figure 2 shows the GOCE geoid up to d/o 20 referred to a hydrostatic equilibrium figure. In Figure 3 a gravity anomaly map of Africa is shown from d/o 21 to 200. The gravity anomalies are primarily related to dynamic topography. Research activities in solid Earth physics related to GOCE are just starting now.

Typical research items in solid earth physics will be:

- Detailed analysis of the anomalous gravity gradient, gravity anomaly and geoid anomaly field in selected regions (such as Africa, Himalaya and Tibet, South America) and comparisons with terrestrial gravity data and topographic data sets
- Study of isostatic compensation mechanisms based on the improved gravity models in the spectral range between d/o 100 and 200 (in terms of spherical harmonics)
- Study of the density anomaly field and tectonic structure under the ice cover of Antarctica
- Joint inversion of GOCE gravity, topography and seismic tomography
- Worldwide studies of dynamic topography



Figure 2: GOCE good referred to a hydrostatic equilibrium figure cf. (Nakiboglu, 1982; Phys. Earth Planet. Interiors or Chambat, Richard & Valette, GJI, 2010)

Figure 3: GOCE gravity anomaly map of Africa from d/o 21 to 200, primarily associated with dynamic topography

In oceanography, dynamic topography is the deviation of the actual mean ocean surface from the geoid. Here the GOCE geoid serves as equilibrium figure, 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 measured from space with such great detail and precision and without the use of oceanographic in-situ data. Geodetic mean dynamic ocean topography is the point of departure for studies of surface ocean circulation, geostrophic velocities, assimilation into numerical ocean circulation models and mass and heat transport.

Taking the difference between the altimetric mean sea surface height h and geoid height Nfrom 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 the 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 pointed out above. Various strategies exist or are under development, see e.g. (Losch et al., 2002, Bingham et al., 2008. Albertella & Rummel, 2009, Bosch & Savcenko, 2010 and others). In particular in coastal zones spectral consistency is difficult to achieve. The associated problems are nicely discussed in Bingham, 2010. See also Knudsen et al., 2011.



Figure 4: Geodetic mean dynamic ocean topography in the North Atlantic by Bingham, 2010.

The effect of the high spatial resolution of GOCE is 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. Janjić et al., 2012. Figure 5 shows the geostrophic velocities computed from a geodetic DOT model for the area of the Antarctic Circumpolar Current up to maximum d/o= 60, 120, and 180. The figure includes the fronts as derived from oceanographic in-situ data.



**Figure 5:** Geostrophic velocities as derived from a geodetic mean dynamic ocean topography model for spherical harmonic expansions up to d/o=60, 120 and 180 (from left to right). Also shown are the fronts derived from oceanographic in-situ data. Units are meters per second.



Some research items in oceanography:

- Comparisons of geodetic DOT models and their underlying data base. Common standards and reductions. Filtering and spectral consistency. Also the altimetric data sets may differ in terms of the used time period, processing strategy, orbit release, reduction models, treatment of sea ice and coastal zones, repeat cycles and selection of altimetric satellites. A common baseline has to be agreed upon.
- Development of a comprehensive error variance-covariance model for geodetic DOT and geostrophic velocities
- Comparative analysis of geodetic mean dynamic ocean topography models and geostrophic velocity fields with oceanic data sets (drifter data, ARGO data etc.)
- Assimilation experiments into various numerical ocean circulation models
- Analysis of ocean mass and heat transport (through adopted sections)
- Analysis of spectral content of geostrophic velocity fields

In geodesy the GOCE geoid is the key to a global unification of height systems. In a series of preliminary tests, intercontinental height connection based on the GOCE geoid could be demonstrated using the GPS-levelling data sets. Currently detailed studies are going on for height datum unification with the geodetic boundary value method and the oceanographic method. It seems that the effect of height datum biases in the required regional gravity anomaly data sets on height datum connection is negligible.

Research items in geodesy:

- global and regional height datum connection/unification
- detection of height off-sets in gravity anomaly data sets
- detailed global analysis of terrestrial gravity anomaly data sets
- new combined high-resolution gravity model (EGM-next generation)
- GOCE gravity models and effect on orbit determination
- Temporal gravity from GOCE: prospects and limitations

Still pending is GOCE research on (1) ocean bathymetry from GOCE gravity gradients, (2) determination of bedrock topography under ice shields and (3) determination of sea ice thickness. There are currently also applications under investigation not listed in Figure 1. These include the (4) recovery of temporal gravity variations such as those induced by earthquakes and (5) the effect of atmospheric density and of the earth's magnetic field on the orbit and on common mode accelerations.





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# **3. PREPROCESSING AND GRAVITY GRADIENTS**

### Data Management

In a project as GOCE involving 11 different parties: the European Space Agency (ESA) and 10 European Institutes grouped in the so-called HPF, a good management of data is crucial. From the Level1b data provided by ESA to the gravity field, final product of the HPF, a lot of intermediate files need to be shared. To manage all data transfer within HPF the Central Processing Facility (CPF) has been created. For the external user community a XML Parser transforms the XML files made available by ESA to column formatted files.

### Central Processing Facility

The CPF is a software whose most important task is to transfer data, all the data involved in the GOCE project and used within the HPF. These data come from:

- ESA, as level1B data, in a XML format and the CPF converts them to Level 2C data formatted in columns.
- Other HPF institutes (called SPF's). These files can be either the external (auxiliary) data products that the SPF's need to process their own products, or the HPF intermediate and final products.

Reciprocally, the CPF sends all the files he ingests to all the SPF's and ESA based upon request. The most important rule is: 'Every file transfer inside the HPF and to/from ESA must be done via the CPF'. One of the most important goal or reason for the CPF was to have one unique central system in charge of the data management, within HPF:

By commodity:

- 1. Therefore all SPF's and ESA make their files available to the CPF, wherever the files must be distributed,
- 2. The providing SPF's or ESA does not need to control the distribution to other parties. As soon as a file has been correctly ingested by the CPF this former is taken in charge by the CPF that will re-try the distribution until success. Please note that, anyway, the distribution of any file can be checked on the CPF Website by any ESA/HPF people.

But of course even more for efficiency:

- 1. It is the same physical file that is made available from one ESA/SPF's and sent to all others.
- 2. The transfer of each file is checked via a UNIX command called md5sum that returns a unique code representing the content of a file. This md5sum code is written in a delivery slip that has to be joined to the data/header file before transfer to/from the CPF and will confirm/deny the success of the transfer.
- 3. The CPF does a (very long) series of formal tests before disseminating the files.

Points 1 and 2 guaranties that all SPF's/ESA use the same data.

Point 3 guaranties the regularity of file with time. There are (much) too many tests to detail them here but they could be grouped as followed:



- Tests on the file: Examples: Check if the name follows the convention name. Check the transfer via the UNIX command md5sum. Check the uniqueness of the file: if a file with the same name/version has not already been ingested.
- Tests on the content of header file: Check the format of all fields. Check the list of input/output files: the required files have to be listed, the optional might be but no other one can be listed if they are not referenced as usual input of a product.
- Tests on the content of data file: Check the format of all fields.

In case of transfer problems, the CPF automatically re-tries the transfer a couple of times and sends an email to the corresponding SPF's to warn them of the failure. To optimise this procedure, and other special configuration, a new distribution scheme has been implemented in August 2009. The main points are:

- Manage differently the distribution scheme for failed distribution files: Each time the distribution of a data file fails, the next try for its distribution will occur 30 minutes after the previous failure.
- Give a higher distribution priority to certain files: OPER files with version 0001 whose distributed has never been attempted,
- Limit the number of 'time consuming files' distributed per distribution process: only 1 file in the list of the time consuming files, among others SST\_PSO\_2, is distributed per process. This allows to send 'not time consuming files' during this process without waiting for the distribution of potentially several 'time consuming files'.

Figure 6 below, show the amount of L1b files with the CONS class received from April 2009. Please note that the Y-axes are different for each product. As the L1b products are generated for each orbit and as there are 16 orbits per day then if there was 1 version of each product there should be around 488 files per month.

The SST products (SST\_NOM\_1b and SST\_RIN\_1b) were mainly processed once by ESA, whereas the STR\_VC2\_1b (and STR\_VC3\_1b not represented here) products were reprocessed end of 2009 and the EGG\_NOM\_1b products were reprocessed several times essentially end of 2009 and during May, June, July and August 2011. The telemetry issue in the summer 2010 is clearly visible, as GOCE did not send any data.

After almost 3 years of operation we can say that the CPF succeeded in its mission. It ingested and distributed all the files he had to, without any interruption and on time. He also prevented from erroneous files to be distributed, successfully sent automatically files whose firsts distribution failed and could manage "big distribution events" as when ESA sent 3 months of reprocessed EGG\_NOM\_1b data at once. 1870 files were then ingested and distributed. For information: It took 4 hours to download them from the ESA server, 19 hours to transform them in L2C data, 2 hours 30 minutes to update the database containing all the information about all the files going through the CPF, and around 6 days to send them to all the institutes that require the product!

#### XML Parser

The external user community has access to the GOCE data from the ESA web site, in XML files. A XML Parser was already developed to convert some Level2 products. In 2010 it was decided to expand this XML Parser to the Level 1b data: therefore the user can directly use the "original" data of the products.





Figure 6: Examples for the number of received products by the CPF since GOCE launch.

#### Gravitational Gradients in the GRF

The main goal of the GOCE mission is to provide a model of the Earth's mean gravity field and therefore the GOCE gravitational gradients need to be corrected for temporal gravity field variations. Also outliers that may occur in the GOCE gravitational gradients need to be searched for and detected in the preprocessing step (Bouman 2004). Along with the external calibration of the gravitational gradients (Bouman et al. 2004), their error needs to be assessed. The steps for gtravity gradients (GG) preprocessing therefore are:

- 1. Correction for temporal gravity field variations;
- 2. Outlier detection and flagging;
- 3. External calibration and error assessment.

These preprocessing steps lead to corrected and calibrated Level 2 GGs in the GRF, which are one of the GOCE final products (EGG\_NOM\_2). These GGs are input to the gravity field analysis as well as to the frame transformation, which leads to GGs in the LNOF (EGG\_TRF\_2). In the subsequent paragraphs the frame transformation, or tensor rotation and the different steps of the GG preprocessing method are summarized. For a detailed description see (Bouman et al. 2009, 2011a).

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We discern tidal and non-tidal temporal gravity field variations which all are in general very small at GOCE altitude compared with the GG signal and error. As an example, Figure 7 displays the gravitational gradient trace and the gravitational gradient temporal  $V_{ZZ}$  corrections for 1 November 2009. The gravitational gradient trace is not zero due to the errors in the diagonal gravitational gradients. Thus the temporal gravitational gradient signals are about two orders smaller or more than these errors at all frequencies.

The GGs data screening method adopted for the GGs is based on a test on the difference between the observed GGs and gradients from a GOCE-only global model. The detected outliers are indicated in the external calibrated GG file (EGG\_NOM\_2) by a flag. Slow and smooth oscillations which can be the case after a data gap triggering a Kalman reinitialization are hard or impossible to detect with our method as we filter to the MBW. In the period from 31 October 2009 to 3. September 2011 only a few outliers were detected, nearly all in the diagonal terms  $V_{XX}$ ,  $V_{YY}$  and  $V_{ZZ}$ . The mean number of outliers is small and stays stable in time. In Table 2 we can see that the standard deviations of these means are small.



**Figure 7:** Spectral density of one day (1 November 2009) of the GG trace and V<sub>zz</sub> temporal signals in EGG\_NOM\_2.

Table 2:	Percentage of detected outliers, based on weekly data. Period between 31 October 2009 and 3
	September 2011.

GG	Mean	Standard deviation	Minimum	Maximum
V <sub>XX</sub>	$4.3*10^{-2}$	$1.4*10^{-2}$	$1.7*10^{-2}$	1.3*10 <sup>-1</sup>
$V_{YY}$	$3.1*10^{-2}$	$1.1*10^{-2}$	$12*10^{-2}$	9.2*10 <sup>-2</sup>
V <sub>ZZ</sub>	$5.5*10^{-2}$	$1.2*10^{-2}$	$1.6*10^{-2}$	1.0*10 <sup>-1</sup>
V <sub>XY</sub>	$1.2*10^{-3}$	$3.6*10^{-3}$	0	$2.2*10^{-2}$
V <sub>XZ</sub>	$2.4*10^{-3}$	$3.8*10^{-3}$	0	$2.3*10^{-2}$
V <sub>YZ</sub>	$1.4*10^{-3}$	$4.7*10^{-3}$	0	3.1*10 <sup>-2</sup>

Three different methods are used in the external calibration of the GOCE GGs. The baseline method is the calibration using a global gravity field model, which is used to compute model GGs at satellite level and these GGs serve as reference values for the GOCE GGs to

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determine, for example, GG scale factors (discussed in this section). A second calibration method uses GOCE SST data and GOCE GGs to estimate the spherical harmonics of a global gravity field model, truncated at degree and order 80, together with calibration parameters (Visser 2007). The third calibration method uses terrestrial gravity data. Least-squares collocation (LSC) is used to compute GGs at satellite altitude from the gravity data in selected regions. These GGs serve as reference values with which the GOCE GGs may be calibrated.

Figure 8 shows GG scale factors versus time using global models and GOCE GPS data for calibration. There is one plot for each of the six gravitational gradient components. The time, from 31 October 2009 to 3 September 2011, is indicated in GPS seconds. Some scale factors are missing: some because there were no data available as in February 2010 or July/August 2010 when GOCE had telemetry problems, or because ESA did a shaking on the satellite to determine new internal calibration parameters or because special events perturbed the data and triggered to bad scale factors. Except for some outliers GG scale factors stays constant good over the weeks. The YY scale factors seem to show more variation with time, especially after March 2011.



**Figure 8:** GG scale factors calculated by the external calibration using a global gravity field (blue) and GOCE GPS data (red). Period 31 October 2009 – 3 September 2011.

The primary objective of the calibration with GPS is the validation of the GOCE gravity gradients. It can be observed that the scale factors for the diagonal components are close to one with an RMS-about-mean below 0.02 using a three-sigma editing (Figure 8, red lines). For the scale factors for the common-mode accelerations an a priori constraint of 0.01 is used. The dynamic orbit determination leads to a fit of around 20 cm (3D) for the kinematic orbits for daily arcs. Without using the common-mode accelerations, the fit is above 60 cm, which reflects that the common-mode accelerometer observations indeed capture the (remaining) non-gravitational accelerations very well. The formal error for the common-mode scale factors in the X and Z direction is always very close to the a priori constraint or 0.01, which is due to the fact that there is hardly a non-gravitational signal along these axes. For the Y axis, a relatively large non-gravitational signal is remaining, which better allows the estimation of



scale factors for this axis. This is reflected by the formal errors, which is in general between 0.008 and 0.009, which is not much below the a priori constraint of 0.01, but it does indicate that some signal is present for calibration.



Figure 9: Estimated common-mode scale factors in along-track (left) and cross-track (right) direction. Period November 2009 - August 2011.

The method of GG calibration with terrestrial data is based on the gravity data from 4 regions selected because of available high quality gravity data and smoothly varying gravity anomalies (Arabelos and Tscherning 1998). The 4 areas are located in Northern Europe, Canada and Australia. The area sizes are chosen approximately in the order of 12° x 12°. This allows flybys of 200 s duration in each area, which corresponds to the lower part of the MB of 5 mHz. The calibration with terrestrial data in its present form represents a 'high frequency' GG validation method where larger SF deviations must be expected, but which in general should produce results comparatively close to 1. With the present calibration area size and geographic distribution, approximately 3 sets of GG SFs are computed each day and can in case of excesses rapidly indicate a malfunction or a calibration issue. The results from the period January – June 2010 shown in Figure 10 indicate that the SF results seem to be more diffuse at the end of the period (May - June).



Figure 10: SF results from period 19 January – 6 June 2010



#### **Rotation of the Gravitational Tensor**

A direct point-wise rotation of the GOCE GG from the GRF to the LNOF, or any other frame, would project the larger GG error of  $V_{XY}$  and  $V_{YZ}$  onto the other GGs. A method that would not have this disadvantage is a point-wise rotation with the GOCE  $V_{XY}$  and  $V_{YZ}$  GGs replaced by model GGs, for example computed with a GOCE-only global gravity field model (Pail et al. 2011). Because of the 1/f behavior of the GG error below the MB, leakage effects may occur. That is, as a result of the frame transformation, long wavelength errors in the GRF may leak to higher frequencies in the LNOF. The signal below the MB for all GGs is therefore also replaced by model signal, for example from a GRACE-based global gravity field model.

Because the GOCE  $V_{XY}$  and  $V_{YZ}$  GGs in the GRF are replaced by model GGs, the GGs in another reference frame will be a linear combination of GOCE GGs and model GGs also in the MB. The model content in the GGs in the LNOF is estimated by a separate rotation of GOCE and model gravitational gradients (both sets filtered as described above), and by computing the relative model contribution to the total GG signal confined to the MB (Fuchs and Bouman 2011). The relative model contributions in the LNOF are shown in Table 6 for  $V_{XX}$ ,  $V_{YY}$ ,  $V_{ZZ}$  and  $V_{XZ}$ . The largest rotation from GRF to LNOF is around the Z-axis. Therefore the relative model content in  $V_{ZZ}$  is only 2 %. The rotation from GRF to LNOF is large towards the poles where the GRF follows the transition from ascending to descending tracks and vice versa. Thus the relative model content for the other GGs is largest towards the poles, see Figure 11.

Gravitational gradient	Model content in LNOF
$V_{XX}$	25.8 %
$V_{YY}$	35.4 %
V <sub>ZZ</sub>	1.8 %
V <sub>XZ</sub>	21.7 %

**Table 3:** Relative model content in the rotated GGs  $V_{XX}$ ,  $V_{YY}$ ,  $V_{XZ}$  and  $V_{ZZ}$ 



Figure 11: Average latitude plot of the relative model content in the rotated gradients in the LNOF

The diagonal GGs of the rotated gravitational gradient tensor are evaluated using the state-ofthe-art global gravity field models, EIGEN-5C and EGM2008 (Förste et al. 2008, Pavlis et al. 2008). The differences of these GGs with respect to the GOCE GGs were computed and band-pass filtered, which emphasizes the MB where the largest impact of GOCE is expected. For all three gravitational gradients the agreement over the oceans between GOCE and



EIGEN-5C / EGM2008 is good, whereas the agreement between over the continents is not so good (see Figure 12 for  $V_{XX}$ ). Especially in regions where the terrestrial gravity data is known to be of poor quality or not existing, the GOCE and model values are quite distinct and it is evident that GOCE delivers new valuable gravity field information.



**Figure 12:** V<sub>XX</sub> binned averaged differences 31 October 2009 - 11 January 2010: Left panel GOCE - EIGEN-5C (N=360); Right panel GOCE - EGM2008 (N=360)

The differences of the GOCE V<sub>YY</sub>gradients with respect toITG-GRACE2010(Mayer-Gürr et al. 2010) are shown in Figure 13. The residuals South of Australia and Northern Canada do not represent real gravity signal but are related to a drift in differential scale factors and can largely be reduced by adjusting the in-flight calibration parameters. The trackiness for high latitudes is probably caused by the well-known presence of trackiness in GRACE-only solutions in North-South direction. Further analyses were based on the external calibration of the accelerations using the STR data and a global gravity field model (Rispens and Bouman 2009, 2011). To assess the stability over time of the calibration parameters, the data period from 1 November 2009 until 9 January 2010has been split into seven periods of each approximately 10 days. For these seven data periods, calibration parameters have been estimated and plotted as a function of time. In general, the parameters are consistent from one period to the next with the exception of some of the differential scale factors (DSF), which show a linear trend. Linear interpolation of the DSF values obtained after the in-flight calibrations of October 2009 and January 2010 show the same trend. This indicates that the differences in internal calibration estimates for the DSF are in fact caused by a slow variation in (differential) scale factors.



Figure 13: V<sub>YY</sub>binned averaged differences 31 October 2009 - 11 January 2010: GOCE - ITG-GRACE2010 (N=180)



# 4. GOCE ORBITS

The GOCE orbit determination and validation is carried out by three chains:

- Rapid Science Orbit (RSO) determination aiming at a latency of less than 1 day after Level 1b product availability at a precision of 50 cm 1-dimensionally (1D);
- Precise Science Orbit (PSO) determination aiming at a precision of 2 cm 3dimensionally (3D);
- Orbit validation.

The RSO chain is in operation at the Astrodynamics and Space Missions (AS) chair at the Faculty of Aerospace Engineering (FAE), Delft University of Technology, whereas the PSO chain is in operation at the Astronomical Institute of the University of Bern (AIUB). The orbit validation is carried out by the Institute for Astronomical and Space Geodesy (IAPG) of the Technical University Munich (TUM).

The GOCE orbit determination supports:

- Quality checks of Level 1b data:
  - Format/conventions of SSTI data (RINEX);
  - Consistency of coarse orbit solution;
- Performance assessment SSTI and gradiometer:
  - A/B sides;
  - Data coverage (e.g. L2 tracking);
  - Common-mode accelerometer observations;
- Gravity field determination:
  - Geo-location of gravity gradients;
  - Time series of orbit positions plus statistical information for gravity field determination (complementary to gravity gradients);
- International Laser Ranging Service (ILRS):
  - Orbit predictions (Jäggi et al, 2011).

The GOCE orbit determination provides the following Level 2 products:

- Rapid Science Orbit product:
  - Reduced-dynamic orbit solution:
    - SP3 file (position + velocity @ 0.1 Hz);
    - Observation residuals;
  - Kinematic orbit solution:
    - SP3 file (position @ 1 Hz);
    - Observation residuals;
  - Rotation matrices (J2000  $\Leftrightarrow$  ECF);
  - Quality Report;
  - Precise Science Orbit:
    - Reduced-dynamic orbit solution:
      - $\circ$  SP3 file (position + velocity @ 0.1 Hz);
      - Observation residuals (interim only);
    - Kinematic orbit solution:
      - o SP3 file (position @ 1 Hz) & variance/co-variance matrix;
      - o Observation residuals (interim only);



- Rotation matrices (J2000  $\Leftrightarrow$  ECF);
- Quality Report.

For more details is referred to Bock et al (2007), Bock et al (2011), Visser et al (2009) and Visser et al (2010).

### **<u>Rapid Science Orbits Production</u>**

The RSO chain was started a few days after the launch of GOCE on 17 March 2009. Within a day after Level 1b product availability, first orbit solutions were generated successfully and feedback was provided to the PDS leading to Level 1b SSTI data improvements. During April 2009, the RSO orbit determination setups were updated/tuned and at the end of this month the Level 1b data delivery was sufficiently stable to start automatic RSO product deliveries. Thus, RSO product delivery covered the largest part of the GOCE commissioning phase from end of March until November 2009. The quality of the RSO orbit solutions improved quickly from below 1 m to a few dm 3D at the end of the commissioning phase, well within the requirements.

RSO products have been generated for the entire nominal GOCE mission (November 2009 – April 2011) as well, except for three periods with missing GOCE data due to several anomalies. These three periods cover 13 February 2010 (1 day), 8 July to 31 August 2010 (55 days) and 3 to 5 January 2011 (3 days). During the nominal mission phase, several adjustments have been made in the RSO product generation strategy, which are listed in Table 4. Regular updates of the GPS antenna PCV file or the file describing the GOCE mass history are not included in this table (for more information is referred to previous paragraphs and to Bock et al, 2011).

Date	Event
3-8/12/2009	Temporary use of IGR instead of rapid CODE products for kin RSO.
12/1/2010	Adjust check of available GOCE data for different file versions.
13/1/2010	Adjust GOCE antenna offsets according to technical note for kin RSO.
15-16/1/2010	Temporary use of IGR instead of rapid CODE products for kin RSO.
20/1/2010	Adjust GOCE antenna offsets according to technical note for rd RSO.
4/3/2010	Fix of numerical round-off error in pre-processing for kin RSO.
1/4/2010	Start use GOCE PCV map for kin RSO.
9/9/2010	Adjust empirical acceleration constraints and start use of GPS and GOCE PCV map for rd
	RSO.
6/10/2010	Fix problem with GPS ground station velocities for rd RSO.
6/1/2011	Start use of redundant GPS receiver without GOCE PCV map.
10/2/2011	Resume use of main GPS receiver with GOCE PCV map.
20/4/2011	Switch to IGS08 GPS PCV file.
22/4/2011	Switch to ITRF2008 ground station coordinated for reduced-dynamic RSO.

**Table 4:** Events impacting production of RSO



Figure 14: Latency of RSO product with respect to input data availability

Figure 14 gives an overview of the SST RSO product latency for the nominal mission. For most days, the SST RSO product is generated less than 12 hours after the availability of the GOCE data, which means that the SST RSO product meets the latency requirement of 1 day after data availability by a significant margin. In general, the latency is largely determined by the waiting time for the auxiliary GPS data. Relatively short latencies of less than 12 hours are due to late deliveries of the GOCE data, when the latency is no longer determined by the availability of the auxiliary GPS data. The minimum latency of the SST RSO product is determined by the computation time for the SST RSO product, which is less than three hours. Outliers in the product latency are usually due to non-nominal deliveries of the GOCE and auxiliary GPS data. The first large outlier in early December 2009 is due to late deliveries of the AUX IGSR product, which were only generated after a few days using a back-up machine. The second large outlier in February 2010 occurred after the GOCE anomaly and is due to (waiting for) late GOCE data. Starting up after the GOCE SSTI anomaly in early January 2011 with data from the redundant GPS receiver also required several days, which is visible in Figure 14. The large latency outlier around April 2011 is due to a power outage in Delft.

#### **Precise Science Orbits Production**

The Precise Science Orbit (PSO) product covers nearly the entire time span of the nominal mission phase and a large part of the commissioning phase. Products are available from mid of April 2009 until mid of April 2011 (in total 627 days). SSTI data from the main receiver and antenna (SSTI-A) are used for the generation of the official PSO product on 627 days. Only on 36 days (January 6 to February 10, 2011) data from the redundant receiver and antenna (SSTI-B) are used for the official PSO product. Additional data from SSTI-B are available from parallel data acquisition in March/April 2010.

In order to achieve the required orbit accuracy systematic error sources in the processing have to be reduced as much as possible. Antenna phase centre variations (PCVs) are one of the main error sources for orbit determination of LEOs (Jäggi et al, 2009). Therefore, the PCVs of

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the two SSTI antennas had to be determined and used in the orbit generation process (please note that they are used by the RSO chain as well). Based on phase observation residuals, empirical PCV maps are generated from several days of data (154 days for SSTI-A, 58 days for SSTI-B, see also Bock et al, 2011). Figure 15 shows these PCV maps for the two SSTI antennas. Since the amount of data is more than double for SSTI-A than for SSTI-B, the map for SSTI-A is smoother. Different near-field environment effects may be noticed for both antennas (note the differences in the lower right corner of the figures).



Figure 15: PCVs (mm) for SSTI-A (left) and SSTI-B (right). Azimuth of 0° is pointing into flight direction. The PCVs are derived from 154 (SSTI-A) and 58 (SSTI-B) days of data, respectively.

#### **Product Quality**

#### SSTI and Accelerometer Common-Mode Performance

The RSO and PSO chains involve a number of procedures for checking the performance of the GOCE GPS receiver or SSTI. These procedures show that the GOCE SSTI is a reliable high-quality, dual-frequency state-of-the-art space-borne GPS receiver. In general, SSTI tracking data is continuous with hardly any gaps and with 10 or more channels being active (see e.g. Figure 16).

An important aspect of the SSTI performance is the tracking at the  $L_2$  frequency (IJssel, J. van den et al, 2011). It has been observed that between 6 and 10% of the observations are equal to zero (Figure 17) and can thus not be used for forming ionospheric-free observations for the orbit determination. The  $L_2$  losses in the middle of passes (indicated by red in Figure 17) especially impact the kinematic PSO orbit product, since it leads to the introduction of more carrier-phase ambiguity parameters (see below). In addition, these losses concentrate at the poles and display a pattern correlated with the magnetic equator (Figure 17, bottom). Kinematic orbit solutions are therefore expected to have a relatively smaller precision for the polar areas. The number of losses appears to be maximal during autumn. Figure 17 suggests that these losses keep growing, but in fact it has dropped since the start of 2012 (not covered by this report).



Figure 16: Typical profile for number of channels tracking GPS satellites as a function of time (left) and associated histogram (right)



L2 zero observations in the middle of pass



**Figure 17:** Loss of L<sub>2</sub> observations as a function of type (begin/end/middle of pass and total: top) and as a function of location (bottom)

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The number of SSTI observations (Figure 18; divided by 1000; blue: SSTI-A, cyan: SSTI-B) mainly varies depending on the observation geometry, but in March and April 2011 it decreased significantly. At the beginning of each GPS satellite pass and at cycle slips and data gaps phase ambiguities have to be set up. The number of ambiguities (Figure 18; red: SSTI-A, green: SSTI-B) also shows periodic variations. Moreover a significant increase over the whole time span of the mission is visible. This trend is also visible in the percentage of missing  $L_2$  data (Figure 19: both for SSTI-A and SSTI-B, compare with Figure 17) and may at least partially be explained by an increase in solar activity (Figure 20).



**Figure 18:** Number of phase ambiguities (SSTI-A: red, SSTI-B: green) and number of observations/1000 (SSTI-A: blue, SSTI-B: cyan), black lines at the bottom indicate eclipsing periods.



Figure 19: Percentage of missing L2 data for SSTI-A (red) and SSTI-B (green)



Figure 20: Mean Total Electron Content as a measure for solar activity

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The short time periods for which SSTI-B data are available already indicate that the performance of the SSTI-B (Figure 18 and Figure 19) is not exactly at the same level as the SSTI-A, which might be due to the different mounting in-between the top wing of the satellite. In general, however, both SSTI perform well.

Figure 21 shows the consequence of the slight degradation in the SSTI data quality. The percentage of missing kinematic positions in the PSO product also increased during the last two months of the nominal mission phase. The outliers in May 2009, February 2010, and January 2011 occurred, because for these days the data are not completely available due to satellite problems.



Figure 21: Percentage of missing kinematic positions in the PSO product

The reduced-dynamic orbit computations include the estimation of so-called empirical accelerations, which to a good approximation should reflect the non-gravitational accelerations, which remain after the Drag-Free Control (DFC). These empirical accelerations have been used to assess the consistency of the orbit computations by comparing them with the common-mode accelerations (and thus implicitly validate the working of part of the gradiometer as well). An example of such a comparison is displayed in Figure 22 for a day with changing ion thrust levels.



Modified Julian Date since 54996.75 (days)

**Figure 22:** Comparison between empirical accelerations obtained from the RSO reduced-dynamic precise orbit determination (POD) and those observed by the gradiometer ("common-mode"). A mean offset between these two has been removed.

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#### Orbit Comparisons

Figure 23 (top) shows the daily RMS of the precise reduced-dynamic (PRD) vs. precise kinematic (PKI) orbits for the three components and for 3D.

As the number of  $L_2$ -tracking losses increases during the mission, the numbers of larger outliers in the kinematic orbits increases as well and affects the daily RMS too. Figure 23 (bottom) displays the daily RMS if orbit differences (3D) larger than 50 cm are eliminated.



Figure 23: Orbit comparison between Precise Reduced-Dynamic (PRD) and Kinematic (PKI) orbit solutions

Table 5 shows the mean values for the RMS for both cases and all components.

Similarly, Figure 24 shows the differences for the rapid kinematic (RKI) and reduced-dynamic (RRD) orbits without (top) and with (bottom) outlier removal.

The large differences at the beginning of the mission are due to the fact, that the processing of the rapid science orbits had to be tuned during the GOCE commissioning phase. Removing outliers larger than 50 cm reduces the mean of the daily RMS significantly, as Table 6 shows.

Table 5: Mean of daily RMS values of PRD and PKI orbit differences (mm)

PRD vs. PKI	Radial	Along-track	Cross-track	3D
Mean RMS	54.7	26.1	27.2	71.6
Mean RMS (outliers removed)	15.4	10.2	9.0	20.7



Figure 24: Orbit comparison between Rapid Reduced-Dynamic (RRD) and Kinematic (RKI) orbit solutions.

Table 6: Mean of daily RMS values of RRD and RKI orbit differences (mm)

RRD vs. RKI	Radial	Along-track	Cross-track	3D
Mean RMS	90.4	110.2	77.8	168.8
Mean RMS (outliers removed)	57.0	56.3	60.7	101.9

Comparing the reduced-dynamic orbits of the precise science and the rapid science orbits, the differences between outlier removal on and off are mainly at the beginning of the mission, as Figure 25 shows.

The mean RMS of these orbit difference are clearly below the requirements of 50 cm (1D) as Table 7 shows.

Figure 26 shows the SLR residuals for the precise reduced-dynamic orbits. Here it has to be mentioned, that some tracking stations were not used, since they show a larger noise level than the other tracking stations. Also all SLR residuals larger than 20 cm were removed.

Table 7: Mean of daily RMS values of PRD and RRD orbit differences (mm)

PRD vs. RRD	Radial	Along-track	Cross-track	3D
Mean RMS	41.4	77.9	56.0	114.2
Mean RMS (outliers removed)	34.0	42.8	54.4	78.7



Figure 25: Orbit comparison between Precise Reduced-Dynamic (PRD) and Rapid Reduced-Dynamic (RRD) orbit solutions



Figure 26: Comparison with observed Satellite Laser Range (SLR) observations and predicted by the PRD orbit solution

The SLR stations that have been eliminated are listed in Table 8. For all 4 orbit types, the mean value, standard deviation and RMS for the SLR residuals are given in Table 9.

Table 8: Edited SLR stations

1824	Golosilv	1873	Simeiz	1884	Riga	1893	Katzively
7237	Changchun	7249	Beijing	7358	Tanegashima	7403	Arequipa
7406	San Juan	7821	Shanghai				



Orbit type	Mean	RMS-about-	RMS
		mean	
PRD	2.12	15.14	15.29
PKI	1.97	18.47	18.58
RRD	6.98	37.66	38.30
RKI	1.18	42.94	42.96

Table 9: RMS of fit of SLR observations for PSO and RSO orbit products (mm)

#### Summary

The RSO and PSO chains have produced orbit products that nominally meet all latency and precision requirements:

- The latency for the RSO product is typically below 12 hr (requirement is 24 hr);
- The precision of the RSO orbit solutions is typically better than 10 cm 3D (requirement is 50 cm 1D);
- The precision of the PSO orbit solutions is typically around 2 cm 3D with a latency of 1-2 weeks (consistent with the requirements).

In addition, the RSO and PSO chains have supported the Level 1b production by checking and validating products coming from the SSTI and gradiometer. Also, the working of the SSTI-A and SSTI-B is continuously being monitored and assessed, revealing for example many aspects related to the behavior at the  $L_2$  frequency. This monitoring supports the quality assessment of the orbit products, which is important for properly incorporating these products in the gravity field recoveries. Moreover, the PSO chain provides orbit predictions to the ILRS, which results in a higher volume of SLR tracking observations, needed for an independent quality check of the orbit solutions.





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# 5. DIRECT APPROACH GOCE MODELS

### The Direct Numerical Approach

Gravity field modeling using the direct approach is based on the least-squares solution of the inverse problem. The partial derivatives of the spherical harmonic coefficients to be adjusted are computed and normal equations are generated. The data are processed in individual 24-h batches (i.e. daily arcs) and directly taken at the epochs and positions of measurement for the generation of observation equations and normal matrices. (That's why the approach is called "direct"). The daily normal equations are then stacked for specific periods and the resulting normal matrix is inverted using Cholesky decomposition. Three gravity field models have been constructed by means of the direct numerical approach. Successive models were fitted with more and more GOCE data (2, 6.7 and 12 months, respectively), but the solution strategies were changed simultaneously. The impact of the accumulation of GOCE data on model accuracy can therefore not be evaluated with these models. The processing procedure can be summarized as follows:

- 1a Compute Satellite-to-Satellite Tracking (SST) daily normal equations;
- 1b Compute Satellite Gravity Gradiometry (SGG) daily normal equations individually for each component;
- 2 Accumulation of the SGG and SST normal matrices by applying a dedicated weighting scheme;
- 3 Compute a regularized solution;
- 4 Evaluate solution accuracy internally.

The following sections give the descriptions of the three models obtained with the direct numerical approach.

### **Release 1 DIR Model**

The first model was constructed with cycle 1 of the GOCE mission data (1 November 2009 - 10 January 2010) taking prior gravity field information into account and developed to degree and order (d/o) 240. The background model EIGEN-51C was used (Bruinsma et al. 2010), which model is complete to d/o 360 and is based on 6 years of GRACE data and the DNSC08 global gravity anomaly data set (Andersen et al. 2009). Therefore, the first GOCE model obtained via the direct approach must be considered a combined model also, as will become clear in the following.

The SST and SGG data were processed separately:

- The GPS SST observations were in fact not directly used, but substituted by using the orbit positions of the reduced-dynamic precise science orbit (SST\_PRD). The SST data were processed in daily arcs using an iterative least-squares orbit adjustment followed by normal equation computation in a consecutive step.
- The orbit positions were used to geo-locate the gravity gradients, defined in the Gradiometer Reference Frame, and separate normal equations for each of the diagonal components were then computed directly from the filtered observation equations in a single step.

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After accumulating the SST and SGG normal matrices applying specific weights, a regularized solution was computed. Regularization of the gravity field solution is necessary due to the GOCE polar gaps. In the context of the direct approach this is achieved by using the spherical cap regularization (Metzler and Pail, 2005), in which method an external, non-GOCE gravity field model is given as an analytical continuous function over the North and South polar caps to fill the polar gaps in the GOCE data.

The spherical cap regularizing normal system was created using the combined gravity field model EIGEN-51C up to degree/order 240, and as a consequence of the strong constraint the low (2-120) as well as the high (200-240) degrees of the GOCE model are in fact very close to EIGEN-51C. This explains the very good performance of this first model over the oceans at the resolution of 100 km (d/o 200), which is thus in large part thanks to the surface data ingested in EIGEN-51C. Figure 27 shows this effect by comparing the release 1 models to EGM2008.



Figure 27: Geoid height differences of the first release of the models DIR, TIM and SPW, and EGM2008

#### **Release 2 DIR Model**

The second model was constructed with 6.7 months of GOCE mission data (SST and SGG) in the interval 1 November 2009 – 30 June 2010 and also developed to d/o 240. It was decided for this second model and all further direct approach GOCE models to use satellite-only models as prior gravity field information to exclude any indirect assimilation of altimetry and terrestrial gravity data: As background model as well as for the spherical cap regularization the GRACE-only model ITG-Grace2010s was used, which is complete to degree/order 180 and is based on 7 years of GRACE data. Since the maximum resolution of the background model is less high, the spherical cap regularization is achieved in an iterative procedure using ITG-Grace2010S to d/o 150 and zero coefficients to d/o 240 in the first iteration. The further iterations were done in such a way that the last obtained stabilized gravity field model was taken over the polar caps to stabilize the GOCE normal equations again. Three iterations were

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necessary to reach convergence. The stabilizing normal equation of the last iteration step was composed from ITG-GRACE2010S to d/o 150, the previous solution from d/o 151 to 205 and zero coefficients to d/o 240.

The second model compares less good to surface data than the first because of the strong regularization applied to EIGEN-51C in the latter, which is clearly visible in Figure 28. Differences for ITG-Grace2010s are also shown in order to show the impact of the GOCE data especially above degree 140. The importance and the effect of regularization are demonstrated in Figure 29 by comparing to the reference model EGM2008. The left frame presents very large differences between EGM2008 and the free solution, and this ill-conditioned problem due to the polar gap clearly requires regularization. The right frame of Figure 3 shows the differences when spherical cap regularization has been applied.



**Figure 28:** Geoid height differences of ITG-Grace2010s, the three releases of the direct solution (EGM-DIR-1/2/3), and EGM-2008



Figure 29: Geoid differences between EGM2008 and the free (left) and spherical cap regularized (right) solutions

#### **Release 3 DIR Model**

The third release was constructed with 12 months of GOCE SGG data in the time interval 1 November 2009 – 14 April 2011 and 7 years of GRACE and LAGEOS data. This model, developed to d/o 240, is thus the result of solving combined satellite normal equations instead of using a prior gravity field model as a constraint. Spherical cap regularization still has to be applied, which is done in an iterative procedure using a satellite-only model from the same LAGEOS and GRACE data to d/o 130 and zero coefficients to d/o 240 in the first iteration. After two iterations convergence was reached. Additionally the polar cap stabilization was complemented by a global regularization that was applied from degrees 201-240 in the form of a regular Kaula constraint.

The third release still compares less well to surface data than the first due to the strong regularization applied to EIGEN-51C in the latter, but the gain in accuracy for degrees 2-100 thanks to the GRACE data is large. This is shown in Figure 29 and Figure 30. Differences for ITG-Grace2010s are also shown in order to demonstrate the impact of the GOCE data especially above degree 140, as well as the quality of the third release below degree 140. The estimated cumulated error at degree 200 (not calibrated) is 3.5 cm for the EGM-DIR-3.





**Figure 30:** Cumulated geoid height differences of ITG-Grace2010s, the three releases of the direct solution (EGM-DIR-1/2/3), and EGM-2008. The formal cumulated errors are also displayed for the first (EGM-DIR-1) and third model (EGM-DIR-3).





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# 6. TIME-WISE APPROACH GOCE MODELS

So far, 3 time-wise gravity field models have been computed. Table 10 shows the key characteristics of these models.

Madal	al Max. Data pariod		# epochs	Gradiometry	Accuracy	at D/O 200
Model	deg.	Date periou	(in mio.)	components	N [cm]	∆g [mGal[
TIM_R1	224	01/11/2009 - 11/01/2010	6.2	$V_{XX}, V_{YY}, V_{ZZ}$	10.0	3.0
TIM_R2	250	01/11/2009 - 05/07/2010	19.5	$V_{XX}, V_{YY}, V_{ZZ}$	6.1	1.8
TIM_R3	250	01/11/2009 - 17/04/2011	31.3	$V_{XX}, V_{YY}, V_{ZZ}, V_{XZ}$	4.6	1.35

Table 10: Key characteristics of the 3 GOCE TIM gravity field models

The time-wise approach is a least squares solution using full normal equations for GPSsatellite to satellite tracking (SST) and satellite gravity gradiometry (SGG). The full SST normal equations are set up complete to degree/order 100, based on precise kinematic orbits (SST\_PKI) applying the energy balance approach. Co-variance information of kinematic orbits (SST\_PCV) is used as stochastic observation model. Concerning SGG, full normal equation complete to degree/order 224 (release 1) or 250 (releases 2 and 3) based on gravity gradients defined in the Gradiometer Reference Frame (GRF) have been assembled. The R3 model contains also the off-diagonal component  $V_{XZ}$ , which has a relative contribution of 2-3%.

A key element of the TIM processing strategy is the correct stochastic modelling of the gradiometer errors. Digital recursive filters of ARMA type are used to set-up the variance/co-variance information of the gradient observations. Technically, this is done by applying these filters to the full observation equation, i.e., both to the observations and the columns of the design matrix. Thus, the gradiometer error information is introduced as the metric of the normal equation system. Correspondingly, the full spectral range of the gravity gradients enters the gravity field solution, but they are properly weighted according to their spectral behaviour.

The gradiometer error behaviour turned out to change slightly with time. Therefore, individual filter models are fit to data sub-segments, which are shown in different colors for TIM R3 in Figure 31 (bottom). Figure 31 (top) displays the ARMA filters for the V<sub>ZZ</sub> component used for building the metric of the normal equations for these 17 sub-segments, showing variations mainly below and in the lower measurement bandwidth.



Figure 31: Stochastic model for  $V_{ZZ}$  component

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Kaula regularization towards a zero model has been applied for near-zonal coefficients (related to the polar gap), and for degrees > 180 (for release 2 and 3; degrees >170 for release 1) to improve the signal-to-noise ratio. Optimum relative weighting factors and regularization parameters have been determined by variance component estimation. The solution is processed applying a parallelized Cholesky reduction. In addition to the resulting gravity field coefficients, corresponding error information in terms of a full variance/co-variance matrix (VCM) is part of the solutions.

The key philosophy of the TIM processing is to produce a GOCE-only model in a rigorous sense, i.e., no external gravity field information has been used, neither as reference model, nor for constraining the solution. Correspondingly, the SST part is based only on geometric GPS observations (kinematic orbits). The general processing strategy has remained practically unchanged for all 3 releases of time-wise models. This provides the opportunity to evaluate the gain achieved by GOCE when including more and more data.

Figure 32 shows the formal errors of the three solutions in terms of degree medians. The improvements are according to the Gaussian  $\sqrt{N}$  rule of uncorrelated observations, i.e. the gain from TIM\_R1 to TIM\_R2, which contains the threefold data volume, is about  $\sqrt{3}$ , and the further improvement of TIM\_R3 w.r.t. TIM\_R2 is almost  $\sqrt{2}$ .

Rigorous co-variance propagation was applied to the VCMs of all 3 releases to propagate the coefficient errors to geoid height errors on a global grid. Figure 33 shows the specific error structure of this field up to degree/order 200. The zonal



Figure 32: Degree error medians

band structure with larger errors in the equatorial regions is due to the fact that a larger number of observations is measured at high latitudes, because of the meridian convergence, and thus the convergence of the satellite's ground tracks. The asymmetry with respect to the equator and larger standard deviations in the southern hemisphere result from the orbit configuration, because the average satellite altitude is higher in this region, leading to a slightly increased attenuation of the gravity field signals at satellite height. Due to the realistic stochastic modelling of all observation components these formal errors can be considered as very good estimates for the real error behaviour of the solutions.

One specific feature appears in the South of Australia for TIM\_R2 and TIM\_R3, which shows a higher error level than the surroundings. This feature is related to the fact that certain gradient observations of the  $V_{YY}$  component have been taken out from the processing, because they are partly affected by larger errors due to cross-track thermal wind effects. (These spurious tracks will be improved by several modifications in the Level 1b processing in the reprocessed GOCE products.)



It can be shown that the  $\sqrt{N}$  improvement is not only present in the formal errors, but is a real gain of the gravity field accuracy. For this purpose, gravity anomaly differences to EGM2008 up to D/O 200 are analyzed. EGM2008 is mainly based on GRACE, terrestrial gravity field data, and satellite altimetry over the oceans. Generally, with increasing GOCE release the differences become smaller in regions where high-quality terrestrial gravity field data is available, such as North America, Europe, Australia, and partly over the open oceans. Detail analyses show that in those regions again a  $\sqrt{N}$  improvement can be observed, demonstrating that the GOCE TIM solutions are not affected by significant systematic errors. In contrast, in geophysically interesting regions, such as the subduction zone in South America, the East African rift zone or the Himalaya region, where terrestrial data quality is poor, GOCE provides new and unique gravity field information.



**Figure 33:** Geoid height errors of TIM gravity field models derived by full co-variance propagation at degree/order 200: a) TIM\_R1; b) TIM\_R2; c) TIM\_R3.

Figure 34: Gravity anomaly differences to EGM2008 up to degree/order 200: a) TIM\_R1; b) TIM\_R2; c) TIM\_R3



The performance of the TIM models has also been validated by means of GPS/levelling observations in Germany (675 stations). Figure 35 shows the rms of geoid height differences at D/O 190. (The global models have been complemented by EGM2008 beyond this max. degree to reduce the omission error.) For comparison, also the results for the GRACE-only model ITG\_GRACE2010S complete to D/O 180 are shown.



Again the consistency with the GPS/levelling observations improves with the inclusion of more and more GOCE data. It has to be emphasized that the accuracy of the GPS/levelling observations itself is already in the order of 3-4 cm. A new levelling campaign in Germany has revealed that the minimum in central Germany is due to a systematic error in the former German levelling data: this inconsistency to the GOCE geoid will not appear in the future anymore. In this sense, it can be concluded that by now GOCE has achieved a global (!) accuracy level to validate terrestrial high-precision levelling campaigns.

Figure 35: Geoid height differences at 675 GPS/levelling stations in Germany: a) ITG\_GRACE2010S, b) TIM R1; c) TIM R2; d) TIM R3

Figure 36 shows the achievable accuracy of the 3 releases of TIM gravity field models in terms of cumulative geoid height errors (left) and cumulative gravity anomaly errors (right). They are a realistic estimate of the true errors of these three solutions. The numerical values at D/O 200 (= 100 km half wavelength) are also shown in Table 1. Additionally, a performance prediction for a gravity field solution including data until December 2012 is displayed in black color, assuming that there is no data loss until the end of the GOCE extended mission phase. While for gravity anomalies the GOCE mission specification of 1 mGal can be clearly achieved, the specified geoid height accuracy of 2 cm will not be reached even by end of 2012.

Since the time-wise gravity field solutions are completely independent of any gravity field information other than GOCE, they can be used for an *independent* comparison with other satellite-only models (such as those derived from GRACE), terrestrial gravity data or satellite altimetry, and the added value compared to any existing gravity field data or (combined) gravity field models can be evaluated. They can also be used for a *consistent* combination with complementary gravity field information (GRACE, terrestrial data, satellite altimetry) on the level of normal equations. Since in the low degrees the time-wise solutions are based



solely on kinematic GOCE orbits, but no external (GRACE) information, they are not competitive with GRACE models in the low degrees.



**Figure 36:** Cumulative geoid height accuracy (left) and gravity field accuracy (right) for the three releases of TIM gravity field models and a performance prediction for the extended mission period





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# 7. SPACE-WISE APPROACH GOCE MODELS

### **Introduction**

Within the nominal operational phase of GOCE, three gravity models have been computed as GOCE Level 2 Products by applying the space-wise approach to GOCE data corresponding to longer and longer observation periods, while the life-time of the mission increased. The first two models have been made available by ESA to users for science applications.

The main idea behind the space-wise approach is to estimate the spherical harmonic coefficients of the geo-potential model by exploiting the spatial correlation of the Earth gravity field. To this purpose a collocation solution has been devised, modeling the signal covariance as a function of spatial distance and not of time distance, as it happens for the noise covariance. In this way, data which are close in space but far in time can be filtered together, thus overcoming the problems related to the strong time correlation of the observation noise.

A unique collocation solution, although theoretically clean and desirable, is computationally unfeasible due to the huge amount of data downloaded from GOCE. For this reason, the space-wise approach is actually implemented as a multi-step collocation procedure, basically consisting of a filter along the orbit to reduce the highly time correlated noise of the gradiometer, a spherical grid interpolation at mean satellite altitude and finally a harmonic analysis procedure by integration for the computation of the geo-potential coefficients. The whole procedure is iterated till convergence.

The resulting strategy is quite complicated, therefore an exact error covariance propagation is not feasible. As a consequence, the error covariance matrix of the estimated coefficients is derived by using Monte Carlo techniques.

### Data Used and Produced in the Space-wise Approach

Herewith a list of the used input data (with the corresponding product name) is provided in order to clarify the starting point of the space-wise models computation:

- common mode accelerations (EGG\_CCD\_2C) measured by the on board gradiometer, to be used in the energy conservation approach to model the loss of energy due to non gravitational forces acting on the satellite;
- the satellite attitude quaternions (EGG\_IAQ\_2C) and the gravity gradients (EGG\_GGT\_2C and EGG\_NOM\_2) measured by the on board gradiometer;
- kinematic satellite orbits (SST\_PKI\_2I) and the corresponding error estimates (SST\_PCV\_2I) used for the determination of the SST-only solution; this was decided because reduced dynamic orbits, although more accurate, are strongly affected by the prior model used for their computation;
- reduced dynamic orbits (SST\_PRD\_2I) mainly used for geo-locating gravity gradients, but also as a reference for data gap filling and outlier correction in the kinematic orbits; rotation quaternions between inertial and Earth-fixed reference frames (SST\_PRM\_2I); Earth rotation parameters (AUX\_IERS), Sun, Moon and planetary ephemerides (AUX\_EPH) and spherical harmonic coefficients from the



ocean tide model FES2004 (ANC\_TID\_2I) used for modeling tides in the energy conservation approach;

- the GOCE Quick-look model (EGM\_QCO\_2I) was used as prior model only for the first release;
- other gravity field models, in particular EGM2008, EIGEN\_5C and ITG\_GRACE2010 (ANC\_ICGEM) are used as reference models, for internal comparisons or to derive degree variances, meaning that their coefficients do not directly enter in the solution.

The data periods on which the computation of the three space-wise models were based are as follows:

- from 30 October 2009 to 11 January 2010, corresponding to about 73 days of data;
- from 30 October 2009 to 6 July 2010, corresponding to about 6 months of data;
- from 30 October 2009 to 14 April 2011, corresponding to about 1 year of data.

As for the output data, they are always represented by the set of estimated spherical harmonic coefficients of the geo-potential model (EGM\_SPW\_2I) and the corresponding full error covariance matrix (EGM\_SVC\_2I).

#### **Preprocessing**

It is most evident that the quality of the final gravity field solution also depends on the capability to detect and correct outliers and data gaps.

Remaining in the spirit of the space-wise approach, outliers and data gaps are replaced with values estimated by collocation after removing a certain reference signal (e.g. reduced dynamic orbits for repairing kinematic orbits) to make the residuals as much stationary as possible. In particular, available data before and after the data gap (or the outlier) are used to estimate an empirical covariance function that is then used to predict values in the gap by collocation. However, residuals sometimes present a long period behaviour that cannot be predicted by a local collocation around the gap; for this reason, a cubic spline interpolation is used to remove these long period biases.



**Figure 37:** Cubic spline interpolation (in red) around the gap. Data (in blue) are differences between kinematic and reduced dynamic orbits.



**Figure 38:** Collocation prediction (in green) inside the gap after removing spline interpolation (in red). Data (in blue) are differences between kinematic and reduced dynamic orbits.



Finally it has to be stressed that the replaced values are only used in the time-wise steps (e.g. the Wiener filter along the orbit) when it is useful to have a continuous flow of data. In the core of the space-wise approach, i.e. in the gridding procedure by collocation, the interpolated values are not used, because the gridding procedure does not require that the input data are regularly sampled in time. This is an advantage of the space-wise philosophy.

#### SST Data Analysis

The low frequency part of the gravity field is estimated from satellite tracking data and then it will be used to reduce the long period signal when dealing with gravity gradients. The implemented procedure basically consists of three steps:

- estimate of the gravitational potential along the orbit by applying energy conservation;
- gridding of the potential on a sphere at mean satellite altitude by applying collocation;
- recovery of the spherical harmonic coefficients from the gridded data by numerical integration.

Error estimation at each step is implemented by Monte Carlo methods.

#### <u>SST + SGG Data Analysis</u>

The space-wise solution is computed according to the iterative scheme reported in the figure below. Basically the signal long wavelengths are removed by exploiting the low degrees of the estimated SST model, while the high variance and the long time correlation of the gradiometer noise are reduced by applying a Wiener filter along the orbit. In this way gridded values on a sphere at mean satellite altitude can be reasonably computed by applying collocation to local patches of data, making the solution feasible from the computational point of view. Starting from the gridded values, spherical harmonic coefficients are derived by numerical integration. The procedure is iterated by synthesizing observables along the orbit from the estimated coefficients in order to recover the signal cancelled out by the Wiener filter (by means of the so called complementary Wiener filter) and to correct the data rotation from GRF to LORF. It can be shown that the whole iterative procedure, apart from the numerical approximations due the local gridding, is equivalent to a unique and direct collocation from original data to spherical harmonic coefficients.



Figure 39: The space-wise iterative scheme

#### **Release 1 of the Space-wise Model**

The first release computed by the space-wise approach is based on the first two months of data delivered by GOCE; the relatively small amount of data made it possible to process them as a unique dataset.

The standard scheme as described in the previous section was implemented, including the use of a prior model, which is required for the gridding in a standard remove-restore procedure.

In particular, in the first release the chosen prior model was the Quick-look model delivered by HPF for the considered time period. Actually, it must be remarked that this model is not entirely a GOCE-only model since in it both reduced dynamic orbits and polar gaps regularization come from EIGEN5C. Therefore the resulting space-wise model inherited this external information and cannot be considered pure "GOCE- only" at low degrees and at low orders for any degree. In addition, EGM08 was used to modify the estimated potential along the orbit so to reduce its error at very low frequency, e.g. spikes in the empirical error power spectrum.

The error std for the estimated coefficients are based on Monte Carlo simulations and for the first release 400 samples were used.

#### Release 2 of the Space-wise Model

The main feature of the second release is represented by the removal of the dependencies on data not provided by the GOCE mission, in order to produce a GOCE-only model.



Besides, other two features have been incorporated in the space-wise scheme, namely: a semiautomatic pre-processing of the data to detect and repair outliers, data gaps, etc. and a combination method to merge space-wise solutions based on data covering different time periods. In fact, the analyzed dataset covers a time period of eight months, which is definitely a too large amount of data to be processed as a whole. In particular, the full dataset has been divided into five subsets of different length as shown in the figure below.



Figure 40: Subsets of data used for the second release of the space-wise model:in grey, discarded subsets of data; in green, subsets of data used in the model computation

The standard space-wise approach scheme was applied to each data subset, obtaining different solutions (i.e. data grids and spherical harmonic coefficients). Then the intermediate grids were merged together by weighting them according to their error covariance so to obtain a unique and final estimate of the gravity field model.

For the second release again 400 samples were used for the Monte Carlo simulations.

#### **Release 3 of the Space-wise Model**

The same processing strategy used for the second release was implemented for the computation of the third model; the amount of data covered a larger time span (about one year and a half).

However, the improvement of this solution with respect to the second release turned out to be lower than expected, especially at high degrees where over-regularization is applied. This is due to the fact that degree variances are used to model the residual signal in the collocation gridding, while a better modeling based on the available Monte Carlo samples could and will be implemented.

For the third model 500 samples were used for the Monte Carlo simulations.



Figure 41: Subsets of data used for the third release of the space-wise model: in grey, discarded subsets of data; in green, subsets of data used in the model computation.

A comparison between the Trr grid at mean satellite altitude estimated within the third model computation and the corresponding one generated from EGM08 is reported in the figure below. What can be seen is that the model shows deviations in regions where terrestrial gravity data included in EGM2008 are known to be of low quality.





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Finally, the last figures show:

- the empirical error degree variances for the three space-wise models;
- the coefficient error standard deviations for each computed space-wise model.



**Figure 43:** Empirical error degree variances for the three space-wise models, computed as differences from EGM08.





Figure 45: Coefficient error std of the space-wise model, release 2



Figure 46: Coefficient error std of the space-wise model, release 3





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# 8. GOCE GRAVITY FIELD MODELS PERFORMANCE

The global gravity field models resulting from the level 2 processing generally are validated by three methods. These are:

- (1) Orbit fits and altimeter crossover residuals applying different gravity field models. This mainly investigates the performance of the low degree and order coefficients of the gravity field models as well as resonance orders for specific orbit configurations.
- (2) Error estimates from the least squares solutions based on the full variance/co-variance matrices. Variance/co-variance matrices provide valuable information about the internal quality estimates of a gravity field model. It is an important to identify to what extent these estimated errors are realistic.
- (3) Signal content and comparison of independent gravity field information with those computed from the global models in order to identify the external accuracy. In principle any observed gravity field quantity, which has not been used in the global models can be used for this purpose. It turned out that one of the best data sets to be applied for estimating the external accuracy are GPS/Levelling derived geoid heights.

In the following a selection of results of the three validation methods is shown. For the methods applied it is referred to Gruber et al (2011), where a complete description is provided.

#### Orbit Fits and Altimeter Crossovers

The quality of all the GOCE gravity field models has been assessed by orbit computations for a selected number of satellites flying at low to medium altitudes from about 450 to 6000 km. The EIGEN-5 models serve as reference (Förste et al, 2008). These satellites are ERS-2, CHAMP, GRACE-A/B, and LAGEOS-1/2. By this selection, the quality of the GOCE models for different wavelength domains can be assessed. In addition, orbit tests have been done for GOCE itself, which can be considered as a consistency test. For more details about the selected data, orbit computation methods, etc., is referred to Gruber et al (2011).

Selected results are displayed in Table 11 to Table 13, Figure 47 and Figure 48. All the GOCE models do not meet the performance of the pre-launch EIGEN-5 models for the selected satellites. Only for GOCE, the Space-Wise (SPW) models lead to improved orbital fits (Table 12), which is an indication that these models absorb GOCE orbital resonances that are not properly represented by the prelaunch models. Probably, a worse performance of the GOCE models in terms of orbit computations is caused by (small) pollution of long-wavelength coefficients by GOCE orbital resonances for which possibly higher degree and order coefficients need to be estimated.

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 Table 11: RMS-of-fit of ERS-2 tracking observations (grey: pre-launch, yellow: combination of GOCE, GRACE and terrestrial data, brown: combination of GOCE and GRACE data, blue: GOCE only).

Model	SLR [cm]	PRARE RNG [cm]	PRARE RR [cm/s]	SXO [cm]	DXO [cm]
EIGEN-5C	4.3	4.1	0.25	6.7	6.9
DIR1	4.3	4.2	0.25	6.8	6.9
DIR2	4.5	4.3	0.26	7.1	7.3
DIR3	4.2	4.0	0.25	6.8	7.0
SPW1	4.4	4.2	0.25	6.8	6.9
SPW2	4.3	4.1	0.25	6.9	7.0
SPW3	4.4	4.1	0.25	6.9	7.0
TIM1	5.0	4.6	0.28	7.3	7.4
TIM2	4.5	4.3	0.26	7.1	7.3
TIM3	4.5	4.2	0.26	7.0	7.3

Table 12:	RMS-of-fit of GOCE orbits (colours: see
	Table 11)

Model	X [cm]	Y [cm]	Z [cm]
EIGEN-5S	10.6	11.8	15.7
DIR1	8.7	9.6	11.7
DIR2	8.2	9.5	11.9
DIR3	9.1	10.3	12.4
SPW1	11.2	12.2	15.1
SPW2	17.8	18.2	18.8
SPW3	14.3	15.5	16.4
TIM1	14.7	15.7	18.7
TIM2	12.8	14.5	17.2
TIM3	12.4	12.5	15.4

Table 13:	RMS-of-fit of GRACE-A orbits (colours:
	see Table 11).

Model	X [cm]	Y [cm]	Z [cm]
EIGEN-5S	4.9	3.8	4.8
DIR1	6.7	5.3	6.4
DIR2	7.0	4.7	6.5
DIR3	6.0	4.9	5.5
SPW1	10.3	6.1	7.1
SPW2	89.8	60.4	61.1
SPW3	145.7	88.4	99.6
TIM1	78.4	86.0	48.2
TIM2	126.3	83.3	89.5
TIM3	27.1	20.2	18.8



### Geographical Anti-Correlated Orbit Error

Mean of ERS-2 singe-satellite altimeter crossover residuals averaged in 2°x2° bins [cm].



RMS [cm] of geographically averaged ERS-2 single-altimeter crossover residuals (SXO).

Model	EIGEN-5S	DIR1	DIR2	DIR3	SPW1	SPW2	SPW3	TIM1	TIM2	TIM3
SXO	2.1	2.5	2.3	2.2	2.2	3.0	2.9	3.3	3.1	3.0

Figure 47: Estimate of ERS-2 radial orbit error (ascending minus descending orbital tracks) for 1996 (colours: see Table 11)

#### Geographical Correlated Orbit Error

Mean of ERS-2/TOPEX dual-sat. altimeter crossover resid. averaged in 2°x2° bins [cm]



RMS [cm] of geographically averaged ERS-2 dual-altimeter crossover residuals (DXO).

Model	EIGEN-5S	DIR1	DIR2	DIR3	SPW1	SPW2	SPW3	TIM1	TIM2	TIM3
DXO	1.9	1.9	2.3	2.4	1.9	2.3	2.4	2.9	2.9	3.0

Figure 48: Estimate of mean ERS-2 radial orbit error for 1996 (colours: see Table 11).

#### Variance/Co-variance Error Estimates

All GOCE gravity field models as summarized in

Table 1 are delivered with their full variance/co-variance matrices describing the error structures of the resulting spherical harmonic coefficients. This is unique for GOCE because usually such information is not made available to the users. Variances and specifically co-variances of the coefficients provide valuable information about the estimated errors from the least squares solution and about correlations between these coefficients. Correlations indicate



to what extent individual coefficients can be estimated independently, which reflects how good the set of observations is suited to determine an individual coefficient. In the following a few results for the estimated and propagated errors are shown. It shall be mentioned already at this point that estimated errors not always represent realistic errors. This depends a lot on the data preparation and weighting. For this reason in addition to internal error estimates also absolute errors shall be determined. This will be addressed in the next sub-section.

Figure 49 shows the estimated errors for the two most recent and most accurate GOCE based gravity field models DIR3 and TIM3 (see explanations provided in

Table 1). Comparing both solutions immediately exhibit some basic differences between both models. First, the error structures differ significantly for the low degree and zonal/near zonal (order zero and close to order zero) coefficients. The reason for this is the inclusion of additional information from the GRACE mission in the DIR3 model (in terms of normal equations). On one hand the GRACE measurement system provides much more accurate information for the lower degree coefficients and on the other hand GRACE flies in a polar orbit covering the complete Earth. For the latter reason errors in the zonal/near zonal coefficients can be drastically reduced, while the error structure becomes much more homogeneous because of the first reason. In contrast, the TIM3 model is purely based on GOCE information. Lower degree coefficients are determined from the kinematic orbit in a satellite-to-satellite high-low tracking mode, while medium to high degree terms are solely based on gradiometer information. Apart from the problem in the zonals and near zonals (due to the polar gap of the GOCE orbit) the general error structure is quite homogeneous and as expected. As a third observation one can identify that the error level of the DIR3 model is significantly lower than the one of the TIM3 model. The reason for this could be twofold. Either the level of GOCE observation errors was chosen smaller than for the TIM3 model or the GRACE normal equations applied in the DIR3 model significantly improved the internal accuracy of the estimated coefficients.



Figure 49: Estimated standard deviations of spherical harmonic coefficients for the DIR3 model (left) and the TIM3 model (right), both based on 1 year of GOCE data. Both figures show log10 of the coefficient errors. Negative x-axis values represent sine coefficients of order m ( $S_{nm}$ ), positive x-axis values represent cosine coefficients of order m ( $C_{nm}$ ).

Another option to quantify the error level of a global gravity field model is by computing so called cumulative error degree variances. They are computed by the sum of all coefficient variances up to a specific degree. By computing the square root and converting them into geoid heights one can identify the mean geoid error over the globe when truncating the



spherical harmonic series at a specific degree. Figure 50 shows the cumulative geoid errors for all GOCE models computed by HPF.



Figure 50: Cumulative error degree variances (square root) in terms of geoid heights for all HPF GOCE models.

From Figure 50 one can draw the following conclusions. For the TIM and DIR GOCE gravity field model series a steady improvement with the inclusion of more GOCE data can be identified. For the SPW3 model there is still some uncertainty in the error estimates, which led to the decision not to distribute this model to the user community. In general this behavior is very positive as it shows, that by adding more data the error level indeed can be reduced and that the quality of the GOCE gravity gradients in general is stable. As a second observation one can identify the mean geoid error e.g. at degree 200, which corresponds to a spatial resolution of about 100 km. Here the TIM3 model delivers a value of about 6 cm, while the DIR3 model claims an accuracy of about 3 cm. The difference between both estimates mainly is caused by the facts already described above (inclusion of GRACE and/or data weighting). One also should note that the mean error level is influenced by the large error for the zonal/near zonal coefficients. Excluding those one could reduce the TIM3 errors to 4-5 cm (see also Figure 36).

In order to identify the spatial structure of the estimated errors a propagation of the full variance/co-variance matrix to geoid heights is performed for all models. As from a mathematical point of view it is not allowed to cut out a piece of the co-variance matrix the full matrices are used here. Figure 51 shows the geoid standard deviation maps for the DIR3 and TIM3 models. Both maps confirm the findings described above. In addition one can identify in both maps a small asymmetry with respect to the equator, which is caused by the orbit geometry, i.e. a slightly higher altitude at the Southern hemisphere compared to the Northern hemisphere. The TIM3 model show slightly increased standard deviations South of Australia, which is resulting from a down weighing of data in this region for specific arcs (see chapter 6 for more details). It shall be noted that the standard deviations in mean are much higher than the ones identified from Figure 50. The reason for this is that the complete spherical harmonic series has been used instead of a truncating it at degree and order 200 (see comment made above).



**Figure 51:** Geoid height errors (standard deviations) propagated from full variance/co-variance matrices. Left: DIR3 model up to degree/order 240, right TIM3 model up to degree/order 250 [m].

#### Signal Analysis and Validation by GPS/Levelling Geoid Heights

An interesting question is to what degree and order GOCE is sensitive to the Earth's gravity field. This can be investigated for example by computing signal degree variances showing the mean gravity signal per degree. As the real signal level per degree is not know one usually compares it to so-called degree variance models. Figure 52 shows the signal degree variances for all HPF GOCE models and the Kaula degree variance model.



**Figure 52:** Signal degree variances (square root) for HPF GOCE models and the Kaula degree variance model in terms of geoid heights. Left: complete spectrum, right: Zoom-in from degree 180 to 240.

From Figure 52 the following conclusions can be drawn. The SPW models suffer from some lack of signal for the high degrees and orders. This corresponds well to the higher error level of these models as shown in Figure 50. The DIR models behave not unique for the 3 releases. The reason is that the general processing philosophy has changed in course of the project. The most recent 3<sup>rd</sup> release model (DIR3) for the high degrees is well comparable to the TIM models as this is not based on terrestrial a-priori information (like DIR1) and constrained towards the Kaula degree variance model for the unobserved frequencies (in contrast to the DIR2 model). For the three TIM models one clearly can observe the increased signal content

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per model release. In general for both models (DIR3 and TIM3) one can assume a full signal content approximately up to degree and order 190, which corresponds to a spatial resolution of about 105 km.

In order to assess the real quality of global models geoid heights derived from the models are compared to independent geoid heights from GPS/Levelling. For this comparison a number of processing steps has to be performed per data point in order to account for the omission error and other systematic effects. For a detailed description of the procedure it is again referred to Gruber et al (2011). For testing the models we have available data sets for complete Europe, a denser data set for Germany only, Australia, Japan, Canada and the USA. Below a few representative results are shown. Figure 53 shows maps of differences for the German data set for the most recent GOCE models and the EGM2008 combined model for comparison, all truncated at degree and order 180 (compare also Figure 35 for the TIM model series). Regarding the EGM2008 model as reference, because it is heavily based on a high quality terrestrial gravity data set from Germany, one can identify that both GOCE models show very similar structures and contain nearly the full signal up to degree and order 180. Going to higher truncation degrees would deteriorate the performance of the GOCE models as sensitivity of the satellite starts to decrease. From Figure 35 one can see the significant improvements made with additional GOCE data for a truncation degree and order 190.



**Figure 53:** Geoid height differences in Germany for the DIR3 model (left), the TIM3 model (middle) and the EGM2008 model (right) [m]. All models truncated at degree and order 180. Omission error was estimated from EGM2008. RTM correction applied.

Figure 54 shows RMS values per truncation degrees (computed in steps of 10) for the two national data sets in Germany and Japan. Both are representative also for the results of the other data sets available (not shown here). For Germany (left figure) we identify significant improvements with each release of GOCE models and specifically with respect to the best available GRACE model (ITG-GRACE2010S, Mayer-Gürr et al, 2011). We also can identify from this figure that EGM2008 performs best in this area, which is caused by the incorporation of the high quality German terrestrial gravity data set (see also above). It shall be noted that EGM2008 for all degrees of truncation performs identical, because this model has also been used for estimating the omission error. In general one can regard the EGM2008 line as reference value for this kind of comparison. It also contains the errors introduced into this test by the GPS observations and specifically the spirit leveling errors.



Figure 54: RMS of geoid height differences per truncation degree for Germany (left) and Japan (right) [m].

It is very interesting to observe that the most recent GOCE models (DIR3 and TIM3) outperform EGM2008 for truncation degrees between 150 and 200 for the Japanese GPS/levelling data set (see Figure 54, right). Here we get a significant improvement compared to EGM2008, which means that GOCE delivers high quality additional information further improving the existing global models even if they incorporate terrestrial information. One can argue that in areas where bad or no terrestrial data are available with the GOCE models a dramatic improvement of the geoid is achieved. Unfortunately, for these areas no high quality test data are available.

The results shown in Figure 54 are very encouraging and we saw this kind of improvement for the first time with the 3<sup>rd</sup> release GOCE models. From the comparisons with the German GPS/leveling data, which represents the best data set available so far, one can try to quantify the external error level of the GOCE models. For degree and order 200, which represents our target resolution, we observe RMS of differences at a level of 6 to 6.5 cm for the two GOCE models (for degree 190 the differences RMS is at a level of 5–5.5 cm, for degree 180 at a level of 4.5-5cm). Taking into consideration the error level of the GPS/leveling heights, which is assumed to be at a level between 2-3 cm, there are good reasons to quantify the absolute error level of the GOCE models between 4 and 5 cm. Referring this to the results obtained from the estimated variance/co-variance matrices (see Figure 50 and related paragraph) one could assume that the estimated errors from the TIM3 model somehow represent the absolute error level, while the DIR3 estimated errors seem to be slightly too optimistic.

As a final test in addition to the absolute heights also geoid height differences between all points of a test area are computed and compared to the model derived geoid heights differences. These geoid slope differences are mapped to distance classes and RMS values per class are computed. Figure 55 shows the results for Japan for truncation degrees 180, 190 and 200 respectively. From the results obtained for truncation degree 180 and 190 we clearly can identify the superior quality of the 3tr release GOCE models versus EGM2008. Starting at truncation degree 200 the situation starts to become reverse and EGM2008 performs slightly

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better. As this kind of test is more sensitive to high frequencies of the gravity field this is a good result showing the benefit of GOCE data in global gravity field models.



**Figure 55:** RMS of geoid height slope differences for Japanese GPS/levelling data set and distance class. Omission error is estimated from EGM2008. Top left: for truncation degree 180, top right: for truncation degree 190, bottom left: for truncation degree 200. All in [m]

#### Conclusions from GOCE Gravity Field Validation

From the orbit tests we can conclude that compared to pre-launch models, all released GOCE gravity field models show a degraded performance in precise orbit determination for the selected satellites. This is expected as GOCE is not designed to observe the long wavelength gravity field with highest accuracy. For this spectral range GRACE provides significant better information. Apart from this general observation, there are indications that higher degree and order gravity field terms need to be estimated to properly take into account GOCE orbital resonances. This could improve orbit determination of other low Earth orbiting satellites, where higher order terms in their resonance bands often are neglected. As from terrestrial data resonance bands cannot be estimated properly, because of their not uniform distribution and quality over the globe, GOCE could contribute to some extent to improve them.



Regarding error estimates from the variance/co-variance estimation as well as looking to the signal structure and comparisons with independent gravity field information one generally can conclude that GOCE data provide significant new information for the medium to higher spatial resolution of the Earth's gravity field. In order to quantify the absolute accuracy one could compare the global models with high quality geoid observations obtained with the GPS/levelling technique in Germany and other countries. When analyzing these results we can conclude that the geoid accuracy is at the level of 4-5 cm at degree 200 (corresponding 100 km in the spatial domain) taking into account the error level of the GPS-levelling data. Specifically encouraging are the results obtained in Japan, where we can identify improved quality of the GOCE based models in the spectral range between degree 150 and 200 as compared to the combined gravity field model EGM2008, which includes terrestrial and altimetric information in this region. From this result one can prospect that in regions where only sparse or bad quality terrestrial data is available, GOCE is a completely new source of information providing consistent gravity field information worldwide on the level of accuracy as estimated above.





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