GOCE-ONLY GRAVITY FIELD MODEL DERIVED FROM 8 MONTHS OF GOCE DATA

Roland Pail [(1)], Helmut Goiginger[(2)], Wolf-Dieter Schuh[(3)], Eduard Höck[(4)], Jan Martin Brockmann [(3)], Thomas Fecher[(1)], Reinhard Mayrhofer[(2)], Ina Krasbutter [(3)], Torsten Mayer-Gürr[(2)]

[(1)] *TU München, Institute of Astronomical and Physical Geodesy, Arcisstraße 21, 80333 München, Germany,*
Email: pail@bv.tum.de, fecher@bv.tu-muenchen.de

[(2)] *Graz University of Technology, Institute of Theoretical Geodesy and Satellite Geodesy, Steyrergasse 30, 8010 Graz,*
Austria, Email: h.goiginger@TUGraz.at, reinhard.mayrhofer@TUGraz.at, mayer-guerr@TUGraz.at

[(3)] *University of Bonn, Institute of Geodesy and Geoinformation, Nussallee 17, 53115 Bonn, Germany,*
Email: schuh@uni-bonn.de, brockmann@geod.uni-bonn.de, krasbutter@geod.uni-bonn.de

[(4)] *Austrian Academy of Sciences, Space Research Institute, Schmiedlstraße 6, 8042 Graz, Austria*
Email: hoeck@geomatics.tu-graz.ac.at

ABSTRACT

After presentation of the first GOCE gravity field model based on 71 days of data at the ESA Living Planet Symposium in June 2010 ([11], [12]), an improved optimum high-resolution global gravity field model based on data from November 2009 to July 2010, resolved up to degree/order 250, has been derived from the precise GOCE orbit and satellite gravity gradiometry data applying the time-wise method. Realistic stochastic models for both the orbit and gradiometer observations have been included. Thus, the coefficient error information, provided as full variance-covariance matrix, reflects realistically the true error behaviour of the solution. The resulting GOCE model is assessed and validated against external gravity field models and GPS/levelling data. One of the key features of the time-wise method is that it is independent of any gravity field prior information, and thus the resulting gravity field models reflect the pure performance achievable by GOCE.

1. INTRODUCTION

The dedicated satellite gravity mission GOCE (Gravity field and steady-state Ocean Circulation Explorer; [4]), the first Earth Explorer Core Mission, in the context of ESA's Living Planet programme, strives for a high-accuracy, high-resolution global model of the Earth's static gravity field. GOCE is based on a sensor fusion concept: satellite-to-satellite tracking in the high-low mode (hl-SST) using GPS, and satellite gravity gradiometry (SGG). While the low frequencies are mostly derived from hl-SST, the details of the gravity field are obtained from the analysis of SGG.

The scientific data processing (Level 1b to Level 2) is performed by the "European GOCE Gravity Consortium" (EGG-C), a consortium of 10 European university and research institutes, in the framework of the ESA-funded project "GOCE High-Level Processing Facility" (HPF; [14]). In the frame of this contract, the

"Sub-processing Facility (SPF) 6000", a co-operation of TU Graz, TU München, University of Bonn, and Austrian Academy of Sciences, is responsible for the processing of a spherical harmonic Earth's gravity model and the corresponding full variance-covariance matrix from the precise GOCE orbit and SGG data, and the production of quick-look gravity products in parallel to the GOCE mission for a fast system diagnosis.

The mathematical model for the parameterization of the Earth's gravity field is based on a series expansion of spherical harmonics. The model presented in this paper has a resolution complete to degree and order 250, which requires solving for about 63,000 unknown spherical harmonic coefficients. The determination of these coefficients from the complementary hl-SST and SGG data sets is a demanding numerical and computational task, and thus efficient solution strategies have to be applied to solve the corresponding large normal equation systems. In [9], [10], the rigorous solution of the large normal equation matrix by means of a parallel processing strategy implemented on a Linux-PC cluster was proposed, which represents the core of the time-wise method.

2. ARCHITECTURAL DESIGN

Figure 1 shows the architectural design of the time-wise method, its main components and the product flow through the SPF6000 software system. It is conceived in a highly modular manner that allows the investigation of specific aspects of gravity modelling such as filtering, numerical stability and optimum regularization, complementary relations of SST and SGG and their optimum weighting.

Apart from the Quick-Look processor, it consists of the following main components:

- *SST processor*: The information content of the SST data is exploited by making use of the precise kinematic GOCE orbit and applying the principle of
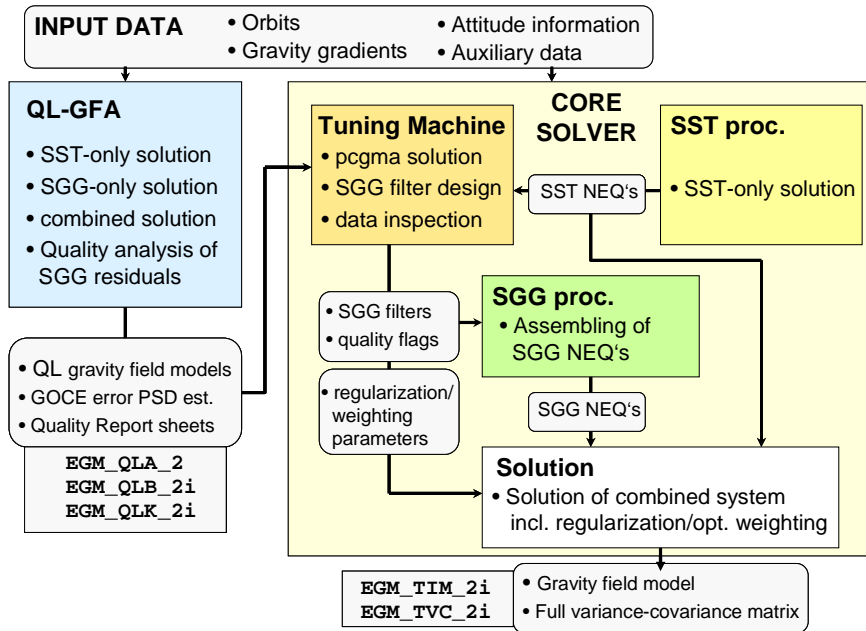
Figure 1. Software architecture and product flow

energy conservation in an inertial reference frame ([1]).

- *Tuning Machine:* It consists of the stand-alone gravity field solver applying *pcgma* (pre-conditioned conjugate gradient adjustment; [15], [2]), jointly with a data inspection and filter design tool. The Tuning Machine is used to tune the involved components of the Core Solver, e.g., to derive optimum regularization and weighting parameters.

- *Final Solver:* It is composed of the SGG processor, which assembles full normal equations applying parallel processing strategies on a Linux-PC cluster, and the Solver, which computes combined gravity models from SST and SGG by means of superposition of normal equations, applying optimum weighting of the individual data types. The solution is processed applying a parallelized Cholesky reduction. The ill-posedness of the normal equations due to the polar gaps is managed by optimized regularization techniques.

3. DATA SETS

The GOCE-only gravity field model is based on the data period from 01-11-2009 to 06-07-2010. The following key products have been used (product identifiers according to [6]):

- Orbits: SST_PSO_2I (sub-products: SST_PKI_2I [kinematic orbits], SST_PCV_2I [variance-covariance information of orbit positions])

- Gradients: EGG_NOM_2

- Attitude: EGG_IAQ_2C (corresponds to columns 56 to 59 of EGG_NOM_2; [6])

Additionally, models for temporal gravity field reduction (ephemeris of Sun and Moon, ocean tide models, correction coefficients for non-tidal temporal variation signals), and for Earth's rotation have been applied.

The gradients are processed in the original gradiometer reference frame (GRF). Thus, the base functions have to be rotated to this frame. The transformation from the Earth-fixed reference frame, in which the spherical harmonic base functions are originally computed, to the inertial frame is computed by in-house routines (i.e., the respective orbit sub-product SST_PRM is not used). As a second step, the rotation from this inertial to the target GRF is performed by using the quaternion information provided in EGG_IAQ_2C.

Figure 2 shows the timeline of the data used. The data stream is separated by data gaps into 9 segments, as indicated by the different colors in Fig. 2. In total, effectively more than 6 months of data, corresponding to about 55 million gradient observations, entered the solution.
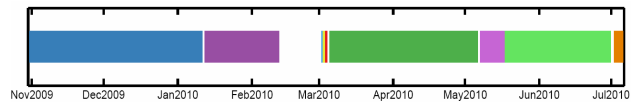

Figure 2. Overview of data stream used for release 2 of the time-wise GOCE gravity field model.

A key element of the SPF6000 processing is the correct stochastic modelling of the gradiometer errors. Digital filters are used to set-up the variance-covariance information of the gradient observations ([15], [16]). 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 behavior. Since the gradiometer error behaviour turned out to change slightly within the analysis period, individual filter models have been fit to the 9 data segment shown above. Figure 3 shows the PSD of these filter models for the V_{ZZ} component. Details on the refinement of the stochastic models for the gradiometer errors can be found in [7].
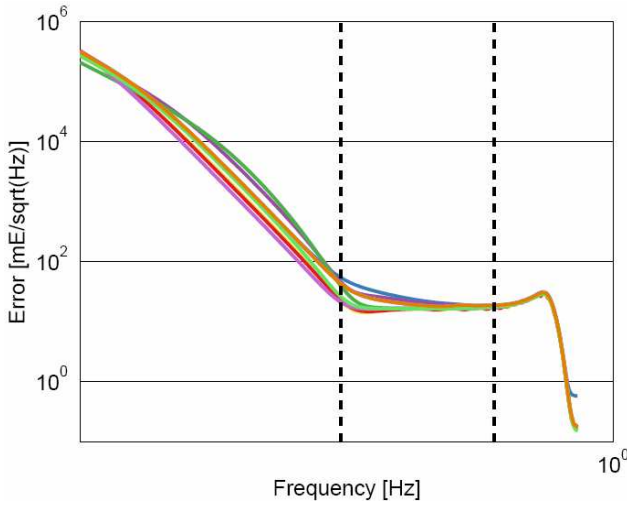
Figure 3. PSD of the ARMA filter models for the 9 data segments shown in Fig. 2, related to the gravity gradient component V_{ZZ}.

4. RESULTS

The resulting gravity field model, resolved up to degree/order 250, is based on a least squares solution using full normal equations (SST and SGG). No external gravity field information is used, neither as reference model, nor for constraining the solution. The gravity field information from kinematic orbits (SST) used for the combination has been resolved up to degree/order 100. Kaula regularization towards a zero model has been applied for (a) degrees > 180, and (b) the polar gaps. Optimum relative weights for the SST and SGG components, as well as regularization parameters have been derived by variance component estimation ([8], [3]).

Figure 4 shows the formal errors of the combined solution in terms of degree medians. The blue curve in Fig. 4 shows the significant improvement of the new model GO_CONS_GCF_2_TIM_R2 compared to the previous release 1 time-wise solution

GO_CONS_GCF_2_TIM_R1 based on about 2 months of input data (red curve). As it has to be expected, due to the increase of the data amount by a factor of about 3, the improvement is in the order of √3 over a wide spectral range. This is demonstrated by the dashed magenta curve, which shows the performance of the 2-months solution, improved by a factor of √3.
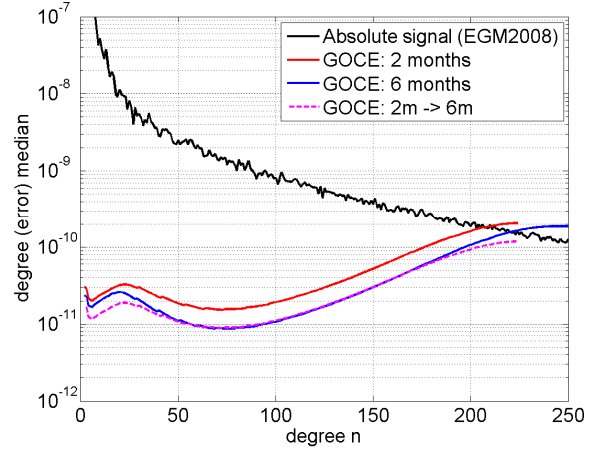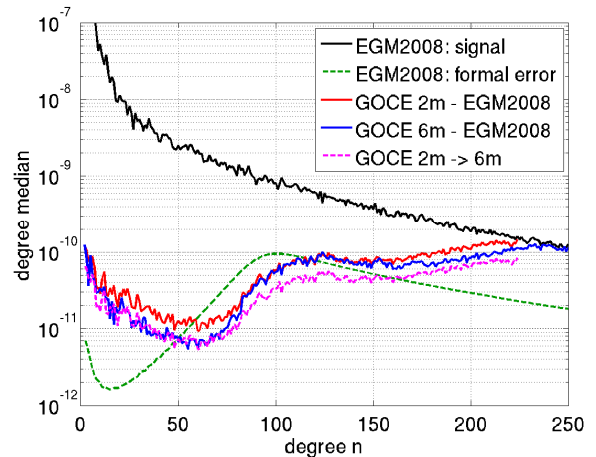

Figure 4: Degree medians of formal errors.

Figure 5: Degree medians of differences of GOCE-only solutions to EGM2008.

It can be shown that this factor of √3 is not only present in the formal errors, but is a real improvement of the gravity field accuracy. For this purpose, Fig. 5 shows the differences of the two GOCE-only solutions and the combined reference gravity field model EGM2008 ([13]). In the low degrees (< degree 80), the √3 improvement is clearly visible, because in this spectral range the reference EGM2008 solution, which is primarily based on GRACE information, can be considered to be superior to GOCE. In the spectral range between 80 and 150, EGM2008 is the dominant error source due to low-quality terrestrial data in selected areas which entered the EGM2008 model. Therefore, the differences of the two GOCE solutions w.r.t. EGM2008 are similar, because mainly EGM2008

contributes to the error budget. The characteristic bump in the degree median curve is also in agreement with the formal errors of the EGM2008 model (green dashed curve). Beyond degree 150 both GOCE and EGM2008 contribute significantly to the error budget. From this analysis it can be concluded that no significant systematic errors are present in this global gravity field solution.

The real improvement of the release 2 of the GOCE time-wise model can be illustrated even more impressively when analyzing gravity anomaly differences to EGM2008 up to degree/order 200. As a reference, Fig. 6 shows these differences for the first release based on 2 months of data, while Fig. 7 displays them for the new time-wise model, clearly showing the noise reduction over the open oceans and regions with high-quality terrestrial gravity field data incorporated in EGM2008.
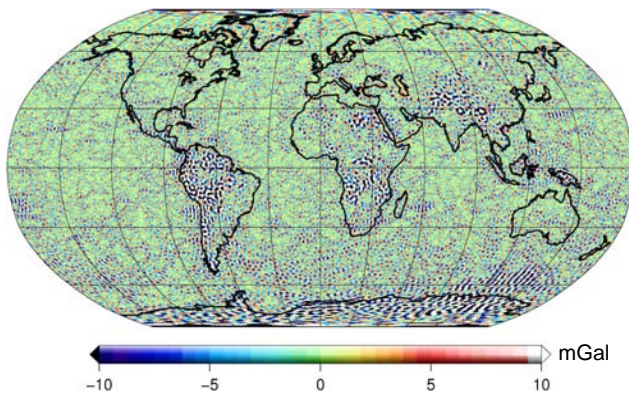

Figure 6: Gravity anomaly differences [mGal] of the first release GO_CONS_GCF_2_TIM_R1 based on about 2 months of GOCE data w.r.t. EGM2008.
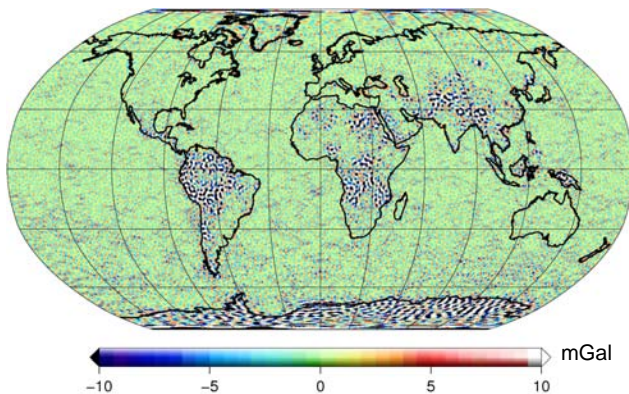

Figure 7: Gravity anomaly differences [mGal] of the second release GO_CONS_GCF_2_TIM_R2 based effectively on about 6 months of GOCE data w.r.t. EGM2008.

Figure 8 illustrates the GOCE redundancy factors of the new model. It expresses the "GOCE-onlyness" of the solution, i.e. to which extent GOCE information was used for the estimation of specific harmonic coefficients. A value of 1 (dark red color) means, that a certain coefficient is estimated only from GOCE information. It nicely shows the Kaula constraints towards a zero model affecting the zonal and near-zonal coefficients (polar gaps), and the high-degree coefficients with gradually increasing impact, starting from degree/order 180. All the other coefficients are determined solely by GOCE information.
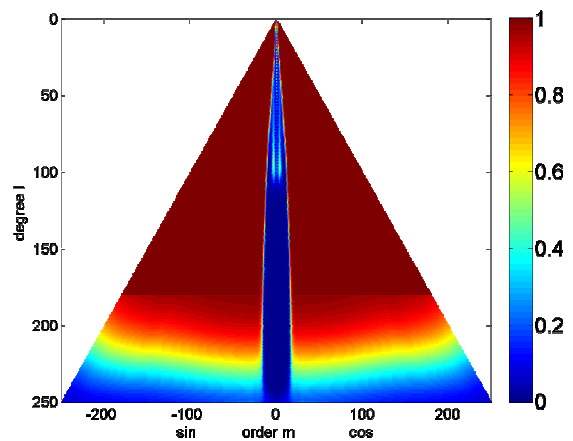

Figure 8. Redundancy factors showing the "GOCE-onlyness" of the release 2 solution.

Together with the coefficient solution, also a full variance-covariance matrix complete to degree/order 250 was output of this processing. In order to prove the plausibility of this matrix, rigorous covariance propagation was performed to propagate the coefficient errors to geoid height errors on a global grid. Figure 9 shows the specific error structure of this field for a covariance propagation up to degree/order 200.

The zonal 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 homogeneous data coverage, almost no longitudinal striping structures appear, demonstrating that due to the GOCE repeat orbit a very homogeneous error structure can be achieved. Also the significantly degraded performance in the polar cap areas, where no observations are available, is correctly expressed by the variance-covariance information.
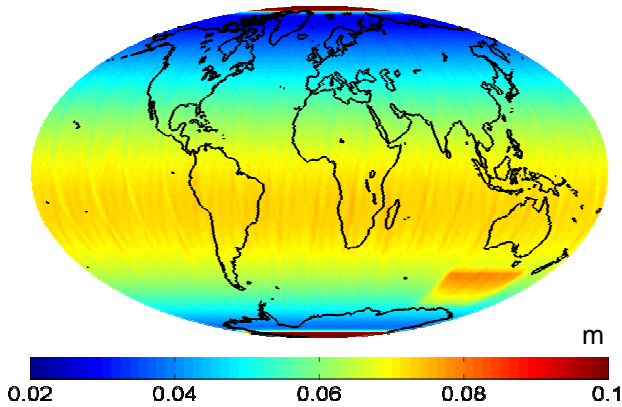
Figure 9. Geoid height standard deviations [m] at degree 200 propagated from the full parameter variance-covariance matrix.

Fig. 10: RMS of geoid height differences [m] between gravity field models and 675 GPS/leveling observations in Germany.

a)

b)

Figure 11: Gravity anomaly differences [mGal] to EGM2008 in the south of Australia of the (a) release 1; (b) release 2 time-wise gravity field model.

One specific feature appears in the South of Australia, which shows a higher error level than the surroundings. This feature is related to the fact that all 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 new release of GOCE products.)

In spite of the fact that the formal errors are larger, by this exclusion of V_{YY} data the quality of the gravity field solution could be significantly improved also in this region. This is shown in Fig. 11, which illustrates the gravity field differences to EGM2008 up to degree/order 200 for (a) the first release and (b) the second release of the time-wise gravity field model.

The solution has also been validated by means of GPS/levelling observations in Germany (675 stations). For a description of the methodology cf. [5]. Figure 10 shows the rms of geoid height differences of several gravity field models. The improvement of the second release time-wise model (dark blue) compared with the first release (light blue) is evident. According to this validation, the deviation of GO_CONS_GCF_2_TIM_R2 from the GPS/levelling observations is about 6.5 cm at degree/order 200. However, it has to be considered that also the latter ones are not noise-free (estimated accuracy of 3 cm).

Based on these and several other validation results, the actually achieved gravity field accuracy of this new time-wise GOCE-only solution is estimated to be 5.5 to 6 cm in terms of geoid height, and 1.8 mGal in terms of gravity anomalies, evaluated at degree/order 200.
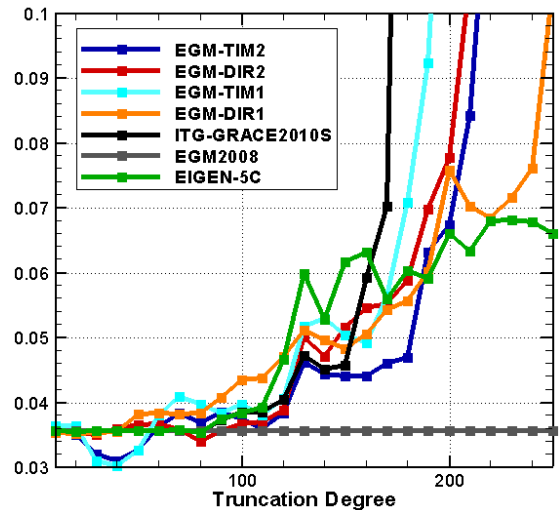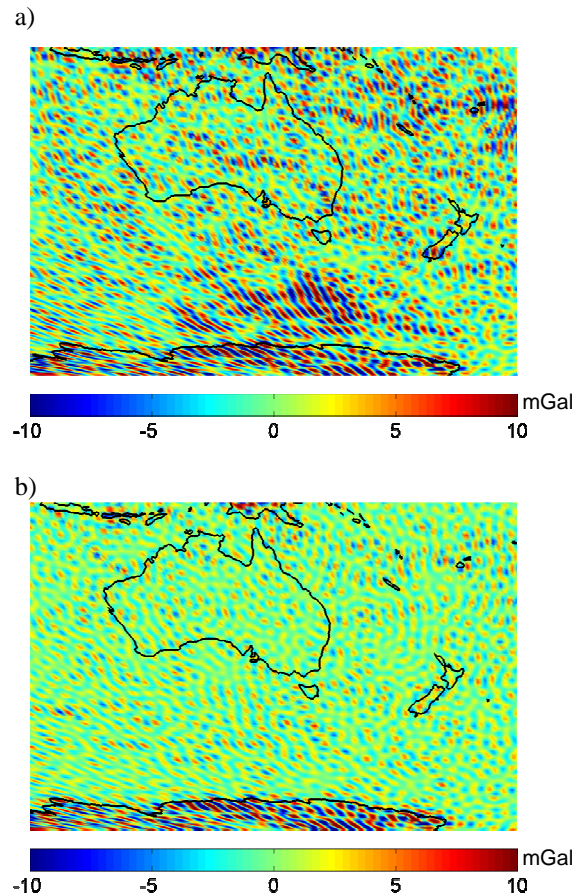
5. MISSION PERFORMANCE PREDICTION

Originally, the nominal GOCE mission end was scheduled for April 2011. However, recently it was decided by the ESA member states to extend the mission until December 2012. Recalling the improvement when including a larger data amount as shown in Figs. 4 to 7, this leaves a very promising perspective. In order to evaluate the impact of GOCE on the global knowledge of the Earth's gravity field and thus on many applications in Earth sciences, Figures 12 and 13 show cumulative geoid height errors and gravity anomaly errors, respectively, in dependence of the harmonic degree (spatial resolution). The red and blue curves show the performance of the 2 months (release 1) and the 6 months (release 2) solutions, respectively, while the black curve represents a performance prediction assuming a successful GOCE mission at the present altitude until end of 2012. In an additional scenario shown as magenta curve, an increase of the GOCE orbit altitude by 10 km in October 2011 has been assumed.
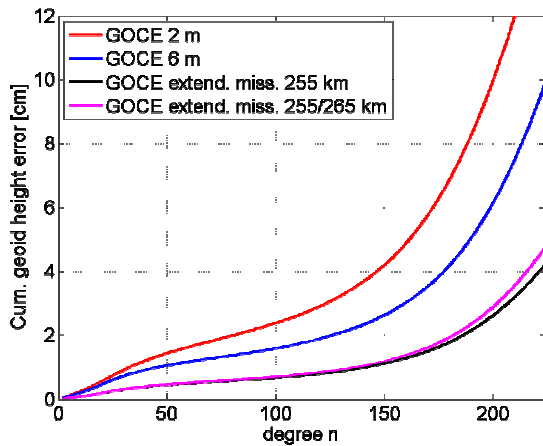

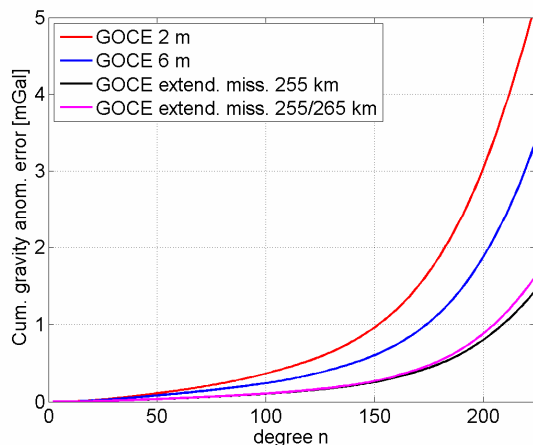*Figure 12: GOCE performance in terms of cumulative geoid height errors [cm].*

Figure 13: GOCE performance in terms of cumulative gravity anomaly errors [mGal].

The results are below 3 cm geoid height error and 1 mGal gravity anomaly error at degree/order 200 (= 100 km half wavelength) at the end of 2012, demonstrating that we might come very close to the original performance goals even though the actual performance of the V_{ZZ} component is degraded by a factor of larger than 2 compared to the original performance requirements.

6. CONCLUSIONS

The key philosophy for the processing of time-wise GOCE global gravity field model in the frame of HPF 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 GPS observations (kinematic orbits).

From a user's point of view, since this solution is completely independent of any gravity field information other than GOCE, it 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. It can also be used for combination with complementary gravity field information (GRACE, terrestrial data, satellite altimetry) on the level of normal equations. Since in the low degrees the solution is based solely on kinematic GOCE orbits, but no external (GRACE) information, it is not competitive with GRACE models in the low degrees.

The new time-wise GOCE solution, including data from November 2009 to July 2010, shows improvements according to the statistical √N rule of uncorrelated observations, demonstrating that the stochastic observation error models are adequate, and no significant systematic errors entered the solution. Since both for SST and for SGG a realistic stochastic model was used, the variance-covariance matrix reflects realistically the true error behavior of the coefficient solution.

The model GO_CONS_GCF_2_TIM_R2 is available via the ESA data archive, and the ICGEM webpage: http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html.

Due to the GOCE mission extension at least until December 2012, performance predictions show that we will be able to come close to the original mission performance specification for GOCE stand-alone models.

7. Acknowledgements

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