# Operational data processing of ESA's GOCE gravity field mission

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**Abstract**

The operational scientific processing of GOCE data will be performed by the European GOCE Gravity Consortium (EGG-C) in the framework of the ESA-funded project "GOCE High-level Processing Facility" (HPF). One key component of the HPF hardware and software system is the processing of a spherical harmonic Earth's gravity field model and the corresponding full variance-covariance matrix from the precise GOCE orbit and satellite gravity gradiometry data. In parallel to two other HPF teams, this task is performed by the "Sub-processing Facility (SPF) 6000". The second main task of SPF6000 is the production of quick-look gravity field products in parallel to the GOCE mission for system diagnosis purposes. The paper gives an overview of the operational SPF6000 software system that has been implemented and integrated at the facilities of TU Graz. On the basis of a numerical case study, which is based on the data of an ESA GOCE end-to-end simulation, the processing architecture is presented, and several aspects of the involved functional and stochastic models are addressed.

**Kurzfassung**

Die operationelle Prozessierung von GOCE-Daten wird im Rahmen des ESA-Projektes "GOCE High-level Processing Facility" (HPF) von einem Konsortium, gebildet aus 10 europäischen Forschungsinstituten (European GOCE Gravity Consortium, EGG-C) erfolgen. Eine Hauptkomponente dieses dezentralen Hardware- und Software-Systems ist die Berechnung eines globalen GOCE-Erdschwerefeldmodells, parametrisiert mittels sphärischen harmonischen Koeffizienten und der zugehörigen Varianz-Kovarianzmatrix, aus GOCE-Orbit- und Gradiometriedaten. Neben zwei weiteren HPF-Teams wird diese Aufgabe von der sogenannten "Sub-processing Facility (SPF) 6000" durchgeführt. Die zweite Hauptaufgabe der SPF6000 besteht in der fortlaufenden Produktion von schnellen Schwerefeldlösungen während der Mission als Beitrag zur Missionskontrolle. In dieser Arbeit wird das operationelle Softwaresystem der SPF6000 vorgestellt, das am Standort TU Graz implementiert und integriert wurde. An Hand einer numerischen Simulationsstudie, die auf Daten einer GOCE-Simulation der ESA beruht, werden die Prozessierungs-Architektur und ausgewählte Aspekte hinsichtlich der zu Grunde liegenden funktionalen und stochastischen Modelle präsentiert und diskutiert.

## 1. Introduction

The dedicated satellite gravity mission GOCE (Gravity field and steady-state Ocean Circulation Explorer; [6]), 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). During the (at least) two GOCE measurement phases of 6 months each, GOCE will provide a huge data set consisting of several 100 million orbit and gravity gradiometry data, which contains abundant information about the gravity field of the Earth on a near-global scale, from very low (derived mostly from hl-SST) to high (derived mostly from SGG) frequencies.

The mathematical model for the parameterization of the global Earth's gravity field is usually based on an expansion into spherical harmonics. The gravitational potential $V$ can be expressed in a spherical coordinate system $(r,\ \vartheta,\ \lambda)$ by:

$$V(r,\vartheta,\lambda)=\frac{GM}{R}\sum_{l=0}^{lmax}\left(\frac{R}{r}\right)^{l+1}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\vartheta)\cdot \cdot\left[\overline{C}_{lm}\cos(m\lambda)+\overline{S}_{lm}\sin(m\lambda)\right] \quad (1)$$

where $G$ is the gravitational constant, $M$ and $R$ are the Earth's mass and reference radius, $\overline{P}_{lm}$ are the fully normalized Legendre polynomials of degree $l$ and order $m$, and $\{\overline{C}_{lm},\overline{S}_{lm}\}$ are the corresponding spherical harmonic coefficients.

In the case of a gravity field model resolution complete to degree and order $l_{max}=250$, this yields approximately 63000 unknown spherical harmonic coefficients $\{\overline{C}_{lm},\overline{S}_{lm}\}$. The estimation of these coefficients from the complementary hl-SST and SGG data sets is a demanding numerical and computational task, and therefore efficient solution strategies are required to solve the corresponding large normal equation systems. During the last decade, several approaches have been developed to perform this task (e.g. [22] [24]

[8] [16] [14]). In [16] [17] the rigorous solution of the large normal equation matrix by means of a parallel processing strategy implemented on a Linux-PC cluster was proposed.

The scientific data processing (Level 1b to Level 2[1)]) 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; [23]). Table 1 gives an overview of the project partners of GOCE HPF.

The HPF project is jointly managed by IAPG and SRON, principal investigator is Prof. Rainer Rummel (IAPG). Table 2 lists the main work packages of GOCE HPF. Usually, several partners contribute to one work package.

The SPF6000 is a co-operation of TU Graz, Austrian Academy of Sciences, University of Bonn, and TU Munich, under the lead of TU Graz. The two main tasks of SPF6000 are:

1. the computation of a global Earth's gravity field model from GOCE data, parameterized by spherical harmonic coefficients, and the corresponding error estimates in terms of a full variance-covariance matrix;
2. the continuous production of quick-look gravity field solutions in parallel to the mission as a tool for GOCE system diagnosis and mission control.

| Acronym | Institution |
|---|---|
| AIUB | Astronomical Institute of Bern, University of Bern, Switzerland |
| CNES | Centre National d'Etudes Spatiales, Groupe de Recherche de Géodésie Spatiale, Toulouse, France |
| FAE/A&S | aculty of Aerospace Engineering, Astrodynamics & Satellite systems, TU Delft, The Netherlands |
| GFZ | GeoForschungsZentrum Potsdam, Germany |
| IAPG | Institute of Astronomical and Physical Geodesy, TU Munich, Germany |
| ITG | Institute of Theoretical Geodesy, University of Bonn, Germany |
| POLIMI | DIIAR – Sezione Rilevamento, Politecnico di Milano, Italy |
| SRON | National Institute for Space Research, Utrecht, The Netherlands |
| TUG | Institute of Navigation and Satellite Geodesy, TU Graz, Austria |
| UCPH | Department of Geophysics, University of Copenhagen, Denmark |

*Table 1: EGG-C members*

| SPF | Task | SPF lead |
|---|---|---|
| 2000 | Central Processing Facility (CPF) | SRON |
| 3000 | Scientific Pre-processing and External Calibration | SRON |
| 4000 | Orbit Determination | FAE/A&S |
| 5000 | Gravity Field Determination – Direct Approach | CNES |
| 6000 | Gravity Field Determination – Time-wise Approach | TUG |
| 7000 | Gravity Field Determination – Space-wise Approach | POLIMI |
| 8000 | Level 2 Products Validation | IAPG |

*Table 2: Work packages / SPFs of GOCE HPF*

1) Level 1 b data are (internally) calibrated instrument time series, while Level 2 data are products which are generated in the framework of HPF, such as precise GOCE orbits, externally calibrated gravity gradients, and finally the gravity field model coefficients and corresponding covariance information.

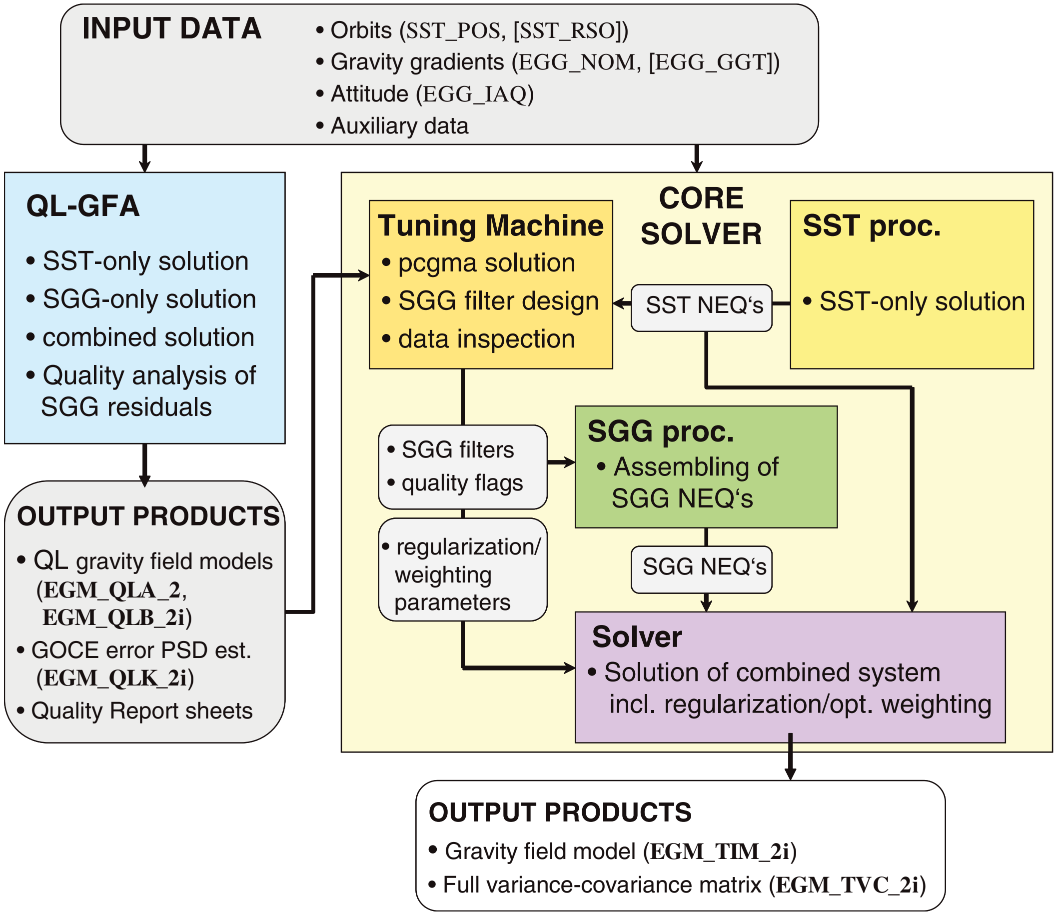


*Figure 1: SPF6000 software architecture and product flow. The official acronyms of the input and output products are given in brackets.*

## 2. Software architecture

Fig. 1 shows the architectural design, the 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.

The data transfer between SPF6000 and the central HPF data repository CPF (Central Processing Facility) is managed via automated interfaces. At SPF6000, the data are stored on a central access local data server.

The software system is composed of two main components: the Quick-Look Gravity Field Analysis (QL-GFA), and the Core Solver (CS), which will be briefly described in the following.

### 2.1. Quick-Look Gravity Field Analysis (QL-GFA)

This stand-alone software system performs the computation of fast approximate gravity field solutions based on SGG and hl-SST data, for the purpose to derive a fast diagnosis of the GOCE system performance and of the input data in parallel to the mission with short latencies. These gravity field products are input to ESA's calibration/validation activities in the frame of the GOCE mission control.

Key tasks of QL-GFA are:

- Check of SGG and hl-SST input data and analysis of partial / incomplete SGG and hl-SST data sets.
- Computation of quick-look gravity field models (SGG-only, SST-only, combined SST+SGG) aiming at a fast analysis of the information content of the input data on the level of the gravity field solution. Additionally, quick-look gravity solutions are statistically tested against reference gravity models.
- Estimation of the gradiometer error PSD (power spectral density) from the residuals of a SGG-only gravity field analysis, and application of previously defined statistical hypothesis test strategies in time and frequency domain [10].
- Production of Diagnosis Report Sheets: All these system diagnosis products are reported by means of a standardized Diagnosis Report Sheet.

QL-GFA solutions complete to degree/order 250 can be processed within the order of one to two hours on a standard PC. The efficiency and speed of QL-GFA is founded mainly on the application of FFT techniques (semi-analytical approach), the assumption of block-diagonality of the normal equation matrix, and also on a simplified filter strategy in the spectral domain to cope with the coloured noise characteristics of the gradiometer. Deviations from this assumption are incorporated by means of an iterative procedure [21] [18]. A detailed description of the functionality of QL-GFA can be found in [20].

QL-GFA will be applied at two stages: Quick-Look-A (QL-A) is applied to Level 1b preliminary orbits (accuracy ~ 10 m) and the Level 1b gravity gradients. The main purpose at this stage is a rough check of the SGG time series, with special concern on the testing of the SGG error PSD. For QL-A, consecutive gravity field solutions will be available in a daily interval. They will be generated fully automated with a latency of maximum 4 hours after arrival of all required input data. The achievable accuracy is mainly dependent on the correct (internal) calibration of the Level 1b gradients.

Quick-Look-B (QL-B) is applied to the Level 2 rapid science orbit solution (accuracy in the decimetre range) and the externally calibrated gravity gradients. Consecutive gravity field solutions will be available in a weekly interval, with a latency of 2 days after the availability of all input data. The maximum degree and order for the QL-GFA gravity field models will be optimized with respect to the global coverage of the input data.

### 2.2. Core Solver (CS)

The objective of the CS is to compute a high-accuracy, high-resolution spherical harmonic model including a quality description of the static Earth's gravity field from GOCE SGG and SST observations. The parameterization of the model will be complete at least up to degree and order 200, and a resolution up to degree and order 250 is envisaged, depending on the actual accuracy of the SGG observations.

The *Tuning Machine*, whose development, implementation and integration is completely in the responsibility of the HPF work package partner University of Bonn, consists of two main modules:

- *pcgma* (pre-conditioned conjugate gradient multiple adjustment; [4]): This module acts as a stand-alone gravity field solution strategy, using the sparse structure of the normal equations [3], and is used to verify and tune the involved software components of the CS in many respects, e.g., to derive optimum regularization and weighting parameters.
- *Data analysis tool*: The data inspection and filter design tool is used to verify external and internal products, and to define the filter coefficients [27] which will be used in the Final Solver.

The *Final Solver* consists of the following main modules:

- *SST processor*: The information content of the SST data is exploited by making use of the precise GOCE orbit solutions (Precise Science Orbits; PSOs) expressed in terms of position and velocity information. The principle of energy conservation in a closed system is applied [7] [1] [2]. The software can process both kinematic (purely geometric) and reduced-dynamic (using a-priori models of the external forces and the gravity field) orbit solutions. However, kinematic orbit solutions are preferred, because they do not contain any a-priori information about the gravity field.
- *SGG processor*: The SGG processing is based on the position information given by the PSOs, and the externally calibrated gravity gradients defined in the Gradiometer Reference Frame (GRF). The complications arising from the coloured noise of the gradiometer are managed by a recursive filter procedure in time domain [24] [25] [26] [28] [16]. The SGG processor

assembles the full normal equations applying parallel processing on a Linux-PC-Cluster.

- *Solver*: The mathematical models for SGG and SST data are combined to the overall mathematical model by means of superposition of the normal equations, applying variance component estimation [9] for an 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 Spherical Cap Regularization [12] [13], a regularization technique which is tailored to the problem of the non-polar GOCE orbit configuration. Together with the GOCE gravity field model coefficients, a statistical error description in terms of the full mean square error matrix (variance-covariance matrix plus regularization bias) is processed.

### 2.3. Product Flow

Chronologically, the first processing steps will be performed by QL-GFA (cf. Fig. 1). The output products are not only transferred to the GOCE mission control via CPF, but are also used as prior information for the CS.

In the Core Solver processing, the SST and SGG normal equations are assembled separately. The SST normal equations (and other internal products) are transferred to the Tuning Machine and the Final Solver. In the Tuning Machine, the SGG normal equations are set-up using a sparse matrix scheme, and, after combination with the full SST normal equations, gravity field solutions are computed applying the pcgma algorithm. The residuals of the adjustment are analyzed by the data inspection tool, and filter coefficients, regularization and weighting parameters are derived, which are provided to the Final Solver. Here, the full SGG normal equations are assembled, and optimally combined with the SST normal equations. Finally, the gravity field coefficients and the mean square error matrix are computed rigorously.

## 3. Numerical case study

The operability of the software system shall be demonstrated by a numerical case study. In the present case, the main objective was the computation of optimum GOCE gravity field models complete to D/O 200.

### 3.1. Test data sets

The numerical case study is based on the data of an ESA GOCE end-to-end simulation [5]. This test configuration was also used during the official ESA Acceptance Review 2 for the testing of the final operational software (at the end of the development phase) in the framework of the HPF, which was performed in spring/summer 2006. The test data sets consist of:

- *Gravity gradients*: 60 days of 1 Hz rate simulated gravity gradients defined in the GRF, based on the gravity model EGM96 [11] complete to degree/order 360, superimposed by colored noise (cf. Fig. 2, black curve).
- *Orbit*: The gradients are defined along an orbit with GOCE characteristics (inclination $i = 96{,}5°$, eccentricity $e < 2 \cdot 10^{-3}$, mean altitude $\sim$ 240 km). The orbit positions (and velocities) were generated by orbit integration, based on the gravity model EGM96, complete to degree/order 200, and including a full external force model and drag free and attitude control (DFAC) simulation. The DFAC performs the attitude control of the satellite and the compensation of non-conservative forces by means of ion thrusters [6].
- *Attitude*: The orientation of the satellite body axes (and hence the GRF) with respect to the inertial frame is given in terms of quaternions, which are computed from a combination of star tracker and gradiometer information. Correspondingly, they include attitude biases and noise [15], related to the star tracker and gradiometer inaccuracies modelled in the end-to-end simulation.

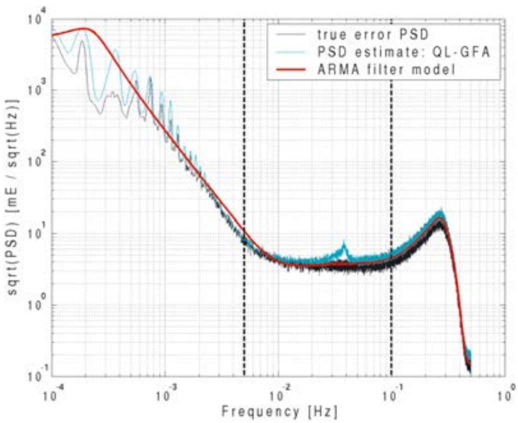


*Figure 2: Gradiometer error PSDs for the gradiometer component $V_{XX}$: true PSD (black), QL PSD estimate (light blue), ARMA digital filter model (red); measurement bandwidth: 5 – 100 mHz.*

### 3.2. Results: QL-GFA

Due to the limited space, this paper concentrates on the results of the Core Solver processing. The results of the QL-GFA, based on the test configuration described in section 3.1, are presented in a separate paper [20].

### 3.3. Results: Core Solver

In the following, the results of the main CS components will be presented. Selected issues of this processing, such as the regularization, the optimum filtering of the SGG observations and normal equations, the actual parameterization, etc. are addressed in [19] in more detail.

#### 3.3.1. SST processing

The SST processing, which is based on the energy integral method, was applied to kinematic orbits. A numerical differentiation procedure using the Newton-Gregory method [1] [2] was applied to the kinematic orbit positions, which results in orbit velocities representing, after application of accelerometry to cope with the non-conservative forces, the basic pseudo-observations. The SST normal equations are set-up complete to degree/order 90, which turned out to be sufficient to finally obtain a smooth combined SST+SGG solution. The light blue curve in Fig. 3 shows the resulting SST-only solution in terms of the degree error median

$$\sigma_1 = median_m\left\{\left|\overline{R}_{lm}^{(est)} - \overline{R}_{lm}^{(EGM)}\right|\right\} \quad (2)$$

where $\overline{R}_{lm} = \{\overline{C}_{lm};\overline{S}_{lm}\}$ are the fully normalized spherical harmonic coefficients, $(est)$ denotes the estimated quantities, and $(EGM)$ refers to the reference model EGM96.

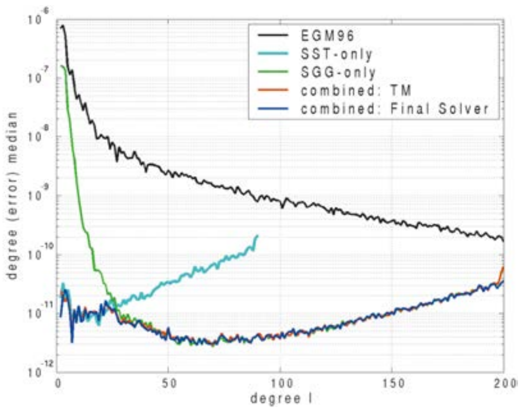


*Figure 3: Degree (error) medians per degree of selected Core Solver gravity field solutions.*

The corresponding SST normal equations are transferred to the Tuning Machine and the Final Solver, where they are used as input product.

#### 3.3.2. Tuning Machine (TM)

One main task of the TM is the approximation of an appropriate SGG digital filter model to introduce the correct metrics to the SGG normal equation system [24] [25] [16] [28]. Fig. 2 shows the error PSD of the gravity gradient tensor component $V_{XX}$ (black curve), and the corresponding filter model using a cascaded ARMA filter with an effective filter order of 52 (red curve). The other main diagonal tensor components $V_{YY}$ and $V_{ZZ}$ (not shown) have similar error characteristics. The corresponding cascaded filter models have an effective filter order of 42 ($V_{YY}$) and 32 ($V_{ZZ}$). (Additionally, the PSD derived by QL-GFA is displayed as light blue curve. For more details confer [20].)

A combined gravity field solution, based on the SST normal equation complete to degree/order 90 described above, and SGG normal equations complete to degree/order 200, was computed by pcgma. The red curve in Fig. 3 shows the results in terms of the degree error median.

#### 3.3.3. SGG processing

The full SGG normal equations were assembled on a Linux-PC-Cluster, which was installed under the umbrella of the initiative “Scientific Supercomputing“ at TU Graz. The key parameters of this Beowulf cluster are: 54 Dual-Xeon 2.6GHz PCs with 1–2 GB RAM, GigaBit-Ethernet connection, performance 210 GFlops.

The final goal of this simulation was an optimum gravity field solution complete to degree/order 200. Since the signal content of the SGG inputdata is degree/order 360, a spectral leakage effect due to the non-parameterized signals fromdegree 201 to 360 has to be expected. In [25], it was shown that the spectral leakage effect mainly affects the coefficients in the spectral region close to the upper limit of resolution (in the present case 200). Therefore, in order to reduce the effect, SGG normal equations complete to degree/order 204 are assembled, and the final solution is truncated at degree 200, thus eliminating the coefficients of degree 201 to 204, which absorb most of the unresolved high-frequency signals. During the assembling of the SGG normal equations, the digital filter model derived by the Tuning Machine was applied to the observations and the columns of the design matrix [24] [25] [16] [28].

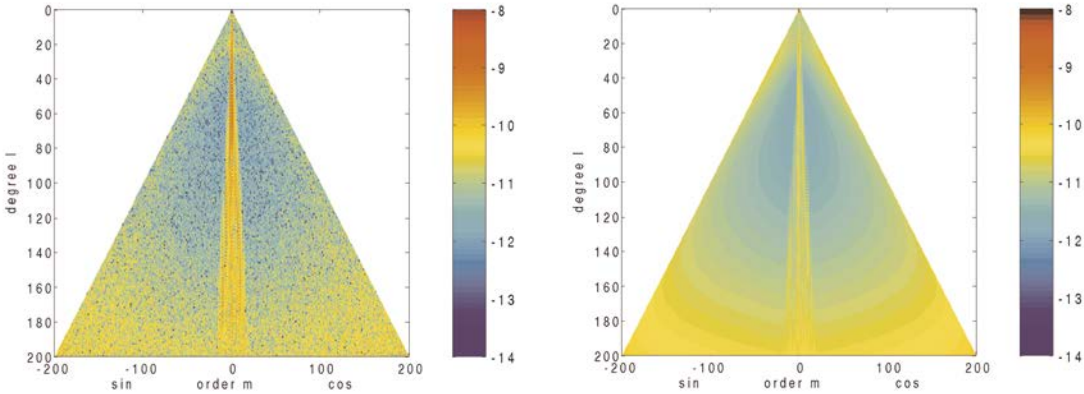


*Figure 4:* *Combined gravity field solution: coefficient deviations from EGM96 (left) and MSE estimates (right). Scaled in* $\log_{10}(|\ldots|)$.

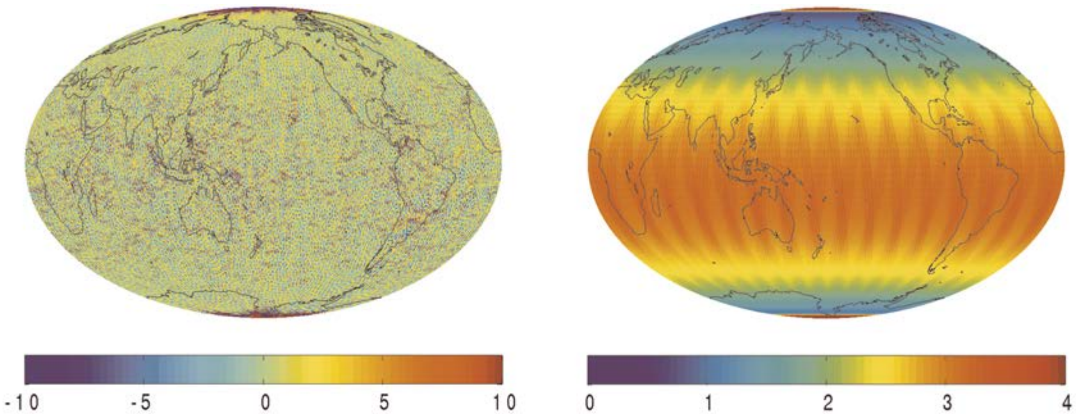

*Figure 5:* *Combined gravity field solution: height anomaly deviations [cm] from EGM96 (left) and corresponding standard deviations (right), degree/order 200.*

### 3.3.4. Final Solver

After the assembling of the SST (D/O 90) and the SGG (D/O 204) normal equations, they are superposed and solved by a rigorous parallel solver. The memory size of the upper triangle of the normal equations (double precision arithmetics) is about 6.5 GBytes for the degree/order 204 system. An optimum weighting based on variance-component estimation [9] among the individual normal equation systems was applied. The optimum weighting factor was computed by the Tuning Machine.

Finally, the large combined SST+SGG normal equation system, complete to degree/order 204, was solved rigorously, and afterwards truncated at degree/order 200 in order to reduce spectral leakage. Fig. 4 shows the coefficient deviations from the reference gravity field model EGM96 (left), as well as the corresponding error estimates (right). Evidently, the absolute errors and the statistical error estimates are quite consistent, except of the (near-)zonals, whose accuracy is slightly overestimated.

The corresponding degree error median of this solution is displayed as dark blue curve in Fig. 3. Evidently, it is stabilized in the low-degree range mainly by the SST component (light blue curve), and dominated by SGG (green curve) from degree 25 onwards.

The combined solutions processed by the Tuning Machine (red curve) and the Final Solver (dark blue curve) show a very good agreement.

The fact that two independent methods and implementations obtain practically identical results supports the conclusion that the remaining coefficient errors are due to the noise of the input data, but are not produced by insufficiencies of the processing algorithms.

Based on the coefficient estimates of the combined solution of the Final Solver (Fig. 4, left), cumulative height anomaly errors at degree/order 200 have been processed, and are displayed in Fig. 5 (left).

The standard deviations of the height anomaly $\sigma_\zeta$ and gravity anomaly $\sigma_{\Delta g}$ difference fields in the latitudinal region $-83.5° < \varphi < 83.5°$, which is covered by GOCE observations, are $\sigma_\zeta = 2.93$ cm and $\sigma_{\Delta g} = 0.81$ mGal, respectively. Considering the fact that only 2 months of input data have been used in this simulation, it can be concluded, that under the presently made noise assumptions of the input products the GOCE mission specifications of $\sigma_\zeta^{(spec)} = 1-2$ cm height anomaly and $\sigma_{\Delta g}^{(spec)} = 1$ mGal gravity anomaly accuracy at degree/order 200 can be achieved. Further, it shall be emphasized that the solution presented in this paper is a GOCE-only solution in a strict sense, i.e., it does not contain any external gravity field models as prior information.

Together with the coefficient solution, also a full variance-covariance matrix (approx. 20 GBytes in ASCII format), complete to degree/order 200, was output of this processing. In order to prove the plausibility of this matrix, a rigorous covariance propagation was performed to propagate the coefficient errors to height anomaly errors on a global grid. Fig. 5 (right) shows the specific error structure of this field. Compared with the amplitude of absolute errors (Fig. 5, left), their statistical error estimates match very well, which proves consistency of this numerical closed-loop simulation study.

## 4. Summary and conclusions

In this paper the architectural design and the main modules of the SPF6000 are described. The software is now fully implemented, and the hardware and software system is integrated and has been tested in the frame of the "Acceptance Review 2" of the HPF project. The software is accepted by ESA for the operational GOCE gravity field processing. The data flow through the SPF6000 and the interplay of the system modules is described based on a numerical case study applying the official ESA test data, and the main output products are presented as an example for a multitude of test scenarios which have been processed to validate the software system extensively during the development phase. Finally, the SPF6000 is ready to process GOCE gravity field solutions, and it will become operable after the availability of the first real GOCE data.

**Acknowledgements**

This study was performed in the framework of the ESA-project GOCE High-level Processing Facility (Main Contract No. 18308/04/NL/MM). It was supported by the Austrian Space Application Programme initiative by the FFG (contracts no. ASAP-CO-008/03 and ASAP-WV-211/05). Funding of our German HPF work package partners was also provided by the GOCE-GRAND project in the frame of the German "Geotechnologien Projekt".

Parts of this work have already been published in [19].

**References**

[1] *Badura, T.*: Gravity Field Analysis from Satellite Orbit Information applying the Energy Integral Approach. Dissertation, 109pp., TU Graz, 2006.

[2] *Badura, T., Sakulin, C., Gruber, C., and Klostius, R.*: Derivation of the CHAMP-only global gravity field model TUG-CHAMP04 applying the energy integral approach. Stud. geophys. geod., 50, 59–74, 2006.

[3] *Boxhammer, Ch.*: Effiziente numerische Verfahren zur sphärischen harmonischen Analyse von Satellitendaten. Dissertation, 95pp., University of Bonn, 2006.

[4] *Boxhammer, Ch., and Schuh, W.-D.*: GOCE gravity field modeling: computational aspects - free kite numbering scheme. In: Rummel et al. (eds.): Observation of the Earth System from Space, 209–224, Springer, Berlin-Heidelberg, 2006.

[5] *De Sanctis, S, Guiotto, A., and Parisch, M.*: Simulator Design Specification. Technical Note, GO-SP-AI-0001, Alenia Spazio, Turin, Italy, 2002.

[6] European Space Agency. Gravity Field and Steady-State Ocean Circulation Mission. Reports for mission selection, The four candidate Earth explorer core missions, SP-1233(1), European Space Agency, Noordwijk, 1999.

[7] *Földvary, L., Svehla, D., Gerlach, Ch., Wermuth, M., Gruber, T., Rummel, R., Rothacher, M., Frommknecht, B., Peters, T., and Steigenberger, P.*: Gravity Model TUM-2Sp Based on the Energy Balance Approach and Kinematic CHAMP Orbits. In: Reigber et al. (eds.), Earth Observation with CHAMP-Results from Three Years in Orbit, 13–18, Springer Verlag, 2004.

[8] *Klees, R., Koop, R, Visser, P.N.A.M., and van den Ijssel, J.*: Efficient gravity field recovery from GOCE gravity gradient observations. J. Geod., 74, 561–571, 2000.

[9] *Koch, K.-R., and Kusche, J.* :Regularization of geopotential determination from satellite data by variance components. J. Geod., 76, 259–268, 2002.

[10] *Lackner, B.*: Datainspection and Hypothesis Tests of very long Time Series applied to GOCE Satellite Gravity Gradiometry Data. Dissertation, 187pp., Graz University of Technology, Graz, 2006.

[11] *Lemoine, F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp, R.H., and Olson, T.R.*: The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, 1998.

[12] *Metzler, B., and Pail R.*: GOCE data processing: the Spherical Cap Regularization Approach. Stud. Geophys. Geod., 49, 441–462, 2005.

[13] *Metzler, B., and Pail, R.*: Spherical Cap Regularization of GOCE normal equation systems. Proc. 3rd GOCE User Workshop, Frascati, November 2006, European Space Agency, Noordwijk, 2006.

[14] *Migliaccio, R., Reguzzoni, M., and Sansó, F.*: Space-wise approach to satellite gravity field determinations in the presence of coloured noise. J. Geod, 78, 304–313, 2003.

[15] *Pail, R.*: A parametric study on the impact of satellite attitude errors on GOCE gravity field recovery. J. Geod., 79, 231–241, 2005.

[16] *Pail, R., and Plank, G.* :Assessment of three numerical solution strategies for gravity field recovery from GOCE satellite gravity gradiometry implemented on a parallel platform. J. Geod., 76, 462–474, 2002.

[17] *Pail, R., and Plank, G.*: GOCE Gravity Field Processing Strategy. Stud. Geophys. Geod., 48, 289–308, 2004.

[18] *Pail, R., and Wermuth, M.* :GOCE SGG and SST quick-look gravity field analysis. Advances in Geosciences, 1, 5–9, 2003.

[19] *Pail, R., Metzler, B., Lackner, B., Preimesberger, T., Höck, E., Schuh, W.-D., Alkathib, H., Boxhammer, Ch., Siemes, Ch., and Wermuth, M.*: GOCE Gravity Field Analysis in the Framework of HPF: Operational Software System and Simulation Results. Proc. 3rd GOCE User Workshop, ESRIN, Frascati, November 2006, SP-627, 249–256, European Space Agency, Noordwijk, 2007.

[20] *Pail, R., Metzler, B., Preimesberger, T., Lackner, B., and Wermuth, M.*: GOCE Quick-Look Gravity Field Analysis in the Framework of HPF. Proc. 3rd GOCE User Workshop, ESRIN, Frascati, November 2006, SP-627, 325–332, European Space Agency, Noordwijk, 2007.

[21] *Preimesberger, T., and Pail, R.*: GOCE quick-look gravity solution: application of the semianalytic approach in the case of data gaps and non-repeat orbits. Studia geoph. geod., 47, 435–453, 2003.

[22] *Rummel, R., van Gelderen, M., Koop, R., Schrama, E., Sansó, F., Brovelli, M., Miggliaccio, F., and Sacerdote, F.*: Spherical harmonic analysis of satellite gradiometry. Neth. Geod. Comm., Publications on Geodesy, 39, Delft, The Netherlands, 1993.

[23] *Rummel R, Gruber, T., and Koop, R.*: High Level Processing Facility for GOCE: Products and Processing Strategy. Proc 2nd International GOCE User Workshop, Frascati, 2004.

[24] *Schuh, W.-D.*: Tailored Numerical Solution Strategies for the Global Determination of the Earth's Gravity Field, Mitteilungen geod. Inst. TU Graz, 81, Graz Univ. of Technology, Graz, 1996.

[25] *Schuh, W.-D.*: Improved modelling of SGG-data sets by advanced filter strategies. ESA-Project "From Eötvös to mGal+", Final Report, ESA/ESTEC Contract 14287/00/NL/DC, WP 2, 113–181, ESA, Noordwijk, 2002.

[26] *Schuh, W.-D.*: The processing of band-limited measurements; filtering techniques in the least squares context and in the presence of data gaps. In: Beutler et al. (eds.): Earth Gravity Field from Space – From Sensors to Earth Sciences, Space Science Reviews, 108, 67–78, 2003.

[27] *Schuh, W.-D., and Kargoll, B.*: The numerical treatment of the downward continuation problem for the gravity potential. In: Sanso (ed.): Hotine-Marussi-Symposium, IAG Symposia, Lecture Notes in Earth Sciences, 127, 22–31, Springer, Berlin-Heidelberg, 2004

[28] *Schuh, W.-D., Pail, R., and Plank, G.*: Assessment of different numerical solution strategies for gravity field recovery. Proc. 1st Internat. GOCE User Workshop, April 2001, WP-188, 87–95, ESTEC Noordwijk, European Space Agency, 2001.

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