THE STATUS OF THE GOCE HIGH-LEVEL PROCESSING FACILITY

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ABSTRACT

The GOCE High-level Processing Facility (HPF) is the part of the GOCE Ground Segment which is dedicated to the scientific processing of the GOCE observations and the production of the final gravity field products provided to the end users. The final acceptance review of the HPF was recently successfully completed. During and shortly after the operational phase of the GOCE mission the HPF will systematically produce GOCE level 2 end products such as orbits and gravity field models of different kinds, derived from the novel and highly precise GOCE gradiometry observations, GPS high-low satellite-to-satellite tracking data and additional measurements. Ten European university institutes and research facilities, having complementary expertise in gravity and geodesy related science fields, together have formed the European GOCE Gravity Consortium (EGG-C), which has been contracted by ESA to develop, implement and operate the HPF throughout the whole GOCE mission lifetime. The HPF is designed and developed with the capabilities to produce on a regular basis so-called quick-look or rapid products, that are mainly of interest for the GOCE performance monitoring, as well as final and precise products, representing the official ESA GOCE level 2 products that will become available to end-users. A unique feature of the HPF is that it will implement and operate three different gravity field analysis techniques in parallel, complemented with dedicated scientific pre-processing techniques and a thorough validation procedure for the derived gravity field models before the official ESA solution will be selected out of them. In this way (scientific) users of GOCE products (e.g. oceanographers, solid Earth scientists, geodesists and others) will benefit from the optimal exploitation of the GOCE data. The paper presents an overview of the organisation and architecture of the HPF and the status of its development.

1. INTRODUCTION

The High-level Processing Facility (HPF) is one of the elements of the GOCE Ground Segment, see Fig.1. Within this Ground Segment, the HPF interfaces only with the Payload Data Ground Segment (PDGS). All relevant GOCE Level 1b data *for* the HPF (cf. [1]) is ingested *from* the PDGS, while all Level 2 output data *from* the HPF is distributed *to* the PDGS. For both types of data traffic, dedicated interfaces have been defined, specifically between the HPF and the PDS (Payload Data Segment) for nominal operations, and between the HPF and the LTA (Long Term Archive) for product re-distribution or after close-out of the PDS. Both PDS and LTA are sub-systems of the PDGS.
HPF Quick-look Level 2 products are needed by the CMF (Calibration and Monitoring Facility), which is another element of the Ground Segment, but CMF obtains these products through its interface with the PDS. HPF also ingests relevant auxiliary – non-GOCE – data from external data providers, specifically IGS (International GPS Service), IERS (International Earth Rotation Service), ECMWF (European Centre for Medium-range Weather Forecast), ILRS (International Laser Ranging Service), ICGEM (International Centre for Global Gravity Field Models) and selected other providers.

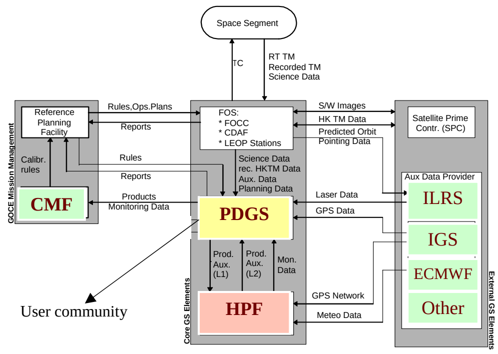

Figure 1. GOCE Ground Segment overview (CMF = Calibration and Monitoring Facility; PDGS = Payload Data Ground Segment; HPF = High-level Processing facility; FOS = Flight Operations Segment).

The main tasks of the HPF are:

- to process the relevant GOCE Level 1b data into consolidated GOCE Level 2 products to be made available for the end-users, using state-of-the-art models and methods,
- to deliver the final GOCE Level 2 products in conformance with the GOCE mission performance requirements,
- to provide quick-look gravity field products for fast performance monitoring of the mission.

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Furthermore, HPF will, during the operational phase, support the Calibration and Monitoring Team of experts that is part of the CMF.

2. EUROPEAN GOCE GRAVITY CONSORTIUM

The HPF is designed, developed, implemented, tested and operated by the European GOCE Gravity consortium (EGG-c) under ESA contract, complemented by significant national and institutional support. EGG-c consists of ten European university and research institutes from seven countries, see Fig.2.

Figure 2. The European GOCE Gravity consortium (in red the managing institutes; in red and yellow the main workpackage managers; in yellow the remaining processing facilities).

These ten groups are:

- AIUB Astronomical Institute of the University of Bern
- CNES Centre Nationale d'Etudes Spatiale, GRGS, Toulouse
- FAE/A&S Faculty of Aerospace Engineering, TU Delft
- GFZ GeoForschungsZentrum Potsdam
- IAPG Institute of Astronomical and Physical Geodesy, TU Munich
- ITG Institute for Theoretical Geodesy, University of Bonn
- POLIMI Politecnico di Milano
- SRON Netherlands Institute for Space Research
- TUG Institute of Navigation and Satellite Geodesy, TU Graz
- UCPH Department of Geophysics, University Copenhagen.

The HPF is managed by IAPG and SRON. Six of the ten groups have the responsibility of a main workpackage as workpackage manager, namely CNES, FAE/A&S, IAPG, POLIMI, SRON and TUG.
The heritage of EGG-c is to be found in the cooperation activities between most of the groups that already started during the time of the Aristoteles gradiometer mission proposal, continuing with the four CIGAR studies (1989-1996) on precise gravity field determination methods and mission requirements, followed by two studies under the title "From Eötvös to Milligal (2000-2002). Before the actual HPF development started, the EGG-c performed a study under ESA contract between mid 2001 and mid 2003 aimed at the definition of the high-level architecture for GOCE Level 2 processing.
The ten groups in the EGG-c have a long-standing experience in the field of geodetic orbit and gravity field modeling and related data processing. Actually, the EGG-c is characterized by the fact that there is a strong internal overlap of expertise on the one hand, and a complementary expertise on the other. The latter ensures that all relevant subjects required for GOCE data processing are covered by EGG-c, while the former implies that HPF has intrinsically the capabilities for independent validation and – if necessary – back-up scenarios.
The expertise and software already available within EGG-c has been re-used in the HPF and adapted and upgraded wherever necessary. On the other hand, novel approaches that have specifically been developed in the last decades aimed at high-accuracy gravity field modeling from satellite measurements, are included in HPF as well. Some specific tasks, in particular related to processing steps that are dedicated and tailored to GOCE, like the pre-processing, external calibration and certain filtering processes, have been developed and implemented from scratch. As a result, HPF constitutes a unique combination of consolidated and promising novel techniques for GOCE Level 2 data processing.

3. HPF ARCHITECTURE

The top part of Fig.3 shows the high-level interfaces between the HPF and the other elements of the GOCE Ground Segment. This figure furthermore illustrates the internal high-level architecture of the HPF.
The main building blocks of the HPF are:

- Central Processing Facility,
- Scientific Pre-processing and External Calibration,
- Orbit Determination,
- Gravity Modeling,
- Product Validation and Selection of Final Products.

In addition to these main tasks, the HPF also provides so-called quick-look or rapid products, that are mainly of interest for the GOCE performance monitoring. All these tasks will be briefly discussed below.

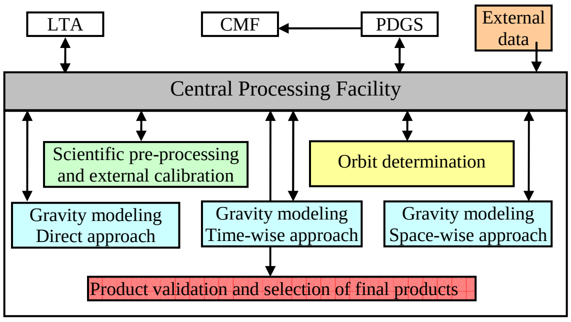

Figure 3. High-level architecture of the HPF. The CPF is the central node for all data flow along the internal and external interfaces.

3.1 Central Processing Facility

The GOCE HPF has been implemented as a distributed facility, meaning that actual processing takes place at different sub-processing facilities (SPF's) at the physical locations of the ten groups of the EGG-c. Nevertheless, HPF has only one interface with the PDGS, for which the so-called CPF (Central Processing Facility) has been developed and implemented. The CPF, implemented at SRON, is furthermore the central facility for data distribution within the HPF, for which ten internal interfaces have been defined and implemented, along which all Level 1b input and Level 2 output products are distributed and collected. In order to keep the internal data network as simple as possible, in principle, no direct interfaces between SPF's are in operation. The main tasks of the CPF are:

- ingest Level 1b data from the PDGS
- convert these products from XML to an internal HPF format
- collect relevant auxiliary products from external data providers
- distribute Level 1b and auxiliary products to the applicable SPF's
- collect intermediate and final Level 2 products from the SPF's, and distribute them to the applicable SPF's
- convert Level 2 products from the internal HPF format to XML
- distribute all intermediate, final and auxiliary Level 2 products to the PDGS
- apply formal checks of all data products flowing through the CPF
- monitor the internal HPF data flow
- maintain a rolling archive for all data.

The CPF is a dedicated GOCE-HPF data facility which has been developed and implemented from scratch, and which has no direct interface to the end-users.

3.2 Scientific Pre-processing and External Calibration

The challenging gradiometer in-flight calibration procedure contributes strongly to the high performance of this novel instrument in the gradient measurement band (MB), between 5 and 100 mHz. This in-flight calibration procedure, however, constitutes a "relative" calibration, where the individual accelerometers are calibrated against each-other, mainly to determine a common and differential scale factor and to determine mis-alignments between the axes of the accelerometers and the gradiometer, see Fig.4. What is needed in addition is a kind of "absolute" calibration to establish the correct physical dimension of the gradients, by determining a scale factor from comparison of the observations with existing and validated external gravity data. For this, the HPF has developed and implemented a so-called external calibration procedure, which is one of the main tasks of the gravity gradient (GG) pre-processing step.

The external calibration method developed and implemented by HPF at SRON consists of a comparison of the high-pass filtered GG's with modeled GG's computed from an existing global gravity field model. In order to validate the scale factor determined in this way, it is compared at FAE/A&S with a scale factor derived from comparison of the GG's with gradients derived from the GOCE SSTI observations through an orbit determination process. Furthermore, the corrected GG's (after applying the scale factor from the external calibration) are tested at UCPH against ground data (terrestrial gravity anomalies) in a few well-chosen regions, since it is to be expected that in particular the high-resolution ground gravity data should be able to constrain the GOCE observations in the lower part of the MB.

Figure 4. Drawing of the GOCE gradiometer

Before the gradients are externally calibrated, possible outliers, remaining after the PDGS processing, will be detected and flagged (at SRON), as well as data gaps. For these cases, fill-in values will be provided from interpolation.

Furthermore, this block of the HPF corrects the GG's for temporal gravity effects, since GOCE will be used to estimate the stationary gravity field. These temporal corrections include ocean and solid earth tides (at FAE/A&S) and non-tidal ocean and atmosphere effects (at IAPG).

The outcome of the pre-processing step are calibrated and corrected GG's in the Gradiometer Reference Frame. For end-users who might want to take advantage of the high resolution (although lesser accuracy) of the gravity gradients over the final GOCE global gravity model, the calibrated and corrected GG's in the GRF are transformed (at SRON) to an Earth fixed terrestrial reference frame. It should be kept in mind, that these Earth-fixed gradients have a degraded accuracy in the MB due to the fact that the two less accurate GG from the gradiometer are mixed with the highly accurate ones during the transformation (rotation) from instrument to Earth.

3.3 Orbit Determination

The accurate GOCE SSTI (Satellite-to-Satellite Tracking Instrument, see Fig.5) observations are used both for accurate reconstitution of the orbit, as well as for long-wavelength gravity field modeling. The ultra-low orbit of GOCE poses specific constraints on precise orbit determination from GPS observations, for which existing well-established processing software at FAE/A&S and AIUB has been tailored. HPF provides on a routine basis both Rapid Science Orbits (RSO) as well as Precise Science Orbits (PSO), the former of which with a shorter latency, the latter of which being made available to the end-user. Actually, for both RSO and PSO two POD techniques have been implemented in HPF, namely kinematic and reduced-dynamic orbit determination. In addition to the GOCE SSTI observations, AIUB provides for the PSO processing high-rate GPS clock corrections.

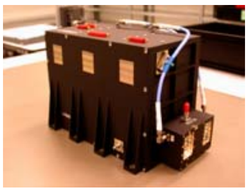


Figure 5. The GOCE GPS receiver and antenna (SSTI)

3.4 Gravity Modeling

Gravity gradients have never been measured before from a satellite. In view of the final realization of a mission like GOCE, major progress has been made in the last decades in the field of updated and novel processing strategies for such observations. Furthermore, the extreme performance requirements of GOCE make it necessary to revisit "classical' approaches in satellite geodesy. Even in the field of processing GOCE GPS tracking observations special attention is required due to the low orbit and strong performance requirements. Three different processing strategies were proposed at the start of HPF and since one cannot predict which method is the best before the real GOCE data becomes available, it was decided to implement all three alternative methods in the HPF processing chain, also for reasons of acknowledging the significant progress that has been achieved in novel methods specifically designed for GOCE. As a result, the gravity modeling block of the HPF now consists of the following tasks:

- Direct gravity field modeling approach, based on updated and improved "classical" methods for gravity field determination from satellite measurements, implemented at CNES and GFZ;
- Time-wise gravity field modeling approach; this is a novel approach, never been used for real data processing, but taking advantage of the homogeneous and continuous data stream from GOCE by a method that takes the whole data set as a time-series along the orbital track. This task is implemented at TUG together with ITG and IAPG.
- Space-wise gravity field modeling approach, implemented at POLIMI and UCPH, in which the GOCE data is gridded and advantage is taken from fast spatial techniques and elegant theoretical models.

Each of the three methods has its own characteristics in terms of filtering, regularization, processing strategies for huge data sets, assumptions and approximations, etc., and each method can be especially tuned to the peculiarities of the real GOCE data.

3.5 Product Validation and Selection of Final Products

One of the strongest features of the HPF is that the whole spectrum of state-of-the-art gravity field and orbit modeling is included in the processing chain, building on long-standing expertise available at the EGG-c teams and exploiting consolidated and new scientific ideas and methods. This is reflected in the fact that two alternative POD techniques and three gravity modeling methods are present, which not only can be used to validate each-other but also can be seen as back-up scenarios. Since the ultimate goal of the HPF is to provide for the end-user only one (the "best") GOCE gravity field model and precise orbit, the HPF has implemented at IAPG and FAE/A&S an extensive evaluation procedure of the alternative products, as well as a selection of the final product.

Both kinematic and reduced-dynamic orbits are compared against each-other, overlap analysis is done, and both orbits are compared to SLR validated orbits.

The three gravity field solutions are compared by means of orbit computations of other satellites, direct comparison of the coefficients and errors, and validated by comparison to several ground data sets, like terrestrial gravity anomalies, altimetry, GPS leveling, global gravity models, etc., see Fig.6.

This validation procedure will result in an extensive quality report, on the basis of which the final (best) GOCE gravity model will be selected.

Together with the products from the pre-processing step, the outcome of HPF processing after the selection consists of the final Level 2 products, listed in Table 1, that are available to the end-user through the PDS user interface. A comprehensive description of these products can be found in [2] and [3].

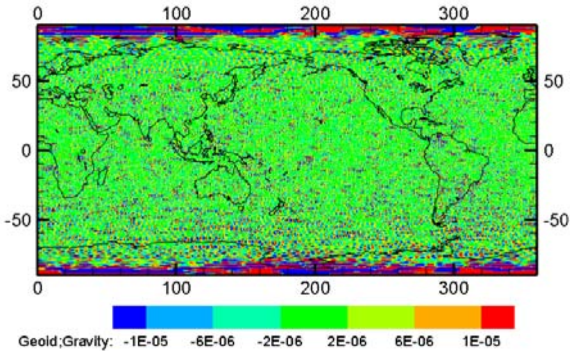

Figure 6. Example of the gravity field solution validation taken from the quality report from the acceptance test of Version 2.Shown are the differences between gravity anomalies computed from the time-wise solution and from EGM96, the input model for the simulations.

Table 1. Final HPF output products

Identifier	Description
EGG_NOM_2	- Externally calibrated and corrected gravity gradients in Gradiometer Reference Frame (2 weeks latency) - Corrections to gravity gradients for temporal gravity variations - Flags for outliers, fill-in gravity gradients for data gaps with flags - Statistical information
EGG_TRF_2	- Externally calibrated gravity gradients in Earth fixed reference frame including error estimates for transformed gradients - Transformation parameters to Earth fixed reference frame
SST_PSO_2	- GOCE precise science orbits final product - Quality report for precise orbits
EGM_GOV_2	- Final GOCE Earth gravity field model as spherical harmonic series including error estimates. Target: 1-2 cm / 1 mGal up to degree and order 200 corresponding to 100 km spatial resolution. - Grids of geoid heights, gravity anomalies and geoid slopes computed from final GOCE Earth gravity field model including propagated error estimates - Quality report for final GOCE gravity field model
EGM_GVC_2	Variance-covariance matrix of final GOCE Earth gravity field model

3.6 Quick-look Processing

In order to support a fast performance monitoring of GOCE in terms of Level 2 products, HPF has implemented a quick-look chain, delivering several quick-look products available for analysis by the participants in the GOCE ground Segment. In particular, HPF provides quick-look orbits (the RSO), quick-look corrected and calibrated gravity gradients and quick-look gravity field solutions based on subsets of Level 1b data (cf. Fig.7). Quality reports of the quick-look products will be delivered as well.

4. HPF DEVELOPMENT

The HPF development phase started in April 2004 and ended with the successful acceptance of Version 2 end of October 2006. Since the HPF exploits to a large extent the expertise available in the EGG-c already before the GOCE mission, large parts of the software were already in place at the SPF's, although all so-called re-used software has been adapted or upgraded to meet the GOCE specifications and all sub-systems were completely included in the acceptance testing of the HPF system. The whole HPF is therefore fully in conformance with the GOCE data processing requirements. HPF has been developed also in conformance with the applicable ESA software and product assurance standards and requirements.
A prototype Version 0 of the HPF was tested, delivered and accepted end of 2004. This version comprised the high-level architecture of the system, all external and internal interfaces, and the full data flow.

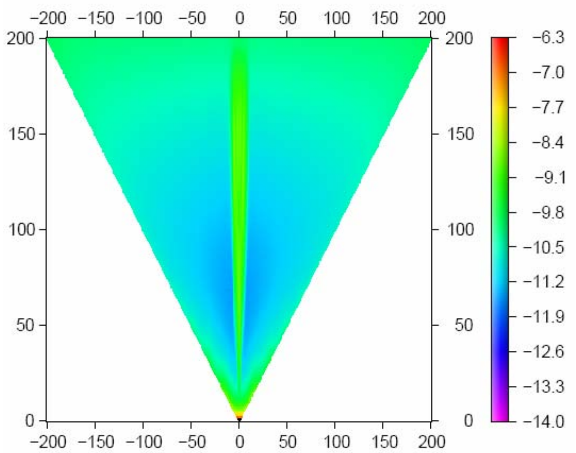

Figure 7. Example of the quick-look gravity field validation taken from the quality report from the acceptance test of Version 2. This is the log10 of the SH coefficient error from an SGG-only solution from an approx. 3 week subset of test data from the end-to-end simulator.

Version 0 of the full HPF system, comprising everything from Version 0 completed with all algorithms (operated at the developer's sites), was tested, delivered and accepted end of 2005. The acceptance of this version confirmed the readiness of the full HPF system to process GOCE data, be it not yet to the utmost performance. This version was tested

using realistic test data coming from the ESA end-to-end GOCE system simulator.
The upgrade of Version 1 into Version 2 included the finalization of a few open issues, some refinements of algorithms, porting of software from developer's sites to operational sites, (wherever applicable) and the processing of more realistic test data. Version 2 was therefore tested with improved performance as compared to Version 1. The final acceptance of Version 2 of the HPF confirms the readiness of the full HPF system to process real GOCE data to the required performance. This milestone concluded the development phase of the HPF. After the successful launch of GOCE, the HPF operational phase will be kicked-off, which comprises the actual processing of real GOCE data during the whole mission lifetime.

5. CONCLUSION AND OUTLOOK

With the test and acceptance of Version 2 of the HPF system, the GOCE High-level Processing Facility is ready to process real GOCE Level 1b data into Level 2 products in conformance with the GOCE mission performance requirements. A unique feature of the HPF is the fact that multiple solution strategies for orbit determination and gravity field modeling are included in the operational HPF system. The results of the different methods are evaluated and validated extensively as part of the HPF processing. Based on the resulting quality reports the final GOCE Level 2 data products are selected and being made available to the end users.
As a result of the delay of the launch of GOCE the kick-off of the operational phase of HPF has been postponed as well. HPF will therefore enter a so-called bridging phase of nearly one year, during which the following activities will take place:

- The addition of certain features to the HPF system based on new – scientific – insights gained during the development phase, features related to a possible improved performance of the HPF system over the mission requirements, or features that improve or better facilitate the operations of the HPF.
- The development, testing and acceptance of Version 3 of the HPF, including the add-on features mentioned above and trying to run the system to the ultimate performance by processing even more realistic, improved quality test data from the GOCE end-to-end system simulator.
- Studies to investigate the impact on HPF processing of long data gaps and significant degradation of the performance of the Level 1b input products.
- Some fundamental studies to consolidate the scientific basis of gravity field processing in view of the extreme performance of GOCE.

The HPF bridging phase, also under ESA contract, enables the continuation of HPF awaiting the launch of GOCE, and provides the opportunity to exploit state-of-the-art scientific knowledge to the benefit of GOCE Level 2 data processing.

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