

# High Level Processing Facility for GOCE: Products and Processing Strategy

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## 1. ABSTRACT

The purpose of the High Level Processing Facility for GOCE (HPF) is to produce systematically GOCE level 2 products, which are orbits and gravity field solutions of different kind. While so-called quick-look or rapid products mainly are of interest for the monitoring of the GOCE performance, the final and precise products will represent the official GOCE level 2 products. They will be further used for level 3 processing by the GOCE users (oceanographers, solid Earth scientists, geodesists and others). The paper summarizes the architecture of the HPF and provides an overview of the planned products and their characteristics.

## 2. INTRODUCTION

The GOCE ground segment is composed of several elements dealing with data processing and data analysis. Fig. 1 shows the current layout of the ground segment elements and their interfaces (for more details see [1]). While the Payload Data Segment (PDS) is responsible for the generation of the level 1b products, which are the internally calibrated gradiometer and GPS observations, the HPF is designed for the determination of quick-look and ultimate precision GOCE orbits and gravity field products based on these level 1b data (see chapter 4 and 5). The processing chain includes various steps from scientific pre-processing and external calibration to the final product validation (see chapter 4). In addition the HPF handles several interfaces to external data providers, which are required for level 2 data processing (e.g. International GPS Service (IGS), International Laser Ranging Service (ILRS) and European Centre for Medium Weather Range Forecast (ECMWF)).

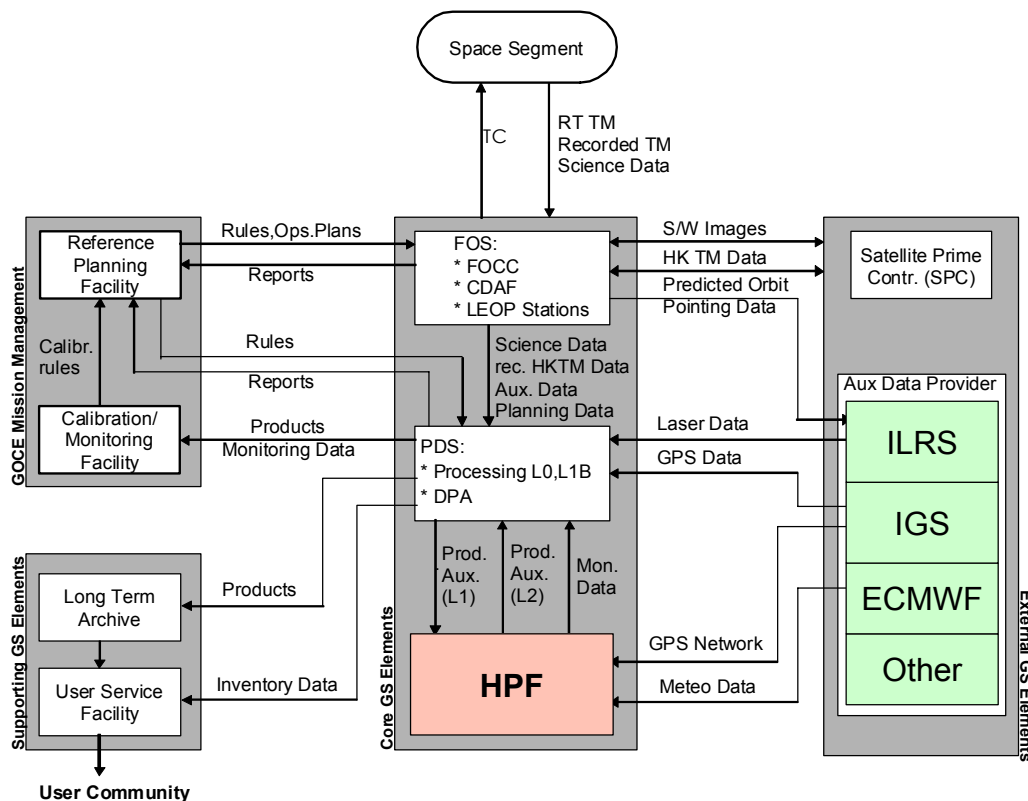


Figure 1: GOCE Ground Segment Elements [1]

The HPF is planned as a distributed system composed of several processing nodes. The development and operation of the HPF is intended to be done under ESA contract by the European GOCE Gravity Consortium (EGG-C). The consortium contributes significantly with its own facilities to the overall project goal. More details about the architecture of the HPF and the EGG-C is provided in the next chapter.

### 3. TASKS AND ARCHITECTURE

#### 3.1 High Level Processing Facility Tasks

The mission objective of GOCE is to provide a model of the global gravity field and geoid with highest possible accuracy and spatial resolution. More specifically the objective of GOCE is to determine the Earth's gravity field with an accuracy of better than 1 mGal, the global geoid with an accuracy of better than 1-2 cm and to achieve both with a spatial resolution of 100 km (half-wavelength) or better, which corresponds to a spherical harmonic expansion up to degree and order 200 [2]. In order to fulfil these objectives, a dedicated scientific data analysis is required. Starting from these objectives the major tasks for the HPF are as follows:

- a. The generation of level 2 products (orbits and gravity fields) from level 1b data generated by the PDS (nominal and calibrated products for the gradiometer and the GPS-receiver): The level 1b products consist mainly of gravity gradients in the gradiometer reference frame and pseudo-ranges and phases from the GPS receiver. They require a comprehensive scientific data processing before they can be translated into satellite positions, the corresponding velocities and gravity information in terms of a set of spherical harmonic coefficients, geoid heights, geoid slopes and gravity anomalies. These are the main products expected by the scientific users from the GOCE mission in geodesy, oceanography, glaciology, etc..
- b. The generation of GOCE calibration and validation products (external calibration of gradiometer data, quick-look gravity field and orbit solutions for data validation): The level 1b gradiometer products are internally calibrated. This means that calibration and non-linearity parameters are applied, which are derived from a dedicated data analysis of observations taken during satellite and electronic shaking manoeuvres. At this point no relation between the observed gravity gradients and the real gravity field has been established. In order to do so an external scientific calibration of the gravity gradients is performed by comparison with existing gravity information. Further-on level 1b products from both sensors, SST and SGG, have to be validated permanently in order to warrant a continuous high quality data flow, which is required to meet the mission objectives. For this reason the HPF implements several validation tools, which permanently survey the quality of the level 1b products by derivation of so-called quick-look or rapid products on a level 2 basis. This means orbit and gravity field solutions are systematically generated from partial data sets of new GOCE observations with latencies of a few days. These solutions are further validated in order to find out whether the mission performance requirements are met.
- c. The acquisition of auxiliary data needed for level 2 products generation: For level 2 data processing a wide range of ancillary data are required on a permanent basis. The most important are Earth rotation parameters from the International Earth Rotation Service (IERS), GPS orbit, clock and ground station data from the International GPS Service (IGS), satellite laser ranging data from the International Laser Ranging Service (ILRS) and atmospheric parameters from the European Centre for Medium Range Weather Forecast (ECMWF). Apart from this a variety of supporting data like planetary ephemeris, solar flux, geomagnetic indices, tide models, digital terrain models, external gravity field information and others have to be acquired. The HPF will acquire all ancillary data, check their quality and store them in a local HPF processing archive as well as in the long term GOCE archive, in case they are required for reprocessing purposes.

In summary one can say, that the HPF represents the interface between the pure satellite system (which is represented by the pre-processed level 1b products) and the science level 3 users. It applies scientific analysis techniques to the satellite observations in order to derive quantities adequate for level 3 analysis. This enables the exploitation of the mission in a multi-disciplinary approach.

#### 3.2 High Level Processing Facility Architecture

The HPF is intended to be developed and operated under ESA contract by EGG-C. The HPF is a distributed system led by a principal investigator and a management team. At this level also a central processing facility is implemented in order to facilitate the data flow from and to the other ground segment elements and internally within the HPF. Six high-level work packages, which represent the major steps for level 2 processing have been defined. For these work packages individual teams have been formed under the responsibility of individual work package managers. They represent some

of the best available expertises for each of these tasks. These teams are on one hand composed of existing institutionally/nationally funded personnel and on the other hand from additional personnel specifically working for the HPF development and operations. The teams are supported additionally by so-called scientific consultants, who are expected to contribute to specific scientific questions, which might come up during the HPF development. By this approach it is ensured that the whole available expertise within EGG-C is available for the work packages. Table 1 below shows the participating groups, their activities and roles within the HPF development and operations (the work package manager is responsible for the work package; partner institute are responsible for sub-work package(s) and are fully integrated in the HPF; scientific consultant provide scientific support without work package responsibility).

**Table 1:** HPF / EGG-C organisational architecture with a list of all activities and a distribution of the roles (major responsibilities for HPF development and operations are marked in italic)

<b>Institution</b>	<b>Activities / Work Packages</b>	<b>Role in Work Package</b>
IAPG: Institute of Astronomical and Physical Geodesy, Technical University Munich, Germany	<ul style="list-style-type: none"> <li>Financial, contractual and technical management</li> <li>Scientific pre-processing and external calibration</li> <li>Orbit determination</li> <li>Gravity field determination: time-wise approach</li> <li>Level 2 products validation</li> </ul>	<ul style="list-style-type: none"> <li><i>Principal investigator &amp; team management</i></li> <li>Partner institute</li> <li>Partner institute</li> <li>Partner institute</li> <li><i>Work package manager</i></li> </ul>
SRON: National Institute for Space Research, Utrecht, The Netherlands	<ul style="list-style-type: none"> <li>Technical and project management</li> <li>Scientific pre-processing and external calibration</li> </ul>	<ul style="list-style-type: none"> <li><i>Team management, central processing facility</i></li> <li><i>Work package manager</i></li> </ul>
FAE/A&S: Delft University of Technology, Faculty of Aerospace Engineering, Astrodynamics and Satellite Systems, The Netherlands	<ul style="list-style-type: none"> <li>Scientific pre-processing and external calibration</li> <li>Orbit determination</li> <li>Gravity field determination: time-wise approach</li> <li>Level 2 products validation</li> </ul>	<ul style="list-style-type: none"> <li>Partner institute</li> <li><i>Work package manager</i></li> <li>Scientific consultant</li> <li>Partner institute</li> </ul>
CNES: Centre Nationale d'Etudes Spatiale, Toulouse, France	<ul style="list-style-type: none"> <li>Gravity field determination: direct approach</li> </ul>	<ul style="list-style-type: none"> <li><i>Work package manager</i></li> </ul>
TUG: Institute of Navigation and Satellite Geodesy, Technical University Graz, Austria	<ul style="list-style-type: none"> <li>Scientific pre-processing and external calibration</li> <li>Gravity field determination: time-wise approach</li> </ul>	<ul style="list-style-type: none"> <li>Scientific consultant</li> <li><i>Work package manager</i></li> </ul>
POLIMI: DIAR - Sez. Rilevamento Politecnico di Milano, Italy	<ul style="list-style-type: none"> <li>Gravity field determination: space-wise approach</li> </ul>	<ul style="list-style-type: none"> <li><i>Work package manager</i></li> </ul>
AIUB: Astronomical Institute, University Bern, Switzerland	<ul style="list-style-type: none"> <li>Orbit determination</li> </ul>	<ul style="list-style-type: none"> <li>Partner institute</li> </ul>
GFZ: GeoForschungsZentrum Potsdam, Dep. 1 Geodesy and Remote Sensing, Germany	<ul style="list-style-type: none"> <li>Gravity field determination: direct approach</li> </ul>	<ul style="list-style-type: none"> <li>Partner institute</li> </ul>
ITG: Institute for Theoretical Geodesy, University Bonn, Germany	<ul style="list-style-type: none"> <li>Gravity field determination: time-wise approach</li> <li>Gravity field determination: space-wise approach</li> <li>Level 2 products validation</li> </ul>	<ul style="list-style-type: none"> <li>Partner institute</li> <li>Scientific consultant</li> <li>Scientific consultant</li> </ul>
UCPH: Department of Geophysics, University Copenhagen, Denmark	<ul style="list-style-type: none"> <li>Gravity field determination: space-wise approach</li> </ul>	<ul style="list-style-type: none"> <li>Partner institute</li> </ul>

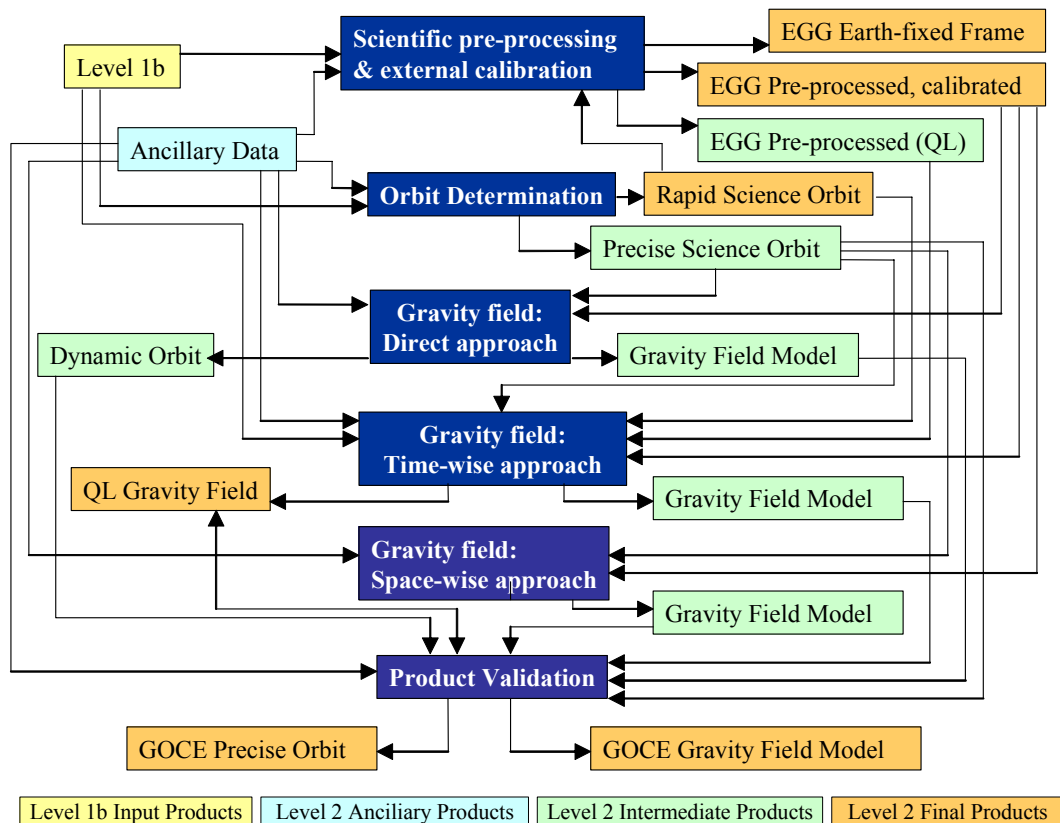
All team members are committed by contract which identifies their roles and responsibilities within the overall HPF design. Technical and project control is done by the management institutions (IAPG and SRON). They are also responsible for the whole system towards ESA. The management also ensures the establishment of any interface to other GOCE ground system elements. Operational data processing is performed in a distributed manner. The work package managing institutions provide significant computational resources for the operational data processing. Rapid and quick-look products generation require a nearly permanent processing. All sub-processing facilities are linked to each other via the central processing facility, which also implements the interface to the other ground system elements and to most of the ancillary data providers.

#### 4. PROCESSING STRATEGY

The recently modified layout of the sensor system of GOCE combined with the challenging mission goals requires a data processing strategy tailored to the system. EGG-C has developed such an approach. It comprises all necessary elements of pre-processing, external calibration and validation of level 1b data as well as the determination of quick-look and ultimate precision level 2 products, namely rapid and precise GOCE orbits, quick-look and precise models of the Earth gravity field derived from GOCE observations. Fig. 2 shows the processing sequence and the product flow through all processing steps from level 1b data to intermediate level 2 and finally to level 2 products. In particular the following processing task are performed:

*Scientific pre-processing and external calibration:*

External calibration is intended to determine bias, scale factor, trend and possible other slowly varying systematic effects (e.g. at frequencies of 1, 2, 3 or 4 cycles per revolution) that remain in the level 1b data after the in-flight calibration by comparison with known absolute gravity signals. The calibrated level 1b products undergo scientific pre-processing, which consists of identification and possible correction of data gaps and outliers using geodetic information, transformation to an Earth fixed reference frame including an error estimate for the transformed gravity gradients and the provision of corrections for the tidal and non-tidal time variable components of the Earth gravity field. The calibrated and scientifically pre-processed gradiometer data are the basis for all further data processing to level 2 products.



**Figure 2:** Processing flow in HPF from level 1b to final level 2 products

*Orbit determination:*

GPS code and phase (SST) observations undergo a first pre-processing during the rapid science orbit determination process. These SST observations or the derived orbit information together with the pre-processed gradiometer observations are the input for the gravity field processors. The GOCE orbits will be determined in two different quality levels (depending on the latency of the product) and with two different approaches (reduced-dynamic and kinematic). While reduced-dynamic orbits make use of the best available force models, kinematic orbits are computed in a pure geometric sense. Both orbit types are necessary for the subsequent processing steps. Rapid science orbits, having a short

latency, are necessary for the pre-processing of the gradiometer data and for the determination of the quick-look gravity field products to be used for GOCE validation. Precise orbits represent the ultimate accuracy for satellite positions and velocities and use the most precise available supporting data sets. Precise orbits represent one of the two fundamental input data sets, complementary to the gradiometer data. For precise gravity field determination the former will determine the long wavelength regime of the gravity spectrum, while the gradiometer data will provide the high frequency gravity information.

*Gravity field determination: direct, time-wise and space-wise approach:*

For gravity field processing three analysis techniques representing the classical approach as well as newly developed dedicated approaches for GOCE are implemented. (1) The classical method combines orbit and gravity modelling using orbit perturbation theory (direct method). (2) The second method is based on the so-called time-wise method. It views the gradient and SST observations as time series along the orbital track. It comprises a gravity gradient (SGG) modelling part, an SST gravity modelling component employing the energy integral approach and a quick look tool that will be capable to give a fast feedback based on partial data sets about the validity of the SGG/SST data for gravity modelling. (3) Finally, as a third method there is the space-wise method, which interprets the SST and SGG data as gravity functional of location in space. All three approaches will provide the GOCE gravity field with the highest possible resolution (degree and order 200 and beyond in terms of spherical harmonics). In the following the main characteristics of the three methods are shortly described:

- (1): The direct method uses a-priori orbits and an a-priori gravity field model, SST observations and common mode accelerations for setting up normal equations for gravity field determination in an iterative manner. The method is based on orbit perturbation theory. Gradiometer observations are processed in a separate linear step that results in a partial system of normal equations which is finally combined with the SST normal equations. The complete system is solved for the unknown gravity field coefficients and the quality information is provided in the a-posteriori variance-covariance matrix.
- (2): The time-wise method uses an approach tailored to GOCE observations. It is based on an epoch-wise (time-wise) processing of SST and SGG observations following the least-squares principle. For SST data analysis use is made of the kinematic orbit solutions applying the energy integral approach. The precise gravity field analysis is complemented by a quick-look tool using a simplified semi-analytical method for the purpose of analysing the quality of the level 1b input data.
- (3): The space-wise approach retrieves the gravity field coefficients from observations which are transformed into a regular grid on a reference surface or into a spatial grid. Spatialized observations will be produced from SST and SGG observations using a Wiener orbital filter. The spherical harmonic coefficients of the gravity field will be computed using fast least squares collocation or spherical harmonic analysis method.

*Product validation:*

The official orbits and gravity field solutions are selected after a comprehensive evaluation of the products has been done. Internal and external comparisons using independent test data sets are performed in order to select the best solutions. The independent data tests and test methods are chosen such as to check the various spectral bands of the GOCE model. The validation sequence includes orbit tests, comparison with terrestrial gravity, with GPS levelling, ocean topography models etc. All test results are summarised in a validation report, which is then the basis for selection of the final GOCE products. A scientific GOCE products advisory group will be established, which will formulate the recommendation of official GOCE products on basis of the validation report.

## 5. LEVEL 2 PRODUCTS

As shown in Fig. 2 during the level 2 processing various intermediate level 2 products are generated. They contain intermediate results necessary for the next processing step in sequence. These products are not foreseen to be provided as standard GOCE products to the users. Final level 2 products, which will be accessible by the GOCE user community are identified in Fig. 2, too. Table 2 provides a more detailed pre-view of these level 2 products, which are generated by the HPF. The latencies of the final products are related to data availability of the level 1b products. Three classes of products can be identified from that point of view. The rapid and quick-look validation products will be available within a few days after level 1b data are provided. For the quick-look gravity field model it is planned to compute weekly a new model that is based on the previous week of new level 1b data. Pre-processed and calibrated gradiometer data and precise science orbits will be available with a latency of two weeks. Both products represent the main input to the gravity field processors. The final gravity field solution, which will be selected from the three competing approaches after an extensive validation will be available about 9 months after completion of each measurement operations phase. The transformed gravity gradients in an Earth fixed frame will be available after approximately 6 months. In order to

reduce the transformation errors as much as possible several months of data will run through that procedure simultaneously.

**Table 2:** HPF level 2 products overview

Identifier	Description	Latency
Pre-processed & calibrated gradiometer data	<ul style="list-style-type: none"> <li>Externally calibrated and corrected gravity gradients in GRF</li> <li>Corrections to gravity gradients due to temporal gravity variations</li> <li>Flags for outliers, fill-in gravity gradients for data gaps with flags</li> <li>Statistical information</li> </ul>	2 weeks
Gravity gradients in Earth-fixed frame	<ul style="list-style-type: none"> <li>Externally calibrated gravity gradients in Earth fixed reference frame including error estimates for transformed gradients</li> <li>Transformation parameters to Earth fixed reference frame</li> </ul>	6 months
Rapid science orbits	<ul style="list-style-type: none"> <li>Rapid science orbit from reduced dynamic approach</li> <li>Rapid science orbit from kinematic approach</li> <li>Rapid science orbit quality assessment</li> </ul>	1 day
Quick-look gravity field models	<ul style="list-style-type: none"> <li>Quick-look Earth gravity field model from SST only</li> <li>Quick-look Earth gravity field model from SGG only</li> <li>Quick-look Earth gravity field model from SST and SGG combination</li> <li>Diagnosis report sheets for all models</li> <li>Quick-look gravity field quality assessment report</li> </ul>	3 days
Precise science orbits	<ul style="list-style-type: none"> <li>GOCE precise science orbits final product</li> <li>Quality report for precise orbits</li> </ul>	2 weeks
Final GOCE gravity field models	<ul style="list-style-type: none"> <li>Final GOCE Earth gravity field model as spherical harmonic series including error estimates</li> <li>Variance-covariance matrix of final GOCE Earth gravity field model</li> <li>Grids of geoid heights, gravity anomalies and geoid slopes computed from final GOCE Earth gravity field model including propagated error estimates</li> <li>Quality report for final GOCE gravity field model</li> </ul>	9 months

## 6. CONCLUSIONS

The HPF is part of the ESA GOCE ground segment and is in charge of the production of level 2 products i.e. precise orbits and gravity field solutions. These level 2 products represent the main and official outcome of the mission and are input to further scientific studies in various disciplines of Earth sciences. The HPF is intended to be developed, implemented and operated by the European GOCE Gravity Consortium under contract of ESA. All EGG-C member institutions (all together 10 university/research institutes across Europe) contribute in an important manner to the HPF by providing additional institutionally/nationally funded personnel and computer resources. A processing sequence from level 1b to quick-look and ultimate precision level 2 products was identified and partly developed during the last years. Quick-look processors are foreseen as a continuous validation tool for level 1b data. Any degradation in the GPS or gradiometer observations should immediately become visible in these rapid gravity field and orbit solutions. For the ultimate precision gravity field model it is planned to develop and run three processors in parallel. Two have been developed directly for GOCE and one is a modification of the classical approach based on perturbation theory. By this the quality of the solutions can be assessed against each other. After an additional extensive external validation of the gravity field products the final GOCE products are recommended to a scientific advisory committee. This group finally selects the official ESA GOCE products.

## 7. REFERENCES

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