# GOCE

# CALIBRATION & VALIDATION PLAN FOR L1b DATA PRODUCTS

**Prepared by:** M. Drinkwater and M. Kern

**Checked by:** GOCE Project

GOCE Cal/Val Team

ESTEC
Noordwijk
The Netherlands

# DOCUMENT SIGNATURE PAGE

| | Name & Function | Date | Signature |
|---|---|---|---|
| Prepared by: | **M. R. Drinkwater** (EOP-SMO) | 22/05/06 | |
| Checked by: | **R. Floberghagen** (EOP-PG) | 22/05/06 | |
| Checked by: | **A. Popescu** (EOP-PG) | 29/05/06 | |
| Approved by: | **D. Muzi** (EOP-PG) | 29/05/06 | |
| Approved by: | | | |

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# 1 PURPOSE OF DOCUMENT

The purpose of this document is to provide a framework for the activities planned in connection with the calibration and validation of Level 1b data products from the GOCE mission. It contains information on the overall context for GOCE-related calibration and validation, together with a summary of each of the planned activities, including information about their goals, methodology and their outputs, as well as a list of participants. The objective of documenting each specific effort is to identify each expected contribution to either calibration or validation of Level 1b products, in order to fully appreciate what areas are covered by existing plans, and whether further attention to detail may be required.

The Calibration and Validation Plan is not intended to provide a detailed work plan with specific details of how the objectives of each effort will be fulfilled, but rather is intended as a living document comprising a comprehensive description of the respective contributions.

The document is the result of a close collaboration between the Agency, Industry, the GOCE Mission Advisory Group, and the GOCE Calibration and Validation Team. The framework for this collaboration was provided by the European Space Agency's Announcement of Opportunity "Scientific Pre-processing, External Calibration and Validation of Level 1b Data Products for the GOCE Mission" issued on 18 July 2003 (RD1), together with additional inputs and recommendations received at two GOCE International User Workshops (see: http://earth.esa.int/goce04/first_igw/ and http://earth.esa.int/goce04).

# 2 CAL/VAL RATIONALE

The overarching goal of performing Calibration and Validation activities is to quantify the GOCE system response (i.e. calibration), to verify the performance by comparison with independent sources of data (i.e. validation), and in doing so to assess and quantify uncertainties in the GOCE measurements. The execution of Calibration and Validation (hereafter known as Cal/Val) activities should therefore ensure that the highest possible quality Level 1b (or L1b) data can be fed into the Level 2 (or L2) data processing system, such that the scientific end users will be able to access the best possible Level 2 GOCE data products.

Uncertainties or errors in the GOCE data may arise from a number of systematic or stochastic sources described in greater detail later in this document. In general, errors result from imperfections in the measurement system and ultimately determine the quality of the Level 1b products.

For the Level 2 Processing Facility to successfully generate products that fulfil the high-level scientific goals of the GOCE mission, it is first necessary to assess the spacecraft performance and to verify that the Level 1b performance requirements are met prior to attempting to generate Level 2 gravity field products. For this reason, this document focuses solely on the plans for calibration and validation of Level 1b products.

For the purpose of clarity in this document we strictly apply the Committee on Earth Observing Satellites (CEOS) Working Group definitions for Calibration and Validation. These are as follows:

*Calibration*

Calibration is the process of quantitatively defining the system responses to known, controlled, signal inputs.

*Validation*

Validation is the process of assessing by independent means, the quality of the data products derived from the system outputs.

In the most simple terms calibration can be understood as to allow the voltages measured by the individual GOCE accelerometers to be converted via ‘scale factors’ into accelerations, and that the differential signals measured by pairs of accelerometers can be similarly converted into gravity gradients along each axis of the gradiometer. Validation ensures that the quality of the products is properly assessed, via quantification of the uncertainties in the Level 1b products.

A team, formed from the approved proposals from the Cal/Val AO, will participate in the overall Cal/Val activities. Each of the contributors will participate in the process of verification/qualification of Level 1b data before the nominal spacecraft-commissioning phase is declared complete. In order for the Level 1b products to be declared valid and publicly released to the scientific community, the evaluation of the Level 1b products must first demonstrate that specific performance criteria have been successfully met. This implies the assessment of the calibration and performance of the primary payload through the inter-dependent methods planned and documented below.

# 3 GOCE MISSION OVERVIEW

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) is the first Core Earth Explorer Mission selected in the context of ESA's Living Planet Programme. The overall goal of the mission is to produce high-accuracy, high-resolution global measurements of the Earth’s static gravity field for use in a wide range of applications in oceanography, solid-earth physics, geodesy, glaciology, and sea-level research (RD2, RD3).

The GOCE satellite launch is foreseen in spring 2007, on a one metric tonne-class Rockot launch vehicle from Plesetsk in Russia. The planned operational lifetime is 20 months, with a possible extended mission of a total duration of up to 30 months.

## 3.1 Mission Objectives

The primary GOCE scientific mission objective (RD4) is to provide a global model of the Earth’s gravity field and the geoid, its reference equipotential surface, with high spatial resolution and accuracy. More specifically, after ground processing, the goals are to determine the Earth’s gravity field and its anomalies with an accuracy better than 1 mGal (1 mGal = $10^{-5}$ $ms^{-2}$), and the global geoid with an accuracy better than 1-2 cm. Both these goals should be achieved at a spatial resolution of 100 km (half-wavelength) or better, corresponding to a spherical harmonic expansion up to degree ($L$) and order ($M$) 200. Degree $L$ represents a spherical harmonic component of the gravity field with half wavelength $\lambda = \pi R/L$ (approx 20,000/$L$; where $R$ is the Earth's radius).

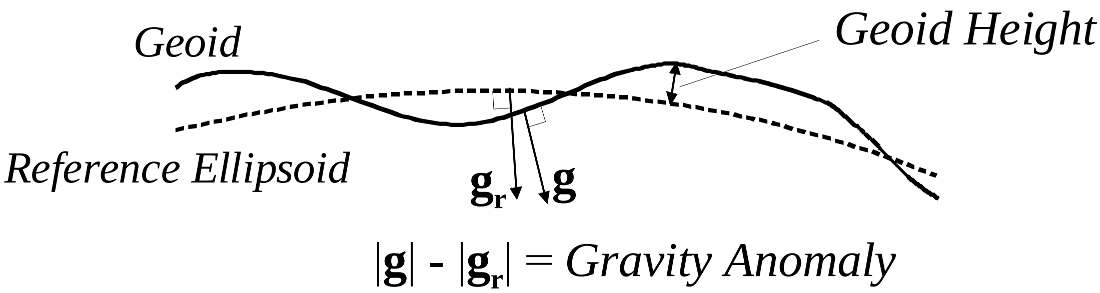


**Figure 1.** Definition of geoid height and gravity anomaly.

The strength of Earth's gravity signal is rapidly attenuated with altitude. Moreover, with a constant instrument resolution, gravity measurement resolution in space depends on orbit altitude (where a reduction in altitude of 60 km improves the measurement resolution by around a factor of 10). Since a high-resolution gravity measurement (and high harmonic degree $L$) is desired by GOCE, as low an orbit as possible is sought. The main trade-off for a low altitude orbit configuration is the effect of disturbing accelerations from atmospheric drag, as well as the demands placed on the spacecraft design and propulsion system. Thus, the nominal orbit altitude of 250 km is a trade-off between scientific performance and the satellite systems capability for rejecting unwanted disturbing accelerations.

The primary scientific requirements for the GOCE mission (RD4) are met by bulk processing of the various measurements – gravity gradients (measured in Eötvös; 1E = $10^{-9}$ $ms^{-2}/m$) and positions along orbit – within the High-level Processing Facility (hereafter known as HPF). The HPF requires calibrated Level 1b instrument measurement data to be acquired simultaneously by the two satellite instruments, the Gradiometer and Satellite-to-Satellite Tracking (SST) receiver, over a time span of several months. The following section briefly describes the satellite payload.

## 3.2 Payload description

### *3.2.1 Primary Payload*

The measurement techniques used to achieve the GOCE mission objectives are gradiometry and precise three-dimensional satellite-to-satellite positioning. In order to accomplish this, the GOCE primary payload comprises two core instruments: an Electrostatic Gravity Gradiometer (EGG) and a Satellite-to-Satellite Tracking Instrument (SSTI). These two instruments are complemented by two star trackers (STR), which provide precise knowledge of the orientation of the spacecraft with respect to the inertial reference frame.

The EGG is a three-axis, six-accelerometer satellite gravity gradiometer, each arm of which comprises a pair of ultra-sensitive capacitive accelerometers, which exploit 'so-called' differential accelerometry. In principle the difference in acceleration measured between each pair of accelerometers is proportional to the gravity gradient in the direction joining that sensor pair through a constant "scale factor". On-orbit calibration is required to derive the appropriate adjustments to the pre-launch scale factors, and the resulting calibrated instrument provides the basis for deriving the full gravity gradients tensor.

SSTI incorporates a geodetic GPS receiver for high-low (hl) tracking between the GPS satellite constellation and the low-flying GOCE satellite (see Figure 2). This technique is later referred to as SST-hl. In this configuration, the positional data derived with respect to the known orbits of the reference GPS satellites are used to extract gravity information through orbit perturbation analysis.

The techniques of gradiometry and SSTI are complementary in that SST-hl allows derivation of the long and medium wavelength part of the gravity field, while gradiometry is especially sensitive to the short-wavelength part. The point of overlap between the gravity retrieval capabilities of SST-hl and gradiometry begins at around degree and order $L = 15$, or the equivalent of 1300 km resolution. The SST-hl overlaps the gradiometer capability up to at least $L = 60$, or the equivalent of 330 km resolution.

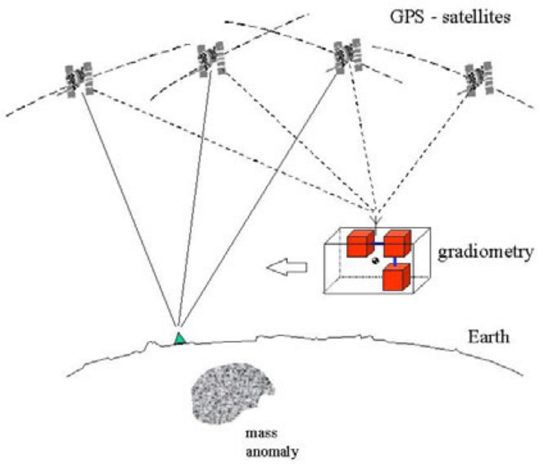


**Figure 2.** Schematic illustration of the combined satellite gravity gradiometer (SGG) and satellite-to-satellite (high-low) tracking mission concept.

### *3.2.2 Secondary Payload*

In addition to the Gradiometer and SSTI, the GOCE spacecraft carries a secondary payload comprising an array of laser retroreflector cubes. Under favourable weather conditions, the Laser Retro-reflector (LRR) provides ground-based tracking of the satellite by satellite laser ranging (SLR) stations. LRR also provides an important independent means of verifying orbits derived using the SSTI.

## 3.3 Ground Segment Overview

The overall concept and architecture of the GOCE Ground Segment (G/S) is described in (RD5). The following gives a brief summary of all elements of the ground segments, depicted in Figure 3.

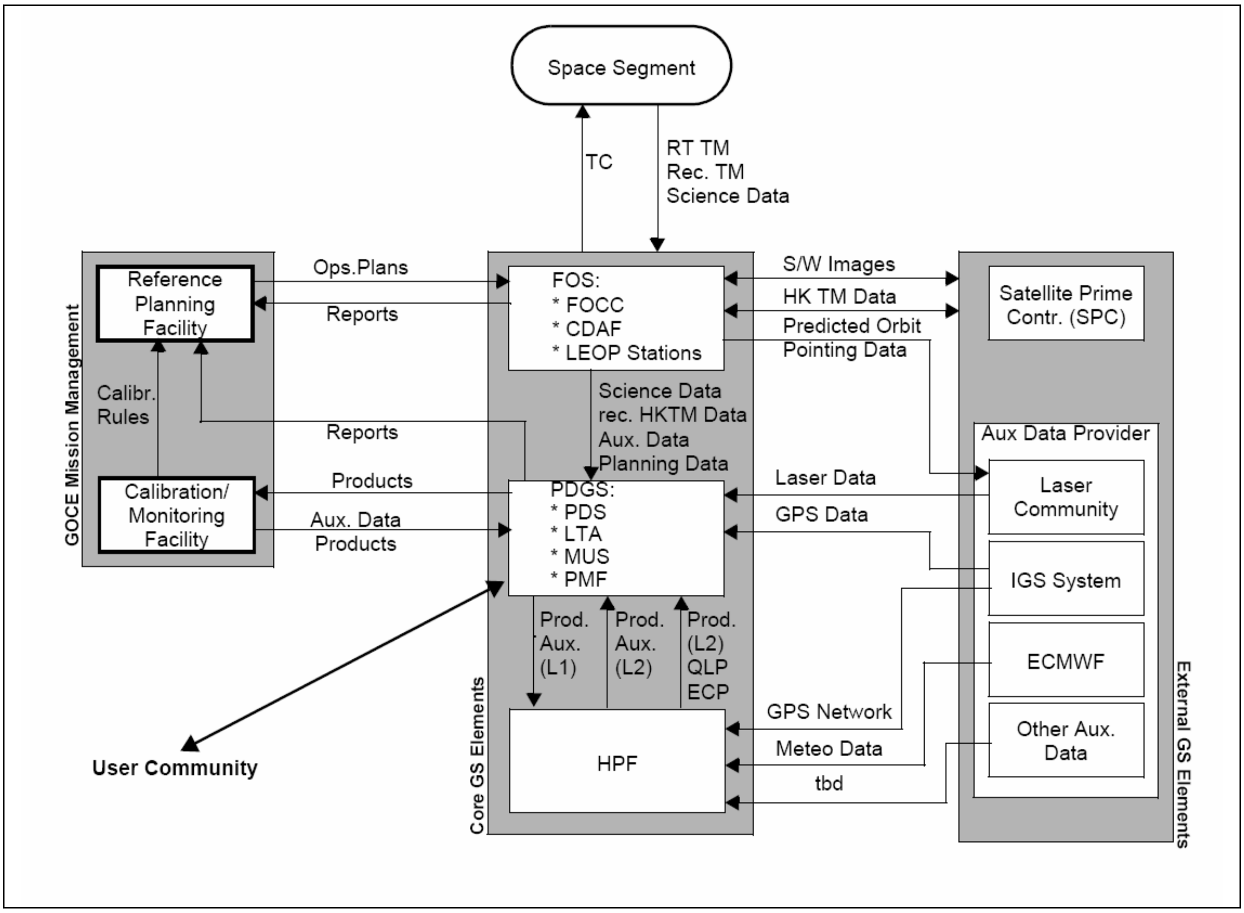


**Figure 3.** GOCE Ground Segment elements.

Regarding the GOCE data product generation, the key components of the G/S in the context of Calibration and Validation activities are the Payload Data Ground Segment (PDGS), the High Level Processing Facility (HPF), and the Calibration Monitoring Facility (CMF).

Within the PDGS, the GOCE Payload Data Segment (PDS), which includes the Instrument Processing Facility (IPF), produces the Level 0 and Level 1b data products and provides them, together with auxiliary parameter files, to the High Level Processing Facility. The HPF in return pre-processes the L1b data, generates Quick-Look (QL) analysis products (with which to assess and verify the L1b data quality), and returns Level 2 products to the PDS.

Meanwhile, the Calibration/Monitoring Facility (CMF) is responsible for the continuous monitoring of the Level 1b product performance on the basis of data collected in the PDS. It also relates the product performance to the spacecraft health, configuration and instrument performance.

The High Level Processing Facility plays an instrumental role in the scientific calibration and validation of the Level 1b data products.

## 3.4 Error budget for gravity gradiometry

Gradiometry is affected by several error sources which can be grouped into four main classes (RD2, RD6):

- Instrument errors (I)
- Instrument-satellite coupling errors (C)
- Satellite errors (S)
- Processing errors (P)

An overview of the gradiometer error budget components is provided in Figure 4 to indicate the primary error contributors.

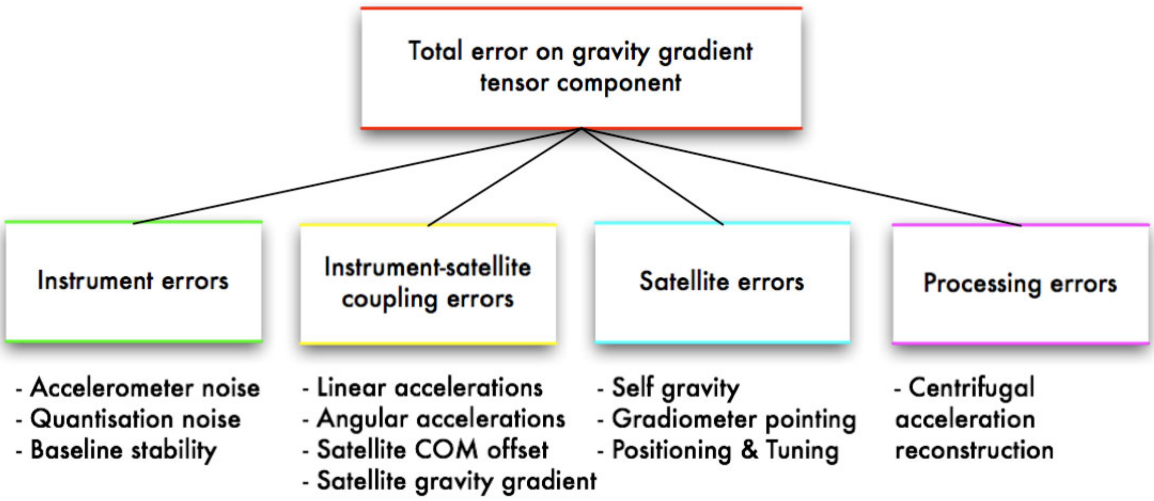


**Figure 4.** Gravity gradiometry error budget overview.

Instrument errors depend only on the EGG performance, and are the result of accelerometer noise, measurement quantisation noise, and the gradiometer baseline stability (RD2, RD6). The instrument-satellite coupling errors depend on the performance of the gradiometer and spacecraft together. They include the coupling of the gradiometer with residual non-gravitational linear and angular accelerations of the satellite; with the residual angular accelerations and the satellite Centre of Mass (COM) offset with respect to the gradiometer centre; or the coupling of the proof mass motion with the static gradient of the satellite self-gravity field.

Satellite errors depend on the performance of the satellite and may be due to; variations in self gravity field caused by thermoelastic deformation of the structure; mixing of the diagonal components of the gravity gradient tensor due to gradiometer pointing errors; or localisation inaccuracies in the gradiometer measurements due to errors in satellite positioning or data errors.

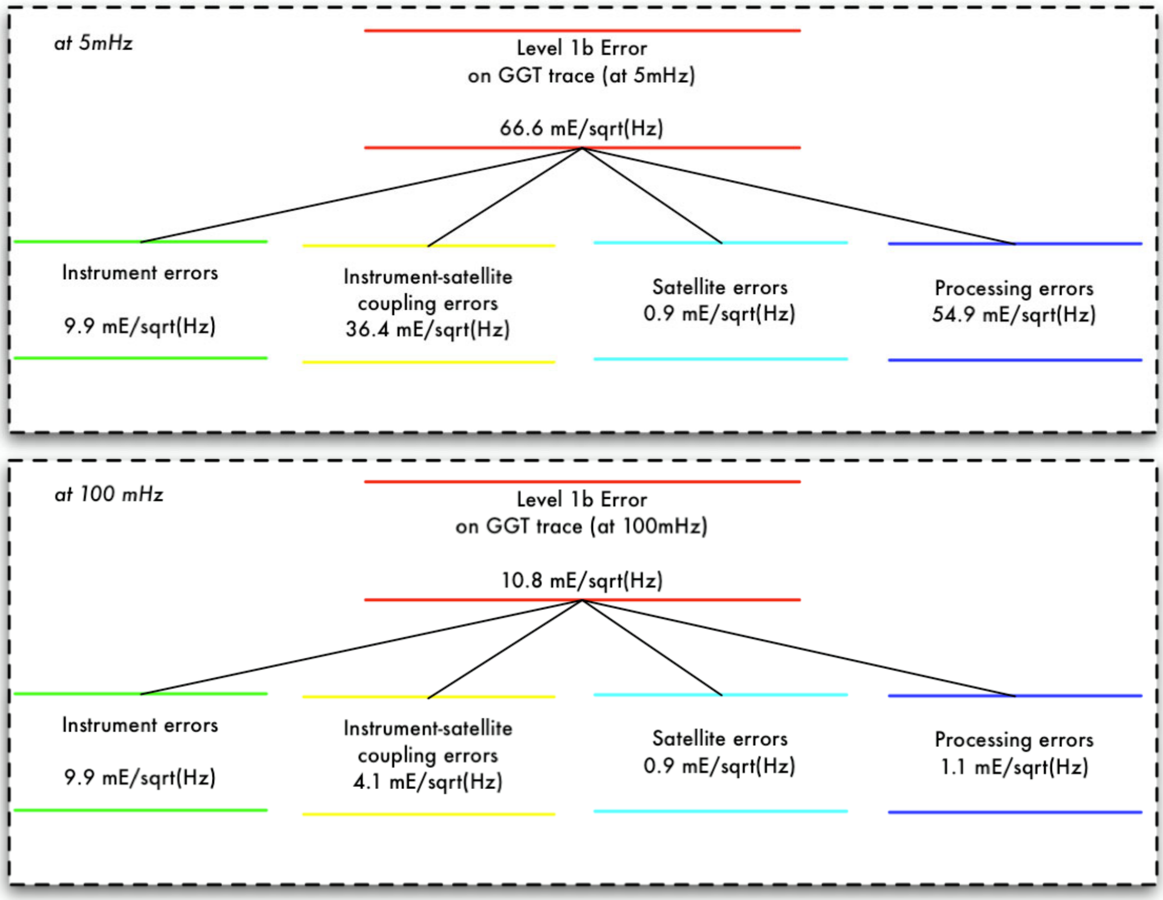


**Figure 5**. Level 1b gradiometry error budget.

Finally, processing errors are the result of residual uncertainty in the reconstructed variations in satellite spin rate, when a combination of star tracker and EGG data are combined during ground data processing. The centrifugal acceleration is the largest contaminant of the along-track (xx) and radial (zz) components of the gravity gradient tensor and must be removed from the data before determination of the Earth's gravity field.

The gradiometer and spacecraft performances were optimised during Phase A-B in order to minimise the error on the $V_{xx}$, $V_{yy}$, and $V_{zz}$ components of the gravity gradient. Moreover, during Phase B - C/D a complete error budget was established (RD6), for the purpose of assigning values for the contribution of each specific error source. The individual error contributors are discussed in further detail below.

### *3.4.1 Gradiometer performance requirements*

The gradiometric performance is not only a function of the gradiometer but of the whole satellite and the environment, so the gradiometric budget includes all satellite and Level 0 to Level 1b processing errors.

The specified GOCE gravimetric mission goal is to provide, after Level 0 and Level 1a/1b ground processing data that conform to the so-called 'trace' requirement. The trace, or residual Earth gravity gradient tensor (GGT) measurement error should not exceed a pre-specified residual level within the measurement bandwidth (MBW = 5 mHz to 100 mHz) in the gradiometer reference frame (GRF) (for definition of the GRF refer to RD6, RD7). The current apportionment of this top-level measurement error to the various contributors is also provided in the error tree of Figure 5, and is shown at the low frequency (5 mHz) and high-frequency end (100mHz) end of the MBW. The apportionment is based in large part on a root-sum-square (RSS) of the error terms, since these various sources are considered in large part uncorrelated (RD6). Note that a contingency margin has been applied with respect to the System performance requirement shown in Figure 6.

Current performance information (at time of System Critical Design Review) would suggest that at a frequency of 5 mHz, the total L1b error is about 67 mE/Hz$^{1/2}$, where around 10 mE/Hz$^{1/2}$ are allocated to the Gradiometer Instrument Errors. Of the remaining part 36 mE/Hz$^{1/2}$ are distributed to the Instrument-Satellite Coupling Errors, the Satellite Errors (1 mE/Hz$^{1/2}$) and the Processing Errors (55 mE/Hz$^{1/2}$), from which the requirements on the quantities driving the satellite subsystem design (residual accelerations, COM location, pointing and alignment stability, etc..) are finally obtained (see next section). The allocated portions are the result of a living iterative-process consisting in the comparison of the requirements to the results of the performance analyses and tests.

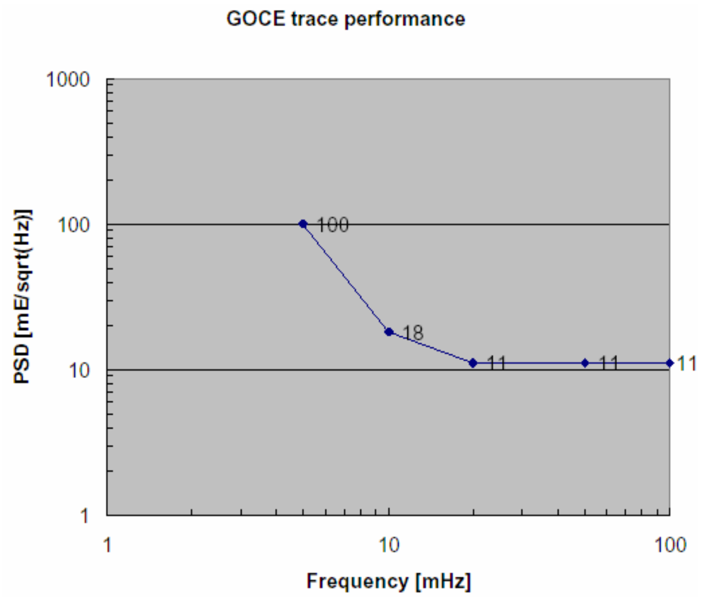


**Figure 6.** The blue curve indicates the trace requirement, based on the yaw-piloting, mode during science measurements (RD8).

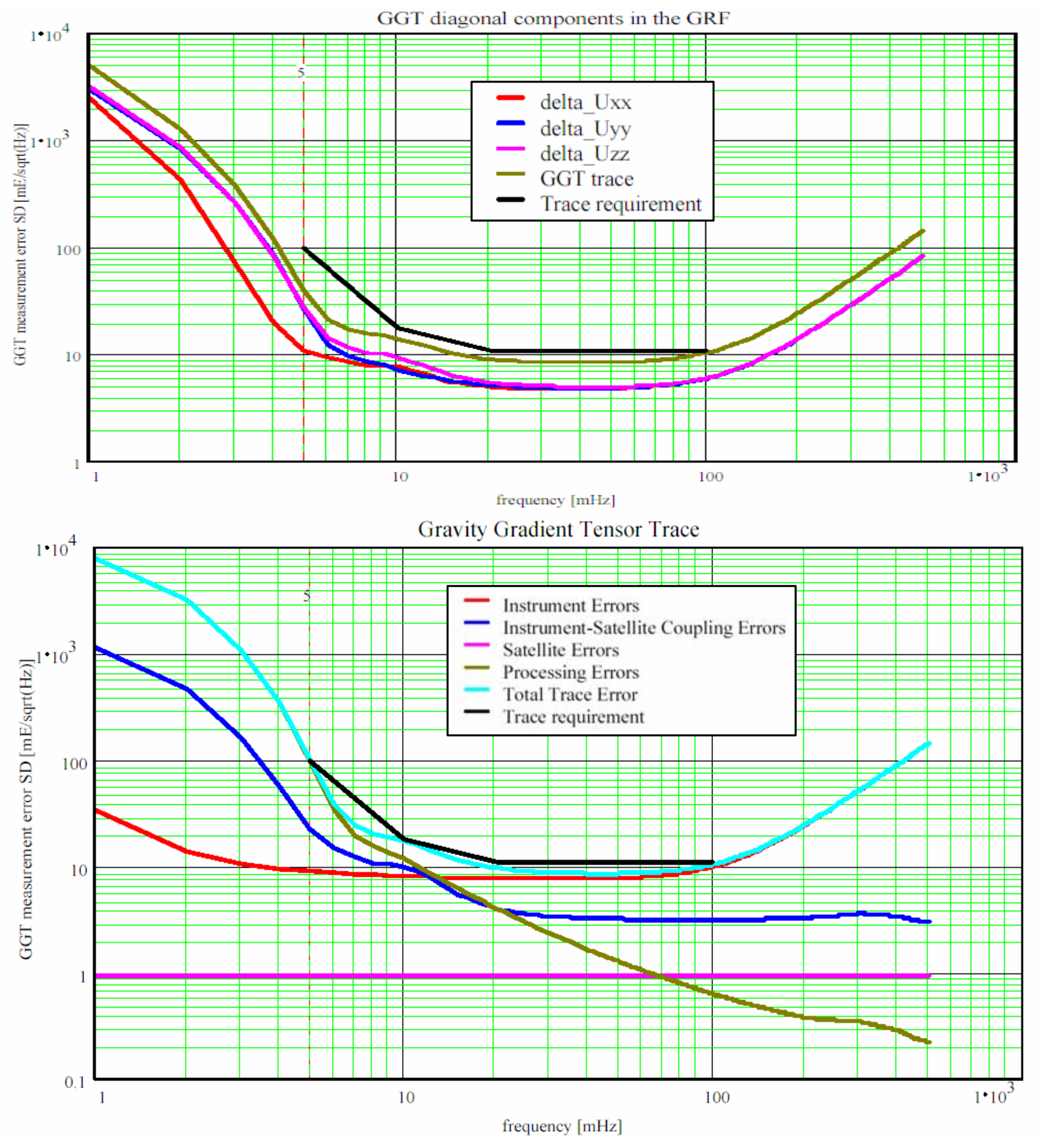


**Figure 7**. Individual contributions to the predicted total Gravity Gradient Trace (GGT) error, based on GOCE system simulations.

### *3.4.2 Trace Performance Criterion*

After Level 0 to Level 1b ground processing, the trace of the gravity gradient tensor diagonal components ($V_{xx}$, $V_{yy}$, $V_{zz}$) shall not exceed the spectral density limits defined in Figure 6 in the measurement bandwidth 0.005 to 0.1 Hz in the gradiometer reference frame. Figure 7 indicates the relative contributions to the tensor trace quantity. Performance is poorer at lower frequencies where the environmental influence is larger as a result on the lack of control on Y and Z linear accelerations, and due to the limited control on angular accelerations (RD7).

## 3.5 Error Budget for Satellite to Satellite Tracking

Reconstruction of the gravity field from the effect it has on the satellite trajectory requires the precise orbit determination (POD) from the 1 Hz satellite to satellite tracking instrument (SSTI) data. Orbit determination by the HPF is undertaken in two steps. First, the reference trajectory of the GOCE spacecraft, or Rapid Science Orbit (RSO) is determined using reduced dynamic (RD) and kinematic (KI) techniques, as part of the Quick-look (QL) processing within the HPF, and shall be accurate to a few decimeters. The GPS data, together with this reference orbit, will then subsequently be used in both reduced dynamic and kinematic techniques to determine the precise science orbit (PSO) with errors reduced to centimetre level.

Kinematic POD does not need as input the non-conservative forces on the spacecraft, thus the achievable accuracy in the determination of the position of the satellite COM depends mainly on the following contributions:

- SSTI measurement noise
- SSTI ground station coordinates error
- SSTI ephemeris error
- Troposphere correction error
- Phase centre location error of the GPS antenna
- The error in the location of the spacecraft COM relative to the GPS antenna

For dynamic POD, errors on the measurement of the non-conservative linear accelerations of the satellite COM, and in the knowledge of the gravity field, must be added to the above list.

The performance specifications for the SSTI measurements (RD8) are:

- Carrier phase noise on L1 less than 0.001m
- Carrier phase noise on L2 less than 0.001m in the absence of anti-spoofing and less than 0.0049m in presence of anti-spoofing.
- C/A code pseudo-range noise on L1 less than 0.5m
- P(Y)-code pseudo-range noise on L1 and L2 less than 0.25m (in absence of anti-spoofing). The requirement is 1.5 m in presence of anti-spoofing.

The expected multi-path effect (due to signal reflection off the satellite structure prior to arrival at the GPS antenna) is less than 0.004 m, while the contribution of multi-path to the code error is expected to be lower than 0.15 m (RD9). All these requirements are applicable to GPS satellites above $15^{o}$ elevation, as seen by the GOCE spacecraft.

## 3.6 Basic Product Description

The three basic levels of data products to be produced by the ground segment (Figure 3) will be the following:

### *3.6.1 Level 0*

Raw data (i.e. prior to Level 0 processing) will be down-linked by GOCE during contact with the Kiruna ground station. Level 0 data consists of the time-ordered science and housekeeping data produced by the Gradiometer, data generated by the platform, and housekeeping data.

Each of these data streams are needed to process the intermediate and Level 1b data products and to check their quality.

The Level 0 scientific product of the Gradiometer contains the 8 control voltages applied to the 8 electrode pairs which surround the proof mass to keep it in a nearly motionless condition at the centre of its cage under the effect of the forces acting on the spacecraft and directly on the proof mass itself. These control voltages, provided by the instrument with a ~1 Hz output frequency (more precisely at 1/0.999360 Hz), together with the relevant instrument and satellite housekeeping and ancillary data, are contained in the Gradiometer telemetry packets downlinked by the satellite.

Level 0 products include:

- satellite and instrument housekeeping data and ancillary data (such as attitude quaternions measured by the star trackers at 2 Hz)
- output of the 6 accelerometers along their 3 measurement axes at 1 Hz
- SSTI data at 1 Hz (see RD10)

### *3.6.2 Level 1b*

The Level 0 to Level 1 processing by the Instrument Processing Facility (IPF) in PDS will extract the control voltages from the telemetry and will arrange them in an ordered time series (e.g. files with the time on the first column and the other parameters on the other columns). Conversion will be performed into engineering units, as necessary. Resulting products include sorted time-series of calibrated, corrected and geolocated data along the orbit in XML, including:

- gravity gradients in GRF together with the GRF to Inertial Reference Frame (IRF) frame transformation matrices,
- linear accelerations and angular rates and accelerations,
- SST measurements and derived positions and reconstructed satellite orbits in Earth-Fixed Reference Frame (also available in RINEX format),
- attitude (position, velocity and time) and orbit data

The pre-processing, essentially consisting of channel decommutation and reformatting by the Instrument Processing Facility (within the PDS) will not contain any scientific evaluation (RD11, RD12). The raw data will contain the readouts from the instruments together with calibration, time attitude and other housekeeping information like temperatures, as required. After calibration, validation and correction of the satellite data, the scientific data will be pre-processed and stored as Level 1b data on appropriate media as they are generated during the mission. The main Level 1b output will be calibrated and validated gravity gradients in the GRF. The Level 1b data shall also include the attitude, angular velocity and angular acceleration history of the satellite. These processing tasks will require the development of special algorithms which will be part of the general industrial development of the satellite and which are needed to verify the gradiometer.

SSTI receiver data will be provided to the HPF. To exploit these data it is necessary to use the IGS service - which routinely computes high accuracy ephemeris of the GPS satellites. In addition to SST Level 1b data the gradiometer Level 1b data products will be transferred to the HPF in order to perform the final data reduction.

#### *3.6.3 Level 2*

Within the GOCE Ground Segment (Fig. 3) the HPF is the core element responsible for generation of the Level 2 products and acquisition of external (auxiliary) products needed to generate these products (e.g. from the IGS and ECMWF). The HPF is a distributed system developed and operated by the European GOCE Gravity-Consortium (EGG-C)

Level 2 products processed by the High Level Processing Facility include (RD13):

- Pre-processed, externally calibrated, and corrected gravity gradients in both Gradiometer Reference Frame and Terrestrial Reference Frame.
- Rapid and precise science orbits.
- Gravity field solutions including variance-covariance matrix and derived quantities (geoid heights, gravity anomalies, and geoid slopes).

### 3.7 GOCE Mission Profile

GOCE will fly in a low-altitude, near-circular, sun-synchronous dusk-dawn orbit (or alternative dawn-dusk configuration) with an inclination of $96.5^{o}$. This particular orbit offers near global coverage (with small polar hole), whilst minimising the eclipse periods. It also presents the advantage of a simplified spacecraft design with fixed solar panels, whereby the orbit plane is maintained such as to maximise the solar illumination of the body-mounted solar panels.

GOCE launch is planned for spring 2007 by a Rockot launcher from Plesetsk, Russia and has a nominal mission duration of 20 months. The spacecraft will be placed into orbit at approximately 270 km target altitude (TBD) (see Figure 8). From this altitude, the orbit will be allowed to decay throughout the 1.5 month duration spacecraft commissioning phase. During spacecraft commissioning, the orbit altitude will be allowed to decay to the nominal operations altitude of 250 km. After an instrument set-up and in-orbit calibration period of 1.5 months, the first Mission Operations Phase (MOP 1) or science measurement phase will take place over a duration of 6 months. During this period, the satellite will maintain a constant altitude in yaw piloted mode. Non-gravitational accelerations, mainly due to atmospheric drag, will be actively controlled by equal and opposite forces applied in the along-orbit direction by the Drag-Free and Attitude Control System (DFACS) use of one of the ion-thrusters. However, due to the reduced attitude control authority, yaw, pitch and roll have consequences for the error structure in the data.

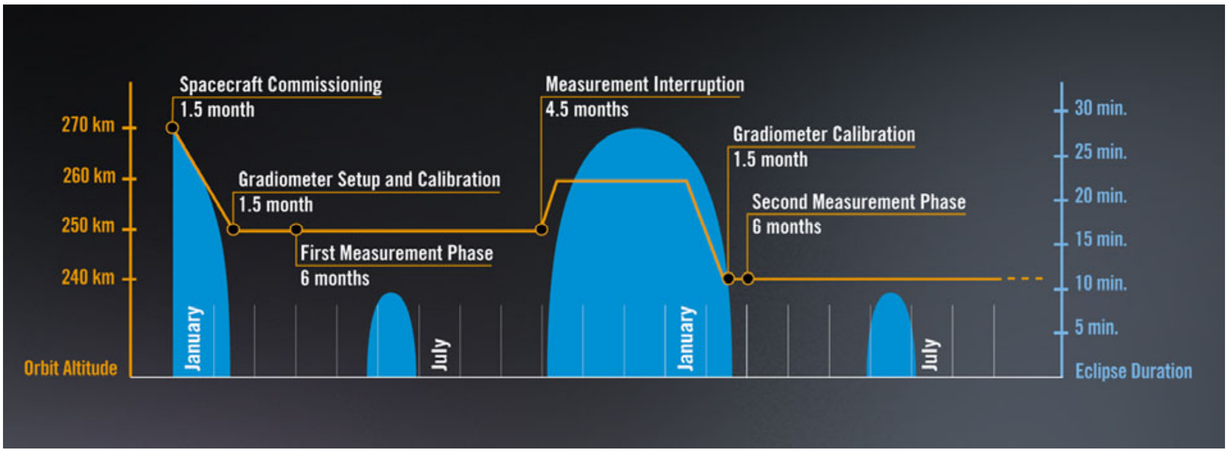


**Figure 8.** The mission profile for a northern-hemisphere winter launch scenario (dawn-dusk orbit) is depicted. A summer launch (in a dusk-dawn orbit) will result in the same eclipse pattern. Major cal/val periods are highlighted at the end of spacecraft commissioning, and after the hibernation period separating MOP1 and MOP2. Note that periodic calibration periods of shorter duration are not indicated.

MOP1 will be influenced by a short season (35 days) of short eclipses (10 minutes maximum per orbit). Prior to the beginning of a longer duration season (135 days) of long eclipses (up to 28 minute per orbit), the six month MOP1 measurement phase will be suspended and the ion propulsion system will be employed to boost the orbit to a hibernation altitude of 260-270 km at which power and fuel consumption is limited. After 4.5 months of hibernation the ion-thruster will be switched off and the satellite lowered to an altitude of 240 km. A second in-orbit gradiometer calibration phase of 1.5 months is planned prior to the second six month scientific measurement or Mission Operations Phase (MOP2).

# 4 SCOPE OF L1B CALIBRATION AND VALIDATION

The accuracy and quality of the Level 1b GOCE products have to be assessed. A basis for this is provided by the calibration and validation procedures described in the following sections. In the first section, however, the main purpose of the Cal/Val Announcement of Opportunity is recalled.

## 4.1 Cal/Val AO

ESA announced an opportunity specifically aimed at the scientific pre-processing, external calibration and validation of GOCE Level 1b data products in May 2003. The announcement (RD1) was open to scientific entities worldwide. The Agency sought the interests of institutes; research groups and scientists concerned with the study of satellite gravity gradiometry and satellite-to-satellite tracking as well as general geophysical remote sensing data.

The main aims of the Cal/Val AO were:

- to solicit contributions to the GOCE calibration and validation, and
- to establish an operational processing facility (PF), and

- o to help elaborate the details of a coordinated calibration/validation strategy.

Figure 9 highlights the Cal/Val AO contributions in the general organization scheme of the GOCE mission. Clearly, the AO involves an important link between the Level 1b products and the Level 2 products and providing quality assessment and data analysis, which is important for the Level 2 processing.

In total three proposed AO Projects were accepted by the Agency. Following the acceptance of their proposals, the scientists were invited to become members of the GOCE Calibration and Validation Team (CVT).

A first meeting of the CVT took place at ESA-ESRIN on 9 March 2004 to coordinate activities related GOCE calibration and validation. The subsequent section summarises these activities and provides a detailed description of currently planned activities in support of calibrating and validating Level 1b GOCE products.

## 4.2 Main Cal/Val Steps

The primary calibration and validation steps are:

1) Pre-launch Calibration
2) Internal Calibration
3) External Calibration
4) Validation

A brief description of each kind of activity is given in the following subsections.

### *4.2.1 Pre-launch Calibration*

A pre-launch gradiometer calibration is performed on ground. The main purpose of the pre-launch calibration is to verify that the specified limits of the instrument after the manufacturing, integration and alignment have not been exceeded. This includes determination of (some parameters of) the calibration matrices, including (in-line differential) scale factors, and (in-line common and differential) quadratic factors. In addition, it comprises the conversion of the instrument-readouts to physically sensible quantities. Although some of the set values cannot be maintained during the ground-to-orbit transition, the pre-launch calibration is of vital importance for the next calibration steps.

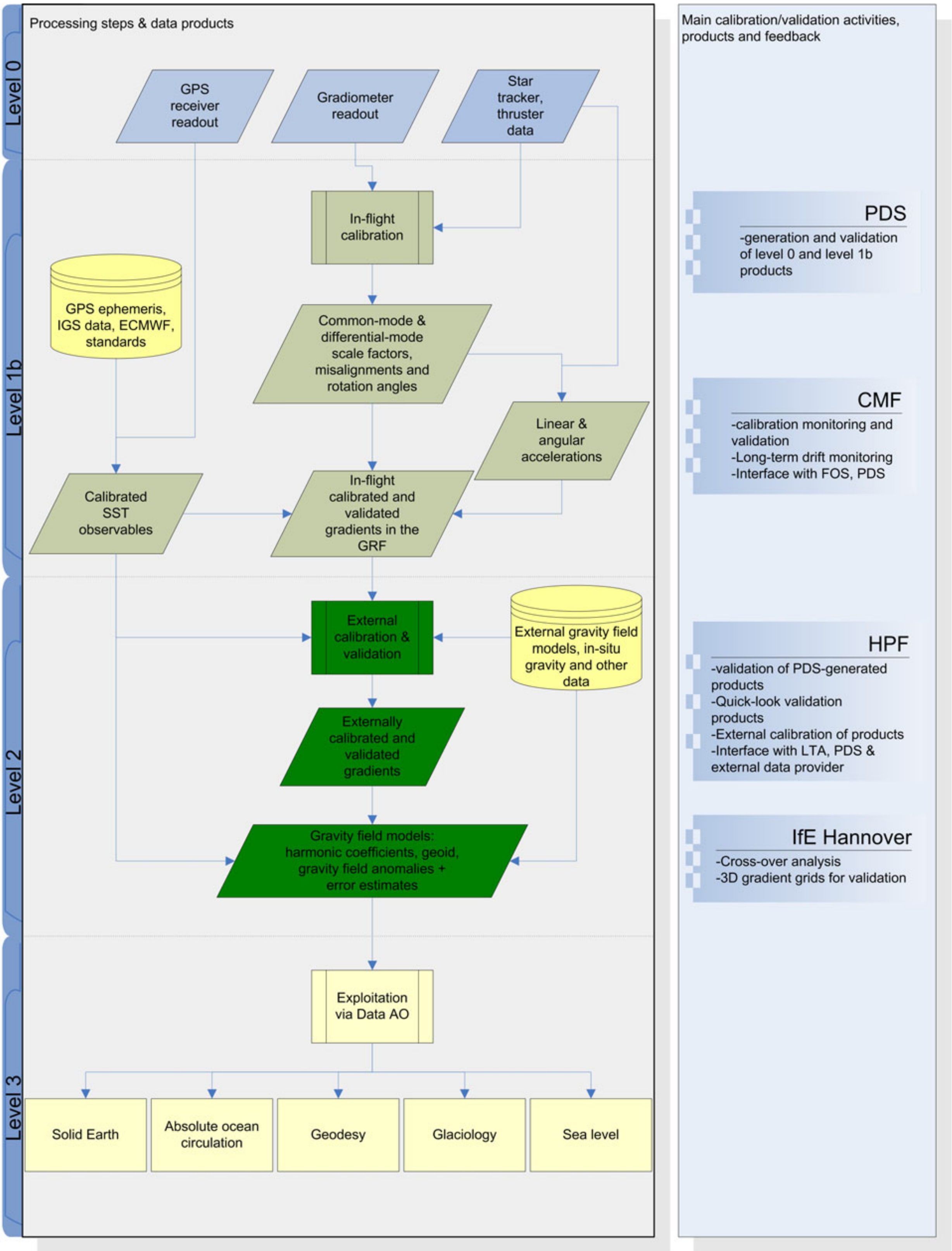


**Figure 9.** Schematic description of data processing steps, products and product flows, together with calibration and validation activities within the Ground Segment and the respective contributions from approved Cal/Val AO Project activities.

### *4.2.2 Internal Calibration*

The internal calibration is performed in orbit. Its main purpose is to check the on-ground calibration parameters after launch but it also ensures that the preset instrument requirements are met. The values of the calibration matrices are determined by imparting an acceleration signal on the gradiometer using the cold-gas calibration thrusters. After this procedure, the common-mode and differential-mode read-outs of the gradiometer are corrected using the measured calibration parameters. Due to the extreme accuracy level of the GOCE measurements, the internal calibration procedure has to be repeated for each MOP. The mission profile foresees two internal calibration phases (one within the first 1.5 months and one after 4.5 months), but additional calibrations during the measurement phases are possible and may be required.

### *4.2.3 External Calibration*

The internal calibration will not be sensitive to all instrument imperfections or gradiometer performance characteristics such as biases. Therefore, an additional calibration procedure is proposed which is called external or '*absolute*' calibration. It is performed during or after the mission and typically makes use of external gravity field information. The external procedure consists of two parts: signal calibration and error calibration. Signal calibration is understood in the sense that actual corrections to the satellite-derived signal (Level 1b data) are determined and applied to the data. Error calibration is understood as error assessment or the activity undertaken to quantify the residual errors in the (calibrated/corrected) Level 1b products. Error calibration involves the actual satellite observations, but may also involve external data sets. It is expected that the calibrated error is compared to the *a priori* error model and differences traced/investigated.

Externally calibrated gravity gradients are a Level 2 product, and the external calibration does therefore not - in the first instance - affect the satellite operations. However, if variations in calibration parameters are found, and these are suspected to be related to phenomena in the satellite (see Error Tracing under Scientific Pre-Processing), there is a clear operational link.

The external calibration may have two purposes: (i) calibration of previously uncalibrated parameters or frequency bands; and (ii) improvement and/or assessment of parameters previously calibrated with accuracy lower than what can be achieved with an external calibration procedure.

The external calibration procedure is also responsible for ascertaining the residual uncertainty in the processed Level 1b gravity gradients (after corrections have been applied) via comparison with existing independent datasets.

## 4.3 Calibration of Level 1b Products

### *4.3.1 Calibration of EGG Observations*

For the electrostatic gravity gradiometer there is foreseen a laboratory pre-flight, on-ground calibration and an in-orbit calibration for the determination of the quadratic factors of the accelerometers and the elements of the inverse calibration matrix. The calibration matrix contains common and differential scale factors, misalignments and couplings of an accelerometer pair (see RD14). In addition, the EGG measurements are externally calibrated using global gravity field models and terrestrial gravity data.

#### *4.3.1.1 Pre-flight, on-ground calibration*

On ground each of the three one axis gradiometers (OAGs) undergoes laboratory functional tests on a special pendulum test bench with four degrees of freedom. This ground calibration method is challenged by the 1g environment, but is designed such as to be sustained by the vertically oriented Less Sensitive (LS) axis of each of the accelerometers. Each proof mass is levitated and the pendulum bench then rocked back and forth, such that the tilt allows the 1g signal to project onto other axes. By oscillating the bench with a known frequency the quadratic scale factors of the accelerometers can be determined and physically adjusted.

Each of the accelerometer Flight Models (FMs) will undergo functional testing on the pendulum bench, with some additional testing of the accelerometer control-loop electronics under microgravity conditions (during freefall experiments at the ZARM drop tower in Bremen). Flight-ready accelerometers will have been calibrated such that the absolute scale factor is known to within 1 part in 100, and such that the difference in scale factors between accelerometers is matched to within 1 part in $10^4$. The accelerometer misalignment will also be established to within $10^{-4}$ radians.

In orbit, by applying high frequency sinusoidal accelerations to the proof masses by means of the control electrodes, an update of the quadratic factors can be determined and the accelerometers can be adjusted.

#### *4.3.1.2 On-orbit internal calibration*

Due to the launch environment, and vibration experienced by the gradiometer, small post-launch misalignments in the accelerometers may introduce coupling amongst the measurement axes and thus errors in the common scale factors and differential accelerations. Furthermore, there may be residual imperfections in the measurement system which simply cannot be tested on-ground (i.e. under 1g) to the accuracy level needed. Thus, an in-flight Gradiometer calibration procedure has been devised (RD14, RD15) which applies shaking of the satellite with a combination of the ion thruster and cold-gas calibration thrusters (RD7). This method relies on the assumption that between 50 and 100 mHz the gravity gradient signal is relatively weak and can be treated as measurement noise relative to the thruster induced acceleration signals.

Gradiometer imperfections (resulting from positional offsets or changes in baseline; rotational misalignment relative to the axis of the OAG; and scale-factor offsets) are grouped into three 6 x 6 calibration matrices (CMs), one for each one-axis gradiometer (or accelerometer pairs 1,4; 2,5; and 3,6). Each CM transforms the common and differential mode accelerations experienced by the accelerometer proof masses in the corresponding OAGRFs to the common and differential mode accelerations measured by the accelerometer pairs in their accelerometer reference frames. Thus, knowledge of the Inverse Calibration matrix (ICM) is required to recover the actual accelerations from those measured by the gradiometer with imperfections. The elements of the inverse calibration matrix are determined in orbit by random shaking the satellite using the thrusters with a predefined spectrum. From these tests, calibration tables are established and applied to the gradiometer raw data by the PDS. Thus the PDS will provide internally calibrated gradiometer observations in the Gradiometer Reference Frame.

#### *4.3.1.3 SGG external calibration with global gravity models (low frequency band)*

The in-orbit internal calibration determines calibration parameters most suitable for the MBW. Under the assumption that the calibration parameters are frequency independent, the calibration parameters can also be applied to other frequency parts. It is, however, possible that residual absolute biases, scale factors, trends and other slowly varying systematic effects remain in the Level 1b data after the internal calibration. Furthermore, additional errors in the Level 1b data, which are introduced in processing the accelerometer and STR data, have to be considered. To account for errors in the low-frequency band, an external calibration using state-of-the-art global gravity field models is suggested.

By means of a rapid science orbit and an *a priori* global gravity field model, SGG data are predicted along the orbit. From the differences to the derived SGG measurements, calibration parameters (such as bias, scale, trend and Fourier coefficients) are estimated in a least squares sense (signal calibration). Power Spectral Density (PSD) plots of the observations, calibration gradients (from the model), calibrated gradients and the effects of the calibration are provided to check the calibration. Remaining uncertainties of the SGG data can be assessed using along track interpolation. This method estimates (interpolation using Overhauser-splines) in each observation point the gradient from e.g. two previous and two following observations. From the differences between the interpolated value and the observed value for all the points of a certain time span (e.g. one orbit or one day) an error model can be derived that can be tested against the *a priori* given error model.

#### *4.3.1.4 SGG external calibration with terrestrial gravity data (high frequency band)*

In addition to global gravity field models, terrestrial gravity data can be used for calibration and validation of SGG measurements. Large databases with densely spaced terrestrial data exist in some areas of the world. By comparing GOCE data with terrestrial data in these well-surveyed regions, certain calibration parameters such as scale factors and biases may be determined. Typically, the terrestrial data will be more accurate than GOCE data for high frequencies but due to the spatial restriction, the calibration is limited to a certain frequency range. A difficult task is to free the terrestrial data from biases and trends due to different height systems, topographic reductions etc. In addition, a suitable upward continuation method has to be developed that transforms the terrestrial gravity data to gravity gradients. Least-squares collocation methods may be used, but other possibilities exist.

#### *4.3.1.5 Gradiometer external calibration in the overlap band between SGG and SST*

The spectral overlap between SGG and SST measurements can be used to calibrate the SGG measurements (Level 1b) in the lower frequencies. Two methods are proposed. The first method determines calibration parameters for the common-mode accelerations in the orbit determination process. The second method is a joint inversion of SST and SGG measurements to a long-wavelength spherical harmonic field (up to degree 70, TBC), where calibration parameters are added as additional parameters. Both methods rely on calibrated SST data.

Outputs are calibrated SGG measurements in the lower frequencies and scale and bias estimates of the SGG data.

## 4.4 Validation of Level 1b Products

Assessment of the quality of Level 1b data is made possible by the availability of quick-look tools using semi-analytical methods, as well as the Calibration Monitoring Facility (CMF) indicated in Figure 3.

### *4.4.1 Quick-look Gravity Field Assessment (QL-GFA)*

Validation of level 1B products can be performed by scientific data analysis, *i.e.* by the HPF providing:

- rapid science orbits,
- quick-look gravity field solutions, and
- quick-look quality assessment tests,

within a short time period.

Scientific pre-processing first includes corrections using the methods described in section 4.3.1.3 – 4.3.1.5. These tasks are strongly linked to the PDS and the Calibration Monitoring Facility (CMF), which are both elements of the ESA GOCE ground segment. The CMF will continuously monitor the accuracy and reliability of the GOCE products. During each measurement phase (MOP1 and MOP2), a time-history of the trace quantity will be continuously computed from the L1b GGT data (in GRF) by the CMF according to the procedure defined in (RD7) and used to evaluate the performance with respect to the trace criterion shown in Figure 6.

The purpose of the quick-look analysis (QLA) is for the HPF to provide an intermediate quality assessment of batches of the SGG and SSTI data used to prepare the gravity field, and to diagnose the system performance prior to use of L1b data in the final gravity field processing. If statistically significant errors (such as systematic errors) are identified, they are recorded in data quality reports. Such diagnostic information will be continuously monitored by the HPF in order to provide quality control and quality assurance of the products.

The QLA tools implemented in the HPF are used to carry out parallel tests of the SSTI data and the SGG data and combinations of the two. The independent SST data analysis is based on the energy conservation laws, and should reveal systematic effects due to non-compensated gravitational effects on the S/C. The independent SGG analysis will apply statistical hypothesis tests to intercompare the *a priori* noise model with the observed residual SGG noise error PSD, and shall enable flagging of data which deviates from the expected noise model, so as to facilitate adjustment of filtering. In the combined analysis of SGG and SSTI, spherical harmonic coefficients are first estimated from the partial SSTI and SGG data and inter-compared to reveal systematic distortions. Further comparisons are made with *a priori* gravity models to test the quality of the QLA solution. Cumulative gravity anomaly errors will be plotted geographically, allowing for instance residual long-wavelength errors in the low-degree range to be identified, enabling optimal weighting of SSTI and SGG data in the gravity field solutions.

Quick-look analysis will be applied at two stages of data processing in the HPF. Quick-look (A) is applied to Level 1b preliminary orbits (accuracy ~10 m) and Level 1b gravity gradients as a rough check of the SGG time series. At this stage, the error level of the quick-look gravity solutions is likely to be quite large and the achievable accuracy is mainly dependent on the correct internal calibration of the gradiometer. Quick-look (B) is applied when level 2 rapid science orbit solutions (with cm range accuracy) and the calibrated gravity gradients become available. In this second phase, the corresponding SST and SGG time series are checked on the level of the Earth gravity field, also testing the gradiometer error model. For Quick-look (B), consecutive gravity field solutions will be available on a weekly basis for performance verification. Compared with an optimum HPF gravity solution, the degradation in accuracy of these QL-GFA solutions should not exceed one order of magnitude over the whole spectral range up to degree and order 200. The maximum degree and order for the QL-GFA gravity field models will be optimised with respect to the global coverage of the input data, and will be at least 70 at the beginning of the operation2.

### *4.4.2 Cross-over validation*

Cross-over validation analysis is proposed by the University of Hannover (Cal/Val AO ID: 2406) as an independent check on the quality of the L1b products delivered by the HPF. This validation approach has been developed to analyse the measured gravity gradients at ascending and descending satellite crossover points for relative validation. This technique is common to existing techniques used for satellite altimetry and would allow relative consistency of the gradients to better than 2 mE, for crossing orbits separated in altitude by less than 10 km. Such an analysis is expected to yield an independent analysis on the quality of the products from the HPF, and to allow the detection of possible time-dependent systematic errors or mal-functioning of the gradiometer. However, the limitation of cross-over analysis is its relative character, which does not allow to identify constant biases or scale factor offsets, or location-dependent systematic errors.

### *4.4.3 Orbit Validation*

Since SSTI data will have an influence on the quality of the gravity field at low degrees and orders, the SSTI observation data must be validated and their quality assessed in a manner consistent with the gradiometer data. Quality checks are presently foreseen for the SSTI that consist of orbit comparisons. One validation tool is the check of orbit overlaps. Typically, consecutive orbits are compared against each other and the differences between the orbits should not exceed a certain limit. Furthermore, the LRR is used for validation of the orbit. Additionally, different orbit solutions are compared against each other. For instance, the rapid science orbits can be used for comparison with the precise science orbit. Finally, external data comparisons are possible using satellite laser ranging (SLR) data.

# 5 SPECIFIC L1b CAL/VAL ACTIVITIES

The purpose of this section is to identify each of the specific activities contributing to elements of Calibration and Validation, together with identifying who is responsible, together with the input requirements, auxiliary data needs, and any interdependencies. The section is split between the contributing work package elements within the HPF contract, and the approved AO projects.

## 5.1 EGG-C ACTIVITIES

Several cal/val activities have been suggested in the Proposal by the European GOCE Gravity Consortium (EGG-C). They are briefly summarised below.

### *5.1.1 SGG calibration with global gravity field models*

| | |
|---|---|
| Objectives | Calibration of SGG measurements with appropriate error measures.<br>Determination of calibration parameters and corresponding error description. |
| Method | Prediction of model gravity gradients along the orbit. Determination of biases, scales, trends and other parameters using some calibration model. Removal of systematic effects from the SGG measurements. |
| Input | Internally calibrated SGG measurements, external global gravity field models such as EGM96, EIGEN2s, GRACE-based models etc. |
| Auxiliary data | Rapid science orbit, precise science orbit |
| Benefits | Lower and higher frequencies of the SGG measurements can be corrected.<br>Entire data set or parts of the data set can be considered. |
| Resp. group | SRON, TUG/AAS is science consultant |

### *5.1.2 SGG calibration with terrestrial gravity data*

| | |
|---|---|
| Objectives | Correction of SGG measurements in areas where terrestrial gravity data are available. Calibration of the shorter wavelengths of the SGG measurements. Determination of (local) calibration parameters and error description. |
| Method | Upward continuation and prediction of terrestrial data using least-squares collocation. Determination of biases, scales, trends for each track crossing the calibration area. Removal of systematic effects from the SGG measurements. |
| Inputs | Internally calibrated SGG measurements, terrestrial gravity data over well-surveyed areas. |
| Auxiliary data | Precise science orbit |
| Benefits | Higher frequencies can be calibrated |
| Resp. group | UCPH, TUG/AAS is science consultant |

### *5.1.3 SGG/SST calibration in overlapping bands*

| | |
|---|---|
| Objectives | SGG calibration in the spectrum between SST and SGG data |
| Method | 1. Determination of calibration parameters for the common-mode accelerations in the orbit determination process. 2. Joint inversion of SST and SGG measurements. Spherical harmonic analysis up to degree and order 70 (TBC) including additional calibration parameters in the least-squares adjustment. After determination of calibration parameters, removal of systematic effects from the SGG measurements. |
| Inputs | SGG measurements, calibrated SST data |
| Benefits | Overlapping spectrum can be calibrated and analyzed |
| Resp. group | FAE/A&S |

### *5.1.4 SGG temporal gravity correction*

| | |
|---|---|
| Objectives | Determination of temporal gravity corrections along the orbit. Application of the correction to the SGG measurements resulting in corrected SGG measurements |
| Method | Determination of major temporal gravity sources. Production of global models for the sources. Conversion of gravity corrections into gravity gradient corrections along the orbit. Application of corrections to the SGG measurements. |
| Inputs | Calibrated SGG measurements, models and data for temporal gravity (tidal models, atmospheric models, ocean models and hydrology data) |
| Auxiliary data | Precise science orbit |
| Benefits | Static SGG data |
| Resp. group | IAPG and SRON, TUG/AAS is scientific consultant |

### *5.1.5 SST temporal gravity correction*

| | |
|---|---|
| Objectives | Determination of temporal gravity corrections along the orbit. Application of the corrections to the SST data resulting in corrected SST measurements. |
| Method | Determination of major temporal gravity sources. Production of global models for the sources. Conversion of gravity corrections into SST related corrections along the orbit. Correction takes place during the orbit determination and gravity field determination. |
| Inputs | SST data, models and data for temporal gravity (tidal models, atmospheric models, ocean models and hydrology data) |
| Resp. group | FAE/A&S and IAPG, TUG/AAS is scientific consultant |

### *5.1.6 SGG frame transformations*

| | |
|---|---|
| Objectives | SGG observations in different reference frames including error measures |
| Method | This can be done by LSC or by rotation by the law of tensors, in both cases including error propagation. Specific care will have to be taken how to deal with the projection of the large off-diagonal errors onto the diagonal ones. |
| Inputs | SGG measurements, accurate rotation angles |
| Resp. group | SRON |

### *5.1.7 Data screening with geodetic information*

| | |
|---|---|
| Objectives | Data screening of the SGG data to detect and remove outliers and discontinuities. |
| Method | Interpolation methods and least-squares collocation are proposed to detect the position of the possible outlier/discontinuity. Reference values from global gravity field models may be used. |
| Inputs | Internally calibrated SGG measurements, global gravity field models |
| Benefits | Gross errors are flagged |
| Resp. group | SRON |

### *5.1.8 Data gaps and interpolation with geodetic information*

| | |
|---|---|
| Objectives | Filling SGG data gaps by interpolated values |
| Method | Least-squares collocation is used to interpolate SGG data gaps. Interpolated values are flagged. |
| Inputs | internally calibrated SGG time series |
| Benefits | Continuous SGG data streams |
| Resp. group | SRON |

### *5.1.9 Quick-look SST data preparation*

| | |
|---|---|
| Objectives | SST data preparation including detection and removal/correction of outliers/cycle slips. Augmentation of SST data by IGS GPS orbit and clock solutions |
| Method | TBC |
| Inputs | SST data |
| Benefits | Consistent SST data set |
| Resp. group | FAE/A&S |

### *5.1.10 Rapid science orbit determination*

| | |
|---|---|
| Objectives | Determination of reduced-dynamic and kinematic rapid science orbits. Comparison and validation of the two orbit products. |
| Method | Determination of the reduced-dynamic and kinematic rapid science orbits for periods of nominally one day. The reduced-dynamic orbits are based on triple-differenced GPS observations while the kinematic orbits use double-differenced GPS observations. The expected latency of the kinematic rapid science orbits is 1 to 2 days. |
| Inputs | Original GPS observations |
| Res. group | FAE/A&S, IAPG and AIUB. |

### *5.1.11 Quick-look gravity field analysis*

| | |
|---|---|
| Objectives | Analysis of partial and/or incomplete SGG/SST data. Test of *a priori* SGG noise model. Diagnosis report sheet, error measures and related statistical confidence levels |
| Method | Use of the semi-analytical method that is based on FFT techniques. Generation of spherical harmonic models based on the SGG/SST data. Validation of the obtained models using external global gravity field models. |
| Inputs | Internally calibrated SGG/SST data, external global gravity field models |
| Resp. group | TUG/AAS, IAPG, and ITG |

### *5.1.12 Quick-look orbit validation*

| | |
|---|---|
| Objectives | Orbit validation based on comparisons between reduced-dynamic and kinematic rapid science orbits. Validation diagnosis sheet |
| Method | Comparison of reduced-dynamic and kinematic orbits |
| Inputs | Reduced-dynamic and kinematic orbits |
| Resp. group | FAE/A&S and IAPG. |

### *5.1.13 Quick-look gravity field validation*

| | |
|---|---|
| Objectives | Validation of quick-look gravity field solutions by means of independent gravity field data such as GPS/leveling, global gravity field models and terrestrial gravity data over well-surveyed areas |
| Method | TBC |

| | |
|---|---|
| Inputs | Quick-look gravity field solutions, GPS/leveling data, global gravity field models and terrestrial gravity data |
| Resp. group | IAPG |

## 5.2 Univ. HANNOVER ACTIVITIES

In addition to the proposal by the EGG-C, other cal/val activities exist that act on Level 1b data. The following activities will take place at the IFE, University of Hannover:

### *5.2.1 SGG validation in satellite cross-over points*

| | |
|---|---|
| Objectives | SGG (relative) validation in satellite cross-over points, outlier detection and identification of systematic errors |
| Method | Identification of possible cross-over points. Horizontal interpolation of measurements. Vertical reduction of measurements using a Taylor series expansion where the derivative of the gradients in the height direction is computed from a global gravity field model. Rotation of the reductions into the required frame. Comparison of SGG data and identification/correction of outliers and systematic errors. |
| Inputs | SGG data, rapid science obits |
| Benefits | Independent relative validation of SGG data |
| Resp. group | IFE |

### *5.2.2 3D-grid of gradients for calibration or validation*

| | |
|---|---|
| Objectives | To prepare a three dimensional grid of gravitational gradients at GOCE altitude over Europe as input for external calibration or validation of SGG data (see 5.1.2). |
| Method | Least-squares collocation (as in 5.1.2) and integral formulas with spectral weighting are used to compute a 3D grid of gravitational gradients at satellite altitude from regional terrestrial gravity data in combination with actual global geopotential models. Errors of the predicted gradients are estimated depending on the quality of the input data. |
| Inputs | Global geopotential models<br>Digital terrain models<br>European terrestrial gravity data collected from different sources |
| Benefits | Reference data is provided to be used for external calibration or validation |
| Resp. group | IfE |

**Table 1**. The following table provides an overview of the above calibration or validation activities. It indicates whether the methods apply to calibration or validation of level 1B data. The responsible group, and possible scientific consultants, are identified.

| Activity/Method | | Cal/Val | Group |
|---|---|---|---|
| 5.1.1 | Determination of calibration parameters using global gravity field models | Cal | *SRON, TUG/AAS* |
| 5.1.2 | Determination of (local) calibration parameters using terrestrial gravity data | Cal | *UCPH TUG/AAS* |
| 5.1.3 | SGG/SST calibration in overlapping bands | Cal | *FAE/A&S* |
| 5.1.4 | SGG temporal variation correction | Cal | *IAPG+ SRON, TUG/AAS* |
| 5.1.5 | SST temporal variation correction | Cal | *FAE/A&S+ IAPG, TUG/AAS* |
| 5.1.6 | SGG frame transformation | Cal | *SRON* |
| 5.1.7 | Data screening with geodetic information | Cal/Val | *SRON* |
| 5.1.8 | Data gaps and interpolation with geodetic information | Cal | *SRON* |
| 5.1.9 | Quick-look SST data preparation | Cal | *FAE/A&S* |
| 5.1.10 | Rapid science orbit determination | Val | *FAE/A&S, IAPG, AIUB* |
| 5.1.11 | Quick-look gravity assessment | Val | *TUG/AAS, IAPG, ITG* |
| 5.1.12 | Quick-look orbit validation | Val | *FAE/A&S, IAPG* |
| 5.1.13 | Quick-look gravity field validation | Val | *IAPG* |
| 5.2.1 | SGG validation using satellite cross-overs | Val | *IFE* |
| 5.2.2 | 3D-grid of gradients for calibration or validation | Cal/Val | *IFE* |

# 6 VALIDATION CRITERIA & DATA RELEASE

The “official” public Level 1b GOCE data products (RD16) will only be selected and released after a comprehensive analysis and evaluation of products has been undertaken. Calibration and Validation will be a continuous effort and internal and external comparisons using independent test data sets will have been performed repeatedly to assure the user that high quality ‘batches’ of data are released. These test results will be summarised in a validation report and used as the basis for Agency selection of the final GOCE products of sufficient quality for data release.

In principle, provided the L1b product performance goals can be met, the L2 scientific requirements can ultimately be fulfilled by the HPF. Thus, the key questions that must be answered prior to data release are:

- Is the L1b data sufficiently well calibrated?
- To what degree is the validation trustworthy?
- To what degree are the data geophysically reasonable?

The answer to the first question will come from the continuous performance monitoring of the Calibration and Monitoring Facility, while answers to the other questions shall arise from the Cal/Val Team's application of the validation procedures defined in this document.

Importantly, in-orbit calibration of the Gradiometer is necessary at the beginning of each 6-month duration scientific measurement phase (i.e. MOP1, MOP2), while periodic in-orbit recalibrations may be necessary during each measurement phase to ensure consistent mission performance.

Ultimately L1b data release is contingent upon the Quick-look processor confirming the quality of the products, as the QL-GFA solutions are primarily dependent on the correct internal calibration of the L1b gravity gradients. It shall be reasonable to assume that L1b products will be released for public issue some interval of time after the beginning of each measurement phase at a point in time when the QL results meet (or exceed) the desired accuracy level of accuracy. This threshold is presently specified as one order of magnitude below required Level 2 performance goal over a spectral range up to and exceeding degree/order 70; and if possible up to degree/order 200 (where the maximum degree and order is dependent on the data time span and global coverage of the input data).

Since processing of a high quality Level 2 gravity product (RD17) is contingent upon a number of pre-processing steps, the following L1b and ancillary product delivery milestones will first need to be met:

- Successful PDS → LTA delivery of 1 Hz pre-processed, corrected, calibrated and geolocated time series data along the orbit (sorted in files), including:
  - gravity gradients in gradiometer reference frame together with the transformation matrices to convert to Inertial Reference Frame (IRF).
  - linear accelerations and angular rates and accelerations,
- Successful PDS → LTA of 1Hz SSTI code and phase measurement data (sorted in files).
- Successful PDS data delivery to GOCE Cal/Val team

After L1b calibration and validation, the ultimate L2 product performance goal is for GOCE gravity products to achieve the following criteria:

- Cumulative geoid error of < 0.02m, at degree/order 200 (half wavelength scale of 100 km).
- Cumulative gravity anomaly error of < 1 mGal, at degree/order 200 (half wavelength scale of 100 km).

Potential problems are foreseen in meeting the above commissioning criteria if:

- problems are experienced with the accelerometers
- the duration of the first calibration period exceeds 1.5 months
- more-frequent, or periodic recalibration is required
- if orbit manoeuvres, or the performance of the DFAC, compromise the six month duration of the MOP1

Alternative strategies will have to be developed should any one of the above occur.

# 7 CONCLUSION

The organisation of the L1b calibration and validation activities outlined in this document meet the primary requirements for assessment of GOCE validation incorporating:

- Verification and assessment of the gradiometer and SSTI calibration
- Validation of the performance and characterisation of the uncertainties in the L1b gradiometer data
- External calibration via comparisons with existing terrestrial data

The suite of planned work detailed in the document address most of the external calibration and validation requirements. However, further planning and coordination is required to ensure that some of the existing planned activities are appropriately tailored to GOCE needs. Thus, this Cal/Val document is regarded as a 'Living Document' which shall evolve as knowledge and documentation of the procedures and methods become further consolidated.

Overall, the activities outlined in this document will make a significant contribution to verifying the calibration of the data, and to ensuring the validity and accuracy of the GOCE products. In particular, the methods to be applied will provide quantitative estimates of the uncertainty in the measurements that are required to meet the mission objectives. These information shall serve as the basis for a thorough assessment of the data quality, and the foundation upon which to take decisions regarding GOCE official data release.

# 8 BIBLIOGRAPHY

RD1 Announcement of Opportunity for Level 1B Cal/Val, GO-AO-ESA-GS-0051

RD2 ESA, Report for Mission Selection, The Gravity field and steady-state Ocean Circulation Explorer Mission, ESA SP-1233(1), 1999.

RD3 Johannessen, J.J., et al., The European Gravity Field and Steady-State Ocean Circulation Explorer Satellite Mission: Impact in Geophysics, *Surveys in Geophysics*, 24, 4, 339-386, 2003.

RD4 GOCE Mission Requirements Document, GO-RS-ESA-SY-0001

RD5 GOCE Ground Segment Concept and Architecture, GO-TN-ESA-GS-0017

RD6 GOCE Performance Requirements and Error Budget of Gradiometer, GO-TN-AI-0027.

RD7 Gradiometer Ground Processing Algorithms Documentation, GO-TN-AI-0067

RD8 System Requirements Document, GO-RS-ESA-SY-0002

RD9 SSTI performance analysis document, GO-TN-AI-0137

RD10 GPS Receiver Ground Processing Algorithms Specification, GO-SP-AI-0004

RD11 Gradiometer Ground Processing Algorithms Specification, GO-SP-AI-0003

RD12 Gradiometer Ground Processing Algorithms Analysis, GO-TN-AI-0068

RD13 GOCE Level 2 Product Data Handbook, GO-MA-HPF-GS-0110

RD14 Gradiometer Calibration Plan, GO-PL-AI-0039

RD15 Gradiometer On-Orbit Calibration Procedure Analysis, GO-TN-AI0069

RD16 Level 1b Product Data Handbook, GO-MA-ACS-GS-XXXX

RD17 Level 2 Product Specification, GO-ID-HPF-GS-0041

# 9 ABBREVIATIONS AND ACRONYMS

AAS Alcatel Alenia Space

AO Announcement of Opportunity

Cal/Val Calibration and Validation

CEOS Committee on Earth Observing Satellites

CHAMP Challenging Minisatellite Palyload for geophysical research and application

COM Centre of Mass

CMF Calibration Monitoring Facility

DFACS Drag-Free and Attitude Control System

EGG Electrostatic Gravity Gradiometer

EGG-C European GOCE Gravity Consortium

ESA European Space Agency

FEEP Field Emission Electric Propulsion

GGT Gravity Gradient Tensor

GOCE Gravity field and steady-state Ocean Circulation Explorer

GPS Global Positioning System

GRACE Gravity Recovery and Climate Experiment

GRF Gradiometer Reference Frame

HPF High-level Processing Facility

IRF Inertial Reference Frame

LORF Local Orbital Reference Frame

LRR Laser Retro-Reflector

MBW Measurement Bandwidth

MOP Mission Operations Phase

PDS Payload Data Segment

POD Precise Orbit Determination

RD Reference Document

RERF Radial Earth-pointing Reference Frame

RSO Rapid Science Orbit

RSS Root-Sum-Square

SGG Satellite Gravity Gradiometry

SLR Satellite Laser Ranging

SST Satellite-to-Satellite Tracking

SSTI Satellite-to-Satellite Tracking Instrument

SST-hl Satellite-to-Satellite Tracking in high-low mode

TBC To Be Confirmed

TBD To Be Determined

# 10 CAL/VAL PARTICIPANTS

| Acronym | Institute | Function | Team Members |
|---|---|---|---|
| AIUB | Astronomical Institute, Univ. Bern, Switzerland | HPF WP4000 Partner | G. Beutler<br>U. Hugentobler |
| CNES | Centre National d'Etudes Spatiales, Groupe de Recherche de Géodésie Spatiale, Toulouse, France | HPF WP5000 Manager | G. Balmino<br>S. Bruinsma |
| FAE/A&S | Faculty of Aerospace Engineering, Astrodynamics and Satellite System, Delft University of Technology, Delft, The Netherlands | HPF WP4000 Manager<br>HPF WP 3000 Partner<br>HPF WP 8000 Partner | P. Visser |
| GFZ | GeoForschungsZentrum Potsdam, Department 1 Geodesy and Remote Sensing, Potsdam, Germany | HPF WP 5000 Partner | M. Rothacher<br>Ch. Förste |
| IAPG | Institute of Astronomical and Physical Geodesy, Technical University Munich, Germany | HPF PI (Management)<br>HPF WP 3000 Partner<br>HPF WP 4000 Partner<br>HPF WP 6000 Partner<br>HPF WP 8000 Manager | R. Rummel<br>Th. Gruber<br>J. Flury |
| ITG | Institute of Theoretical Geodesy, University Bonn, Germany | HPF WP 6000 Partner | W.D. Schuh |
| POLIMI | DIIAR – Sezione Rilevamento, Politecnico di Milano, Italy | HPF WP 7000 Manager | F. Sanso<br>F. Migliaccio |
| SRON | SRON Netherlands Institute for Space Research , Utrecht, The Netherlands | HPF co-PI (Management)<br>HPF WP3000 Manager | R. Koop<br>J. Bouman |
| TUG/AAS | Institute of Navigation and Satellite Geodesy, Graz University of Technology / Space Research Institute, Austrian Academy of Sciences, Graz, Austria | HPF WP 6000 Manager | H. Sünkel<br>R. Pail<br>E. Höck |
| UCPH | Department of Geophysics, University of Copenhagen, Denmark | WP 3000 Partner<br>WP 7000 Partner | Ch. Tscherning |
| IFE | Inst. für Erdmessung, Univ. of Hannover, Hannover, Germany | Cal/Val AO 2406 | J. Müller |

# 11 CONTACTS

| Name | Organisation | Email | Tel: |
|---|---|---|---|
| R. Rummel | IAPG | rummel@bv.tum.de | (49) 89 289 23190 |
| R. Koop | SRON | R.Koop@sron.nl | (31) 30 253 8578 |
| J. Bouman | SRON | J.Bouman@sron.nl | (31) 30 253 5971 |
| G. Beutler | Uni. Bern | beutler@aiub.unibe.ch | (41) 31 631 8591 |
| G. Balmino | CNES-GRGS | georges.balmino@cnes.fr | (33) 5 61332889 |
| P. Visser | FAE/A&S | Pieter.Visser@lr.tudelft.nl | (31) 15 278 2595 |
| M. Rothacher | GFZ | rothacher@gfz-potsdam.de | (49) 331 288 1100 |
| Th. Gruber | IAPG | Thomas.Gruber@bv.tu-muenchen.de | (49) 89 289 23192 |
| W.D. Schuh | ITG | schuh@theor.geod.uni-bonn.de | (49) 228 732626 |
| F. Sansó | POLIMI | fsanso@ipmtf4.topo.polimi.it | (39) 02 23 996504 |
| H. Sünkel | TUG | hans.suenkel@oeaw.ac.at | (43) 316 4120 701 |
| R. Pail | TUG | pail@geomatics.tu-graz.ac.at | (43) 316 873 6859 |
| E. Höck | TUG/AAS | hoeck@geomatics.tu-graz.ac.at | (43) 316 873 6859 |
| C. Tscherning | UCPH | cct@gfy.ku.dk | (45) 35 320582 |
| J. Mueller | IFE | mueller@ife.uni-hannover.de | (49) 511 762 3362 |
| .... | | | |
| S. Cesare | AAS | Stefano.Cesare@aleniaspazio.it | (39) 011 7180 629 |
| P. Touboul | ONERA | touboul@onera.fr | (33) 1 4673 4832 |