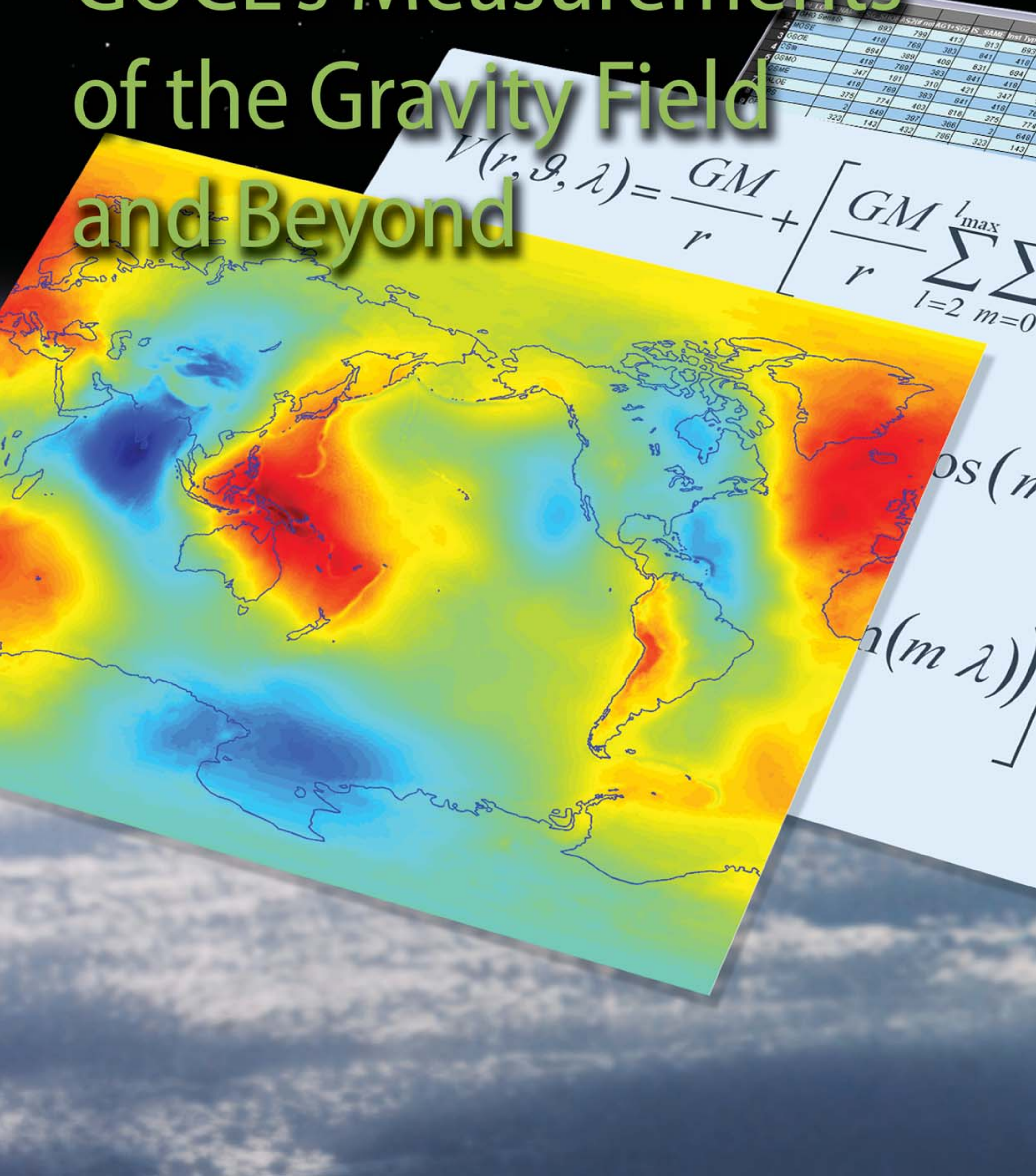
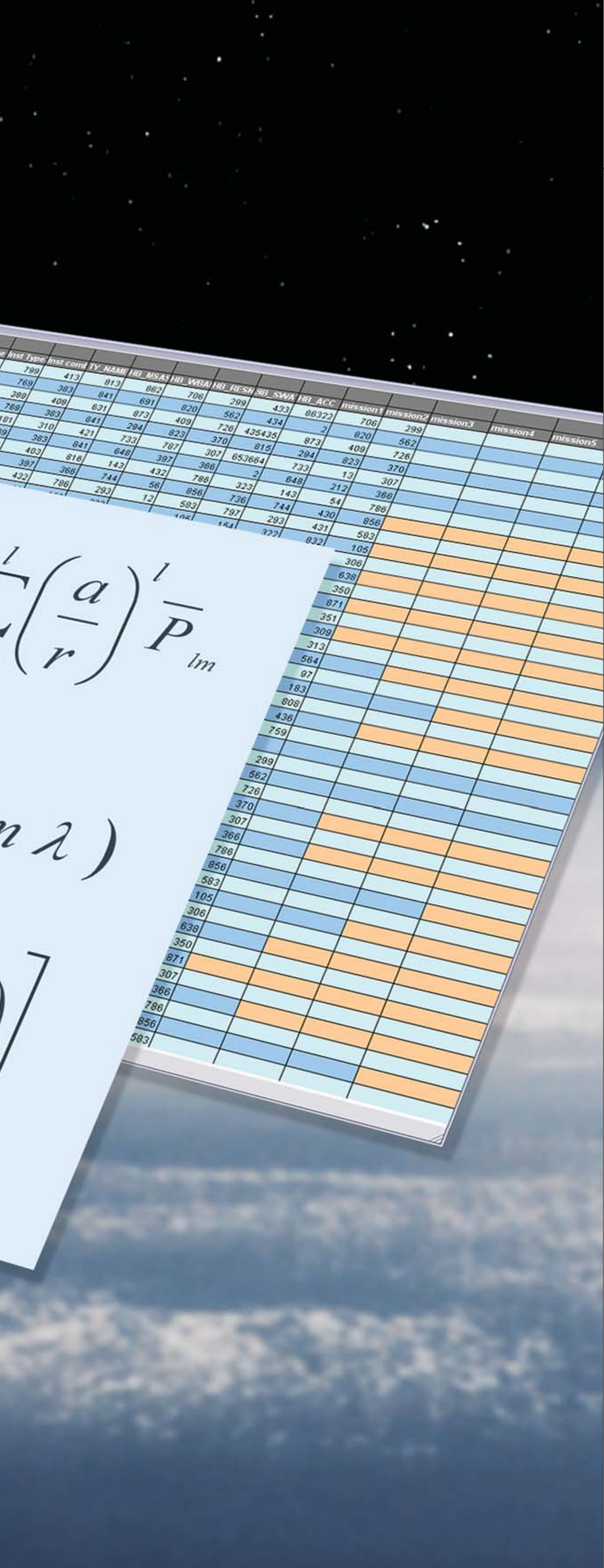
GOCE's Measurements of the Gravity Field and Beyond





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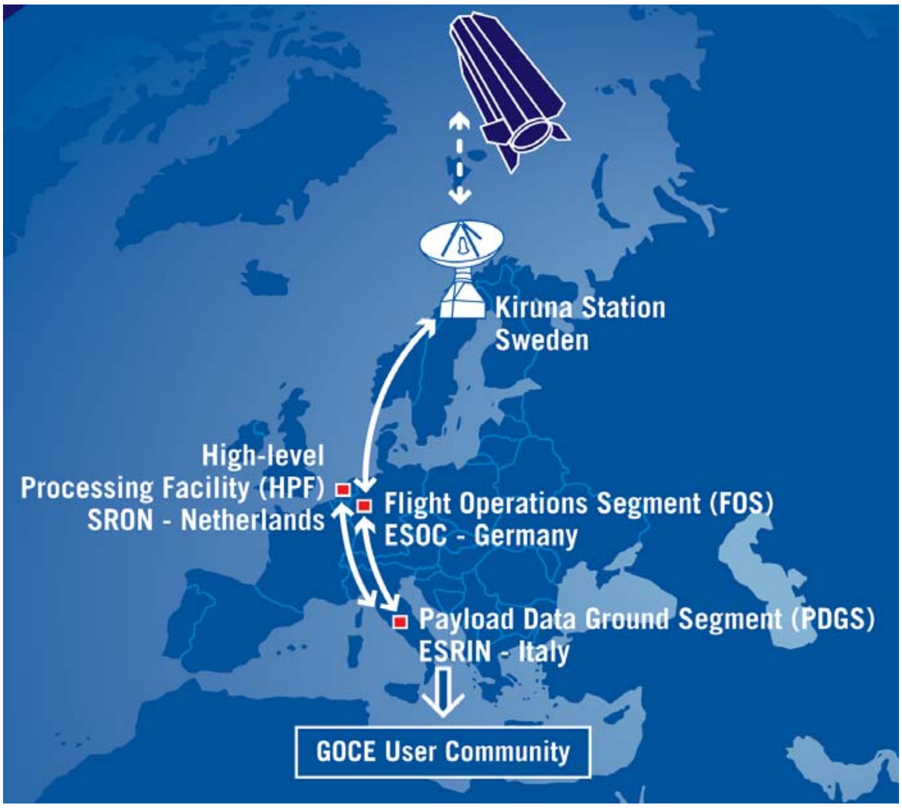
Ocean circulation, sea-level rise and the ocean's role as a regulator of climate are just some of the critical phenomena that can be further studied with the help of GOCE's gravity field products. But how do the spacecraft's measurements become part of this new information source?

Introduction

GOCE will provide users worldwide with well-defined data products, and will be instrumental in advancing science and applications in many disciplines, ranging from geodesy, geophysics and surveying, to oceanography and glaciology. These data products are the starting point for deeper analysis in all related geosciences. All products are available free of charge to scientific and non-commercial users.

But just how will it all work? What are the physical measurements made by the satellite, and how can they be used to provide detailed information about the gravity field over the required range of spatial dimensions from global down to 100 km or less?



GOCE mission ground segment elements and inter-relations

Ground Segment

The ground segment is a key segment of the mission for the generation and quality control of the GOCE mission data products. Overall, the concept and architecture of the ground segment is based on data-driven processing for all steps wherever possible. Human interaction in the scientific data processing flow occurs only in the determination of the ultra-precise science orbits and of the gravity field solution.

Data-driven processing was selected for two reasons: first, little or no operator intervention is required as long as the data processing proceeds nominally; and second, it allows scientists and engineers to focus on critical areas such as instrument calibration, monitoring of the data quality, study of correction parameters, tuning of processing algorithms and parameters, and so on.

The interface to the satellite, including all satellite operations, command and control, is taken care of by the Flight Operations Segment at ESOC, Darmstadt. Regarding the science data product generation, the key components of the ground segment are the Payload Data Ground Segment (PDGS), the High-level Processing Facility (HPF), and the Calibration Monitoring Facility (CMF). The HPF is a distributed processing chain developed and operated under ESA contract by a consortium of ten European institutes, known as the European GOCE Gravity Consortium (or EGG-C).

The definitions for the different levels of GOCE data products are:

Level 0 time-ordered raw data as measured by GOCE. The satellite downlinks the data during contact with a dedicated ground-receiving station.

Level 1b time series of calibrated and corrected instrument data along the orbit. These data include the primary instrument data: gravity gradients, satellite-to-satellite tracking observations and GOCE satellite position; ancillary data such as the satellite linear and angular accelerations and satellite attitude.

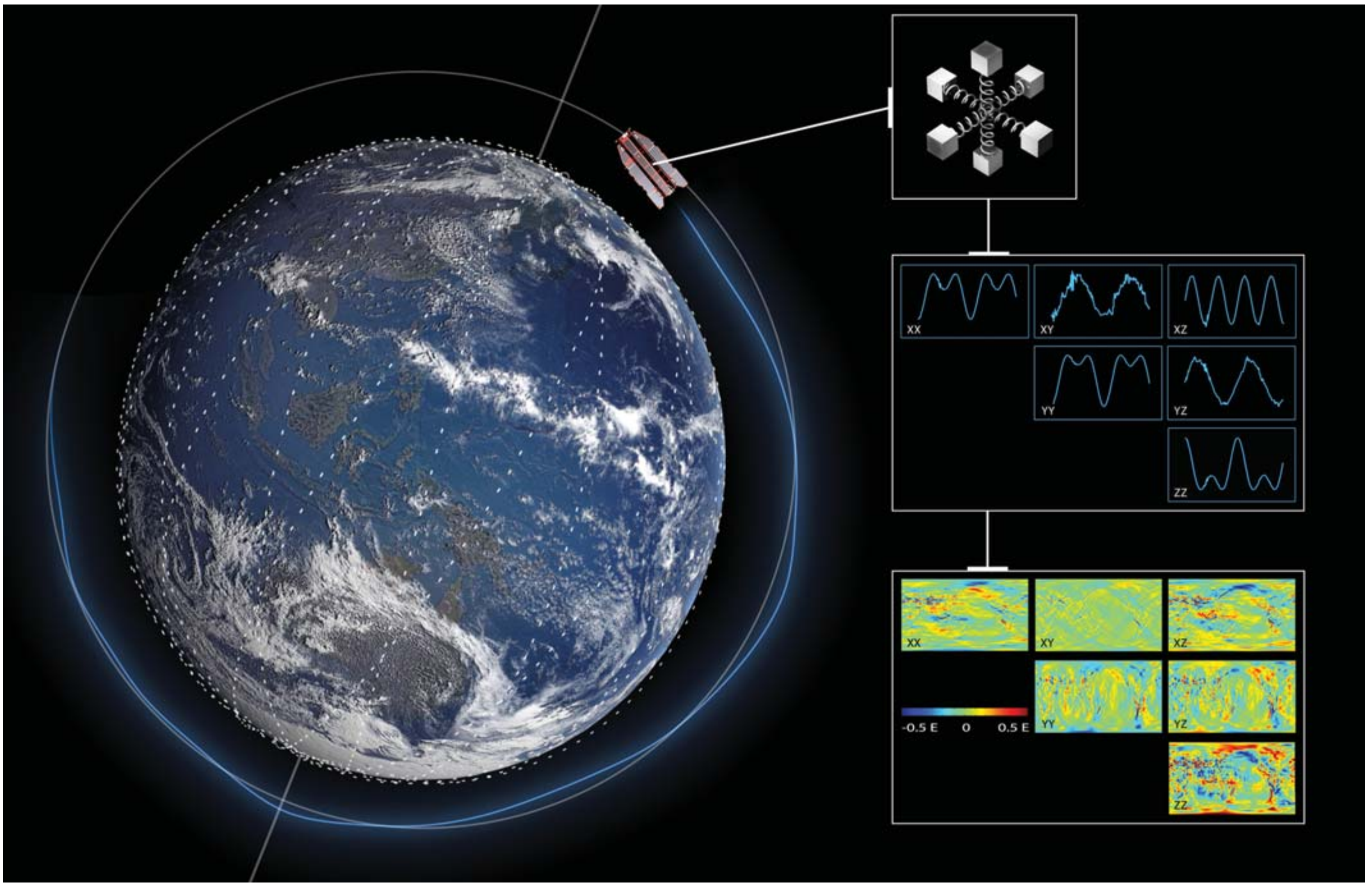
Level 2 time series or models of key GOCE science products based Level 1b data; primary gravity field models and ultra-precise science orbits.

Level 2 data products are regarded as the starting point for further scientific analysis, and will be GOCE-only gravity-field solutions. Such application products – sometimes referred to as Level 3 products – are thus value-added, derivative or custom products developed for application in further studies of solid-earth physics, absolute ocean circulation, geodesy, sea-level rise, etc. Additionally, products requiring combinations of surface or airborne gravimetric data, or other satellite or in situ data with the GOCE data are regarded as Level 3 data products.

Within the PDGS, the Payload Data Segment (PDS), which includes the Instrument Processing Facility (IPF) running all the processing computer code, produces the Level 0 and Level 1b data products and provides them, together with auxiliary parameter files, to the HPF. The HPF in return pre-processes the Level 1b data, generates Quick-Look (QL) analysis products (these are rapid products used mainly to assess and verify the Level 1b data quality), and returns Level 2 products to the PDS for archiving and distribution to users.

Additionally, the PDGS hosts the Long-Term Archive (LTA) for data preservation and archiving purposes, the Multi-mission User Services facilities (MUS) through which the users can obtain access to the data, and the Performance Monitoring Facility (PMF) which monitors the overall mission data production and data flow.

Meanwhile, the CMF is responsible for the continuous monitoring of the Level 1b product performance as well as the satellite performance on the basis of data collected in the PDS. It also relates the product performance to the satellite health, configuration and instrument performance, and is therefore also a satellite performance monitor. Based on the CMF findings, planning files and auxiliary files needed for satellite flight



Collection of time series of gravity gradients (upper right). GOCE will collect such measurements all over the world (lower right) (AOES Medialab)

control, payload calibration operations and/or data processing are generated by the Reference Planning Facility (RPF).

The HPF plays an instrumental role in the overall scientific calibration and validation of the Level 1b data products, as it generates Level 2 quick-look and final products, and also performs dedicated quality assurance functions on the incoming Level 1b data products.

The GOCE mission uses ground stations in Kiruna and on Svalbard to exchange commands with the spacecraft and to downlink data to the ground. During operations, the satellite is monitored and controlled by ESOC, Darmstadt. ESOC generates and uplinks commands to programme the GOCE satellite operations, and processes the housekeeping and instrument data to monitor the health status and performance of the platform and the instruments.

While PDS generates Level 1b data products, the HPF generates the Level 2 products. It is expected that most science, service and application users will eventually be mostly interested in the Level 2 data. Once validated, both types of products are available through the standard ESA user services tools. A common feature of all product levels is that the products contain all corrections and outcome of each individual processing step. The process is therefore essentially reversible, should it be desirable to apply different corrections/steps at a later stage, e.g. based on new insight or new (geophysical) background data and/or models.

GOCE implements the multi-mission concept that is now common to all the missions of the Earth Explorer family. The ground segment and the users must deal with a generalised data representation common to all Earth Explorer missions, and the products follow specific format guide-lines. GOCE products are all ASCII, and the main products are coded in eXtensible Mark-up Language (XML). In XML, each and every data set is characterised by specific tags that prevents format errors and allows immediate validation against existing specific format descriptions like XML standard descriptors. As XML-based product formats are not yet common-place in the geosciences community, ESA intends to provide access to tools that can be used to read and convert mission products into several current product formats, such as RINEX (for GPS data) and others.

The two instrument techniques used to achieve the mission goals are gradiometry and high-to-low satellite-to-satellite tracking (SST-hl), and the primary payload of the mission consists of the EGG and the SSTI. In gradiometry, the difference in the acceleration measured by two accelerometers placed some fixed distance apart provides the basic observable, proportional to the gravity gradient in the direction joining the two sensors through a constant scale factor. In SST-hl, the positional data measured with respect to a constellation of reference satellites in known orbits are used to extract the gravity information through orbit perturbation analysis. In these techniques, knowledge of the orbit allows for the retrieval of the underlying dynamic models that govern the satellite motion, including the Earth gravity field. The two techniques are comple-mentary in that SST-hl works best at providing the long and medium-wavelength part of the geopotential, while gradiometry is especially sensitive to the short-wavelength part. The crossover frequency between the two techniques is not sharply defined, providing redundant measurements in a relatively wide frequency band.

The measurement bandwidth of the EGG is defined to cover the frequency range between 5 mHz and 100 mHz, the upper limit being consistent with the required spatial resolution of 100 km.

Gradiometer Data Processing – First Steps

Getting meaningful gravity gradient information from the science data telemetry received by the ground station(s) starts – as part of the Level 1b processing – from a Level 0 product that contains all gradiometer nominal science mode instrument source packets as extracted from the raw satellite telemetry. These hexadecimal data packets are unpacked, sorted and converted into engineering units.

Data gap information on the time series of data is stored in the product for future reference and use. It is important to note that all GOCE measurements are time-tagged according to GPS system time as well as according to the on-board elapse time counter. The precision of the GPS system time stamping is higher than the one generally ensured by commonplace on-board time to UTC clock conversions since the relationship between the on-board clock and the GPS time is derived from the navigation orbit and clock solution provided by the GPS receiver. Gradiometer and SSTI instrument clocks are therefore aligned with a precision at the level of nanoseconds.

The fundamental observable from the gradiometer are the accelerometer control voltages; these are the voltages that are applied to the electrodes in order to keep the proof-mass levitated at the centre of the glass cage. In total, there are eight electrode pairs for each of the six accelerometers that make up the gradiometer instrument. Control voltages are corrected for gain and phase delay induced by both the accelerometer closed-loop control as well as the read-out circuitry by means of a discrete time filter. The (48) thus-corrected voltages are recombined to obtain the (36) accele-rations – for every accelerometer (6) and every degree of freedom (6). Common-mode and differential-mode accele-rations of the three single-arm (one-directional) gradiometers are finally formed by taking the sum and difference of accelerations measured by each pair in three orthogonal directions. While the common-mode cancels out the gravity gradient signal we are trying to measure, this signal does contain the non-conservative (or surface) forces acting on the satellite, preventing the satellite from being in gravitational free-fall. Therefore, this signal is ideally suited as input for the satellite drag-free control.

The drag-free control system nullifies this common-mode signal along the satellite orbit by proper continuous actuation of the ion propulsion system. The differential-mode signal on the

Final gravity gradient product after preprocessing and geophysical calibration

Corrected and calibrated gravity gradients	
GPS Time	Gradient observation time (sec)
Gravity gradients	Externally calibrated & corrected gravity gradients V_{xx}, V_{yy}, V_{zz}, V_{xy}, V_{xz}, V_{yz} in [1/s^2]
Errors of gravity gradients	Sigmas of all 6 gravity gradients derived from a-priori or HPF estimated gradiometer error model in [1/s^2]
Gradient flags	Flags for each gravity gradient as 1 byte integer. Meaning of numbers: 0: Original gradient (from Level 1b product) 1: Original gradient, temporal corrections added 2: Original gradient with temporal and ext. calibration added 3: Outlier suspected, fill-in provided (from spline interpolation) 4: Outlier suspected, no fill-in, as for 2 5: Data gap, fill-in provided (from spline interpolation) 6: Data gap, no fill-in provided.
Direct tides	Correction applied for direct tides for all 6 gradients in [1/s^2]
Solid Earth tides	Correction applied for solid Earth tides for all 6 gradients in [1/s^2]
Ocean tides	Correction applied for ocean tides for all 6 gradients in [1/s^2]
Pole tides	Correction applied for pole tides for all 6 gradients in [1/s^2]
Non-tidal mass variations	Correction applied for combined atmospheric & oceanic mass variations for all 6 gradients in [1/s^2]
External calibration	Correction applied due to external calibration for all 6 gradients in [1/s^2]

other hand does not contain the surface forces acting on the spacecraft (as they are essentially the same for paired accelerometers). The signal is instead proportional – by the distance between the two accelerometers of a pair – to the derivative of accelerations, in other words the gravity gradient. However, because the satellite is rotating along its orbit, the thus-obtained gravity gradient must be corrected for angular and centrifugal accelerations before we have retrieved a clean gravity gradient measurement in the instrument reference frame. As part of the quality assessment activities the trace of the gravity gradient tensor (i.e. the sum of the three orthogonal gradients) is computed for each measurement epoch (each second), and from this time series the spectral behaviour of the retrieved gravity gradient can also be studied.

Gradiometer angular accelerations are derived from combination of the differential mode accelerations of the one-axis gradiometers. Derivation of the angular rates, needed to compute the centrifugal acceleration term is a rather elaborate procedure that is accomplished in two phases: inside the gradiometer measurement bandwidth (5–100 mHz) the angular rate reconstruction is obtained by integrating the gradiometer angular accelerations. Below a few mHz, however, the gradiometer measurement errors become too large: the angular rate information is instead obtained by differentiation of the star tracker attitude measurements. The combination of the two sources of data is done through a modified Kalman filter.

It is worth mentioning that in case a single accelerometer fails, the failing accelerometer can be 'replaced' – at the cost of a certain performance degradation – by a so-called 'virtual accelerometer' that is obtained by recombination of the acceleration measurements provided by the remaining five accelerometers.

Gravity gradients in an Earth-fixed reference frame. Corrected for temporal gravity field variations, outliers, data gaps and externally calibrated

Gravity gradients in Local North-Oriented Reference Frame (LNOF)	
GPS time	Gradient observation time in [sec]
Position	Geocentric latitude in [deg], longitude in [deg], height in [m]
Gravity gradients	Externally calibrated & corrected gravity gradients V_{xx}, V_{yy}, V_{zz}, V_{xy}, V_{xz}, V_{yz} in [1/s^2]
Errors of gravity gradients	Sigmas of all 6 gravity gradients derived from a-priori or HPF estimated gradiometer error model in [1/s^2]
Gradient flags	Flags for each gravity gradient as 1 byte integer

The precise orbit data product. Variance-covariance information is included for the kinematic orbits (over 9 epochs) and the rotation matrix for each epoch from the Earth-fixed to the inertial reference frame in terms of quaternions

Precise science orbits from reduced dynamic approach (positions and velocities) and kinematic approach (positions), both in Earth-fixed frame	
Kinematic orbit	GPS time in [sec] X, Y, Z position in [m] in Earth fixed frame Clock correction Standard deviation of position and clock Variance-covariance matrix for positions (over 9 epochs)
Reduced dynamic orbit	GPS time in [sec] X, Y, Z position in [m] in Earth fixed frame X, Y, Z velocity in [m/sec] in Earth fixed frame Standard deviation of position and clock
Rotation matrix from EFRF to IRF	GPS time in [sec] Quaternions (4) describing rotation angles

Satellite-to-Satellite Tracking Data Processing – First Steps

In analogy to the case of the gradiometer, the processing of the SSTI/GPS receiver data starts from a Level 0 product that contains all SSTI nominal instrument source packets extracted from the satellite telemetry. The packets are unpacked, sorted and converted into engineering units. The local on-board time and the GPS time of the receiver unit are stored within the time correlation data. Measured carrier phases are corrected for an inter-frequency bias, which results from a different treatment in the analogue receiver electronics of the GPS signal on the two different L-band frequencies. This bias depends largely on the temperature trends and on the receiver characteristics. Invalid data (e.g. due to cycle slips and outliers/offsets) are also identified and flagged.

Pseudo-range measurements (of the distance between GOCE and the transmitting GPS satellites) are corrected for inter-channel bias, i.e. a small bias between the various 12 channels of the receiver. This bias is characterised on the ground and may also be re-evaluated during the mission by sending the signal from the same GPS satellite through all receiver channels. On a parallel track, and in order to assess the noise level of the data, the GPS code measurements are subject to a smoothing process using a suitable order polynomial. Standard deviations of the fit of the measurements to the smoothing polynomial are computed and stored for quality monitoring purposes: they represent a

GOCE gravity field model in different representations including geoid error	
Spherical Harmonic Series (SHS)	Degree; order; C/S-coefficients; sigmas of coefficients (dimensionless)
Geoid heights	30'x30' global grid with geoid heights [m] using wgs84 as reference ellipsoid.
Gravity anomalies	30'x30' global grid with gravity anomalies in [m/s^2] using wgs84 as reference ellipsoid.
North-south deflection of the vertical	30'x30' global grid with north-south deflections of the vertical [arcsec] using wgs84 as reference ellipsoid.
East-west deflection of the vertical	30'x30' global grid with east-west deflections of the vertical [arcsec] using wgs84 as reference ellipsoid.
Geoid height error	30'x30' global grid with geoid height standard deviation computed from error propagation of full variance-covariance matrix[m].

Final gravity GOCE gravity field product

first-hand estimate of the 'noise level' of the range measurements.

An orbit solution is also computed from the filtered pseudo-ranges; this orbit solution is accurate to about 10 metres. To this end, GPS satellite constellation position and clock data are obtained from the International GNSS Service (IGS). Such IGS data are interpolated to SSTI measurement epochs and corrected for GPS satellite antenna phase centre offsets as well as for relativistic effects. A certain robustness is also built in the processing scheme in order to account for a possibly unavailability of one frequency of data from the SSTI, for example in cases of low signal-to-noise ratios. In principle, both a navigation Kalman-filtered solution as well as single-point positioning orbit solution can be computed. The statistics of the computation are stored as a quality indicator for the computed solution. Finally, the position solution is translated from the antenna phase centre to the satellite centre-of-mass.

Level 2 Data Products – The Next Step

GOCE Level 2 products include gravity gradients, precise orbit solutions, as well as gravity field models. All Level 2 data products are generated by the HPF.

Gravity Gradient Products

For processing of the nominal gravity gradients from Level 1b to the Level 2, several processing steps are applied:

- correction of gravity gradients due to external calibration based on readily available gravity field information (our current knowledge of the gravity field);
- determination of gravity gradient errors (uncertainties) from an error model;
- detection of outliers and computation of fill-in values, if possible;
- identification of data gaps and computation of fill-in values, if possible;
- computation of gravity gradient corrections for tides; this includes direct tides, solid Earth tides, ocean tides and pole tides; and
- computation of gravity gradient corrections for atmospheric and oceanic mass variations.

This ensures that the originally observed gravity gradients are reproducible from the Level 2 gravity gradient products.

Transformed Gravity Gradients

For various applications gravity gradients are needed in an Earth-Fixed Reference Frame (Local North-Oriented Reference Frame). The six gravity gradients contained in this product are computed from the four accurately observed gradients which are first high-pass filtered to avoid the large long-wavelength errors present in the GRF gradients to map into the LNOF gradients (the long-wavelength part is replaced by a reference gravity model). The less well-observed gradients V_{xy} and V_{yz} are not used in order to avoid their large error to couple into the transformed gradients.

Because of the dependency on the a-priori gravity field model this product is not useful for gravity field determination, but well suited for many geophysical/oceanographic applications requiring localised gravity gradients in an Earth-fixed frame.

Precise Science Orbits

Precise science orbits are computed from the GPS space receiver phase and pseudo-range observations (SSTI instrument). Two techniques are applied: (1) Reduced dynamic orbits are computed based on a set of a-priori (dynamic) models needed for estimating all forces acting on the satellite. (2) Applying a purely geometric approach for the satellite positioning, 'kinematic' orbits are determined. These are completely independent from any a-priori knowledge of the force models. Both solutions have advantages and disadvantages. While reduced dynamic orbits are somehow smoothed, due to the dynamical modelling, kinematic orbits contain the pure geometrical solution of the positioning problem. Kinematic orbits may therefore be noisier, but may also contain higher frequency orbit information.

Gravity Field Products

From gravity gradiometer data and orbit solutions the final GOCE gravity field models are computed. It is planned to provide (at least) one gravity field model for each measurement operations phase of six months duration, as well as one final model based on all measurement operation phases. Within the HPF, there are three parallel methods implanted for the gravity field determination, providing important redundancy and cross-validation possibilities that will ultimately guarantee the quality of the GOCE gravity field product. These three methods combine traditional methods with novel methodologies developed specifically for the GOCE mission.

A gravity field model consists of several measurement data sets. These are the coefficients of a spherical harmonic series as the initial result of the gravity field estimation procedure and derived quantities like geoid heights, gravity anomalies and deflections of the vertical. Based on the variance-covariance matrix, a complete error propagation is performed to compute the geoid height errors on a regular grid. This grid also is part of the GOCE gravity field solution.

The derived quantities are computed under the assumption of spherical approximations in order to avoid the need of a digital terrain model, which is not part of the GOCE processing system. For applications requiring derived quantities, for example in high-mountain areas, the spherical approximation might be not accurate enough. In this case the accurate formulas involving a digital terrain model have to be applied.

As second product the complete variance-covariance matrix of the spherical harmonic series coefficients is available.

Access to the Data

ESA strives for the widest-possible use of its Earth observation data in research and application areas. All mission data products described here are available free of charge to scientific and other non-commercial users worldwide. In order to establish a first mission data user community, a dedicated Announcement of Opportunity was released in 2006. After a peer-review process this lead to the selection of a first set of user projects, approximately 70 in total spread over nearly 140 research groups, institutes and universities.

A second call for registration of user projects is expected about six to nine months after launch in conjunction with the release of the first data. Nonetheless, user registration can be done at any time, irrespective of the dedicated calls from the ESA, through the Earth Observation Principal investigator web portal: *http://eopi.esa.int/goce*. esa