HOW TO USE GOCE LEVEL 2 PRODUCTS

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ABSTRACT

The GOCE High-level Processing Facility (HPF) is in charge of the production of the following final level 2 products: Calibrated and corrected gravity gradients, precise science orbits and global gravity field models. These products represent the main input to all further applications of GOCE. In order to correctly apply these products the user has to know the definitions, conventions and standards adopted for their generation. The underlying assumptions are described in detail in two documents, which will be released together with the data products. These are the GOCE Standards and the GOCE Product Data Handbook. The standards provide detailed information about the reference systems, the transformations between the reference systems and the adopted geometrical and the dynamical models. The data handbook is intended to provide to the users all required information for the correct use of the products. It includes an overview of the mission and products, general definitions, mathematical and geophysical conventions as well as a description of formats. The paper summarizes the applied standards and conventions and introduces in detail the content of the global gravity field product.

1. INTRODUCTION

The High-level Processing Facility (HPF) is one of the elements of the GOCE Ground Segment. The main tasks of the HPF are (Koop et al, 2006):

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

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

The HPF generates products for internal use, for calibration and validation purposes and for the final user community. The latter are subject of this paper and will be discussed in detail in the next chapters. Chapter 2 provides a short overview of the processing sequence for the final products. Chapter 3, 4 and 5 in detail describe the content of the final Level 2 gravity gradients, precise orbits and gravity field model products of the HPF. The full descriptions of these products can be found in the related GOCE documents (ESA 2006a, ESA 2006b). This paper provides a summary of the products definitions in order to make potential users familiar with them.

The GOCE Level 2 Product Data Handbook (ESA 2006a) provides a general overview about the GOCE mission and the data processing systems. It defines the reference frames and time systems used in the GOCE ground segment, as well as the mathematical conventions applied (e.g. quaternions, spherical harmonic series, error propagation). It provides a detailed description of the geophysical conventions used, namely the approximations applied for the computation of derived gravity field quantities like geoid heights and gravity anomalies, as well as the recipes how to use the accurate formulas. It defines in detail the products accessible to the users in terms of content and format. The GOCE Standards (ESA 2006b), describe in detail the reference systems applied and how the transformations between them are performed. This follows to a large extent the IERS conventions 2003 (McCarthy 2004). Furthermore the geometrical, dynamical, gravity and tide systems applied for the GOCE data processing are specified. The GOCE Standards contain information about all models and constants used in the data processing and shall support the Product Data Handbook.

2. PROCESSING SEQUENCE

The HPF is designed as a distributed processing system (see Koop et al, 2006). Figure 1 provides a rough overview of how the main Level 2 products are inter-connected and what are the major input Level 1b products. One of the most important Level 2 products is the precise science orbit. It is based on the carrier phase and pseudo-range data from the SSTI instrument (GOCE GPS receiver). Applying different techniques

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position and velocity state vectors are determined in a fixed interval. The resulting product is SST_PSO_2.

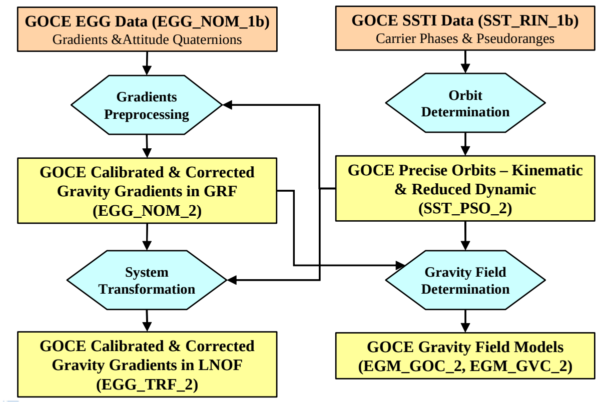

Figure 1: Simplified View of GOCE Level-2 Processing Sequence

Positions and velocities are required for the processing of all other final Level 2 products as well. In order to identify gaps and outliers as well as for calibration and gravity gradient transformation purposes positions are needed in high quality. Both processes provide pre-processed and calibrated gravity gradient products for further use in gravity field determination or geophysical interpretation. The related products are the nominal corrected and calibrated Level 2 gravity gradient products EGG_NOM_2 and the gravity gradients in the terrestrial reference frame EGG_TRF_2.

Pre-processed gravity gradient data as well as precise positions and velocities are applied in the gravity field determination process. This is the major processing step within the HPF system and represents the final outcome of the GOCE mission. Two products contain the resulting gravity field model. EGM_GOC_2 contains the main result, the gravity field spherical harmonic series coefficients as well as derived quantities and geoid height variances. The EGM_GVC_2 product solely contains the huge full variance-covariance matrix of the model coefficients.

3. GRAVITY GRADIENT PRODUCTS

3.1 Nominal Gravity Gradients

Gravity gradients are observed in the Gradiometer Reference Frame (GRF). Its origin nominally is located in the crossing point of the three single axis gradiometer arms, which shall coincide in one point. This frame in addition is located sufficiently close to the centre of mass of the satellite in order to ensure symmetry of acceleration observations around this satellite centre of mass. The three axis of the GRF are fixed mounted with respect to the satellite body. The satellite body closely is oriented in the Local Orbit Reference Frame (LORF). This means the x-axis (roll) approximately is parallel to instantaneous direction of the orbital velocity vector with the same sign as this vector, the y-axis (pitch) is parallel to instantaneous direction of the orbital angular momentum vector (approximately perpendicular to the orbit plane) and the z-axis (yaw) is parallel to the cross product vector of velocity and orbital angular momentum vector, approximately parallel to the radius vector pointing from the geo-centre to the satellite centre of mass.

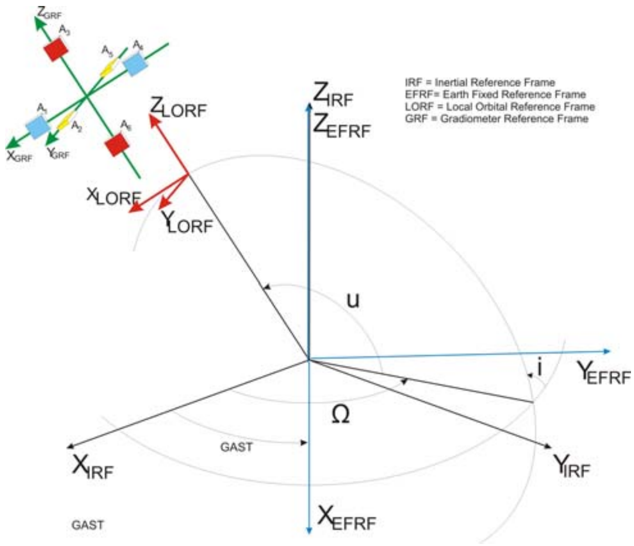

Figure 2: Definition of Reference Frames for GOCE Gradiometry

Figure 2 shows how the fundamental reference frames are related to each other. The GRF does not fully coincide with the LORF. In science mode the satellite will operate in drag-free mode for the flight direction only with platform attitude controlled by the magnetotorquers. In conclusion this means that the GRF is slightly varying in time with respect to the LORF (below ±3° for each axis).

The Level 1b gravity gradients in product EGG_NOM_1b as well as the further processed Level 2 gravity gradients provided in product EGG_NOM_2 are the observations taken in the GRF. In order to use them correctly one needs to know the exact orientation of the spacecraft and consequently of the GRF. This orientation is provided by star camera observations, which are combined with rotational information observed by the gravity gradiometer in a Level 1b process called “angular rate reconstruction”. The result of this process is provided in terms of quaternions in the EGG_NOM_1b product.

For processing the nominal gravity gradients from Level 1b to the Level 2 product, several processing steps are applied. These are in particular (cf. Bouman et al., 2006):

- Correction of gravity gradients due to external calibration,
- 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.

All corrections are applied to the gravity gradients and in addition are provided as separate information in the product in order to make them removable. Also flags are provided marking data records containing fill-in values due to outliers or data gaps. This ensures that the original observed gravity gradients are reproducible from the Level 2 gravity gradient product. The table below provides an overview of the content of the data records in more detail.

EGG_NOM_2: Corrected and calibrated gravity gradients	
GPS Time	Gradient observation time in [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 L1b 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 [$1/s^2$]

In order to use these gravity gradients the following items have to be taken into account by the users:

(1) The gravity gradients are taken as they are observed and corrected for the effects mentioned before. This means that these gradients are not filtered and contain the total signal from inside and outside the gradiometer measurement bandwidth.

(2) All errors provided in the data records are estimated either from a a-priori error model or from an updated error model available throughout the HPF processing chain. They should not be regarded as real measurement errors reflecting the actual instrument performance since these are principally unknown.

(3) All corrections, which are applied, are provided separately in the data records such that they individually can be removed and replaced to the users wishes.

(4) Any manipulated gravity gradient value is flagged. This means filled-in gap values or replaced outliers can be individually identified and removed from the data if required.

(5) In order to apply the product for gravity field determination the orientation of the GRF with respect to the inertial reference frame has to be extracted from the nominal Level 1b gradiometer product (EGG_NOM_1b). The estimated quaternions from the combination of the star sensor observations and the gradiometer rotational measurements are contained in the inertial attitude quaternion measurement data set of the above mentioned product.

3.2 Transformed Gravity Gradients

For various applications gravity gradients are needed in an Earth-Fixed Reference Frame (EFRF). These are provided in the EGG_TRF_2 product. 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 EFRF 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. As Earth-Fixed system a Local North-Oriented Frame is chosen. This frame is defined as follows:

- The Local North Oriented Frame (LNOF) is a right-handed North-West-Up frame with the x-axis pointing North, the y-axis pointing West and the Z-axis Up.
- The origin of the LNOF is located at the nominal satellite centre of mass
- The Z-axis is defined as the vector from the geo-centre to the origin, pointing radial outward,

- The Y-axis is parallel to the normal vector to the plane of the geocentric meridian of the satellite center of mass, pointing westward,
- The X-axis is parallel to the normal vector to the plane defined by the y- and z-axis.

In geocentric latitude and East longitude (φ, λ) of the GOCE centre of mass in the Earth-Fixed Reference System, the 3 axes are defined by the following equations:

$$Z_{LNOF} = \begin{pmatrix} \cos\varphi\cos\lambda \\ \cos\varphi\sin\lambda \\ \sin\varphi \end{pmatrix} ; \; Y_{LNOF} = \begin{pmatrix} \sin\lambda \\ -\cos\lambda \\ 0 \end{pmatrix} ; \; X_{LNOF} = \begin{pmatrix} -\sin\varphi\cos\lambda \\ -\sin\varphi\sin\lambda \\ \cos\varphi \end{pmatrix}$$

The table below provides an overview of the content of the data records in more detail.

EGG_TRF_2: Gravity Gradients in Local North-Oriented reference Frame (LNOF) corrected for temporal gravity field variations, outliers, data gaps and externally calibrated.	
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}, T_{zz}, T_{xy}, T_{xz}, T_{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 as for EGG_NOM_2.

As mentioned before these gravity gradients are transformed from the GRF to the LNOF. In order to perform this transformation a-priori gravity field information needs to be applied. For this reason the long wavelength spectrum of the gravity gradients is replaced with external information (gravity field) and shall not be regarded as original GOCE gravity gradient observations. Nevertheless they are valuable for some geophysical/oceanographic applications (see Bouman et al, 2006). For a correct use of this product the following items have to be taken into account:

(1) The gravity gradients are filtered, i.e. GOCE observations are taken only in the measurement bandwidth, the long wavelength part is replaced with a model. This means that these gravity gradients do not contain observed signal from outside the measurement bandwidth of the gradiometer. Furthermore this means that the transformed gravity gradients cannot be regarded as independent from the global model used.

(2) Because of the dependency on the a-priori gravity field model this product is not applicable for gravity field determination, but well suited for some geophysical/oceanographic applications requiring localized gravity gradients in an Earth-Fixed Frame.

4. PRECICSE SCIENCE ORBITS

Precise science orbits are computed from the GPS space receiver phase and pseudo-range observations (SSTI instrument). Two techniques are applied for this. (1) Reduced dynamic orbits are computed based on a set of a-priori models needed for estimating all forces acting on the satellite. This means some dynamical models are kept in the orbit determination process. (2) Applying a pure geometrical approach for the satellite positioning, so-called kinematic orbits are determined. These are completely independent from any a-priori knowledge of the force models. Both solutions have pros and cons. While reduced dynamic orbits, due to the dynamical modelling are somehow smoothed, kinematic orbits contain the pure geometrical solution of the positioning problem. This implies, that kinematic orbits might be noisier, but also contain higher frequency information. From the integration of the equation of motion in the reduced dynamic approach velocities are determined simultaneously with the positions. This is not possible for the kinematic approach, where velocities cannot be co-estimated, but only with an additional processing step. The following table gives an overview of the product content.

SST_PSO_2: Precise science orbits from reduced dynamic approach (positions and velocities) and kinematic approach (positions), both in Earth-fixed frame. Additionally included is variance-covariance information 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.	
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

The following items have to be taken into account when using the precise science orbit product from GOCE:

(1) Positions, velocities (only for the reduced-dynamic solution) and variance-covariance matrix (only for the kinematic orbit) information are given in the

Earth-Fixed Reference frame (3-axis orthogonal system) with 1 sec time resolution.
(2) The rotation matrix from the EFRF to the inertial reference frame is defined in terms of quaternions. Earth orientation quaternions are provided for every integer second of GPS time and are computed according to IERS Conventions 2003 (McCarthy, 2004).
(3) Rotation matrix quaternions have to be interpolated to time of positions applying the kinematic equation (see ESA, 2006a).

5. GOCE GRAVITY FIELD PRODUCT

From gravity gradiometer data and orbit solutions the final GOCE gravity field models are computed. It is planned to provide one gravity field model for each measurement operations phase of 6 months and one final model based on all measurement operation phases. 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. From 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. Finally the variance-covariance matrix, even if stored in a separate product, belongs to the GOCE gravity field solution. This means that the GOCE solutions consist of two products:
(1) EGM_GOC_2: The GOCE gravity field solution with spherical harmonic coefficients, geoid heights, gravity anomalies, deflections of the vertical and geoid height errors.
(2) EGM_GVC_2: The complete gravity field variance-covariance matrix.

In more details the EGM_GOC_2 product consists of the following data:

EGM_GOC_2: 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 computed from SHS in [m] using wgs84 as reference ellipsoid.
Gravity Anomalies	30’x30’ global grid with gravity anomalies computed from SHS 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 computed from SHS in [arc-sec] using wgs84 as reference ellipsoid.
East-West Deflection of the Vertical	30’x30’ global grid with East-West deflections of the vertical computed from SHS in [arc-sec] 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 in [m].

As mentioned in the introduction 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. The following Figure 3 shall explain what assumptions have been applied:

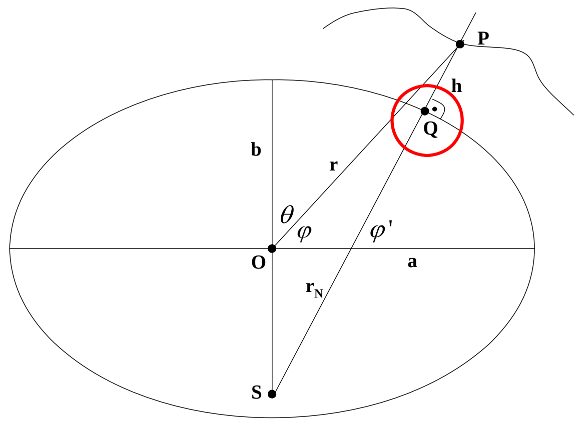

Figure 3: Approximations applied for derived Gravity Field Quantities.

(1) Geoid heights, gravity anomalies and deflections of the vertical are computed on the ellipsoid points Q and not on the surface point P. Over the oceans both points nearly coincide, but over continents, depending on the topographic height, significant differences might result. In case height information is introduced instead of the geoid height, height anomalies shall be computed. For more details refer to the Level 2 Product Data Handbook (ESA, 2006a).
(2) Gravity anomalies and deflections of the vertical are computed based on the spherical approximation of the fundamental differential equation of physical geodesy. In this approximation the real plumb line is approximated by the geocentric vector. In terms of formulas the approximation can be written as:

$$\Delta g = g_P - \gamma_0 = -\frac{\partial T}{\partial h} + \frac{1}{\gamma_0}\frac{\partial \gamma}{\partial h} T$$

$$\Delta g \approx -\frac{\partial T}{\partial r} - \frac{2}{a^{REF}} T$$

$$\xi \approx -\frac{1}{a^{REF}}\frac{\partial N}{\partial \varphi} \quad ; \quad \eta \approx -\frac{1}{a^{REF}\cos\varphi}\frac{\partial N}{\partial \lambda}$$

where T is the disturbing potential, γ the normal gravity, a the semi major axis of the reference ellipsoid used and N the geoid height.

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. All formulas are provided in the Level 2 Product Data Handbook (ESA, 2006a). In any case, by using the coefficients of the spherical harmonic series no approximation is applied. It represents the initial outcome of the gravity field estimation process.

As second product the complete variance-covariance matrix of the spherical harmonic series coefficients is available. This is a very big product and requires a special handling. For this reason this additional product was created. The product consists of a header file and a set of data files with the variance and co-variance values. The files contain the following information:

EGM_GVC_2: Complete variance-covariance matrix for the coefficients of the spherical harmonic series of the GOCE gravity field model EGM_GOC_2	
Header File	GM (Earth mass times gravity constant) a (Radius) Maximum degree Sequence of coefficients Sequence of files
Data File(s)	Harmonic order of the file Number of data values Data entries for this order

Each data file contains data for one harmonic order. Figures 4 and 5 shall illustrate the structure of these data files.

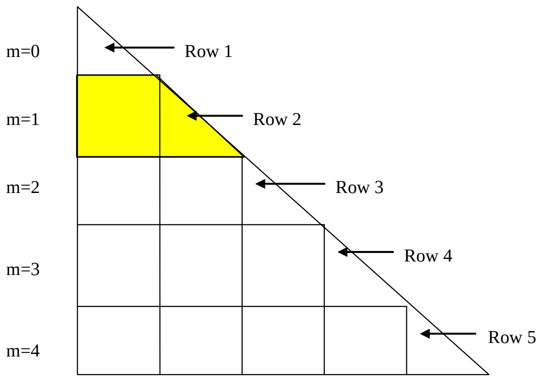

Figure 4: Sequence of Files for Product EGM_GVC_2

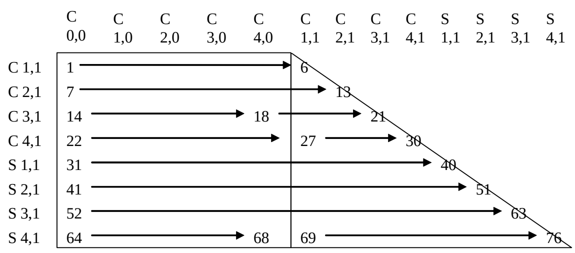

Figure 5: Sequence of Data Entries in each Data File of Product EGM_GVC_2

In Figure 4 each line (e.g. the yellow marked boxes) represents one data file. This means co-variances for each order are stored in separate files. Figure 5 shows the sequence of data entries in each data file. Together with the header file all information is available to read the full variance-covariance matrix properly on any computer system. By this structure it is ensured that no file will become larger than 250 MB assuming as maximum degree and order of 250 for the GOCE solution.

6. SUMMARY AND CONCLUSIONS

The HPF prepares final Level 2 products for the GOCE user community. This includes corrected and calibrated gravity gradients in different reference frames, precise orbits and gravity field solutions in different representations including the variance-covariance matrix of the spherical harmonic coefficients. All products are described in detail in the Level 2 Product Data Handbook (ESA, 2006a). The underlying models and standards are described in the GOCE Standards document (ESA, 2006b).

The gradients are provided in their original reference frame, the GRF, with their full signal including corrections and fill-in values in case of outliers or data gaps. Full signal in this context means that these gradients are not filtered and contain the signal from outside the measurement bandwidth. In contrast the gravity gradients in the terrestrial reference frame (after rotation from the GRF) are filtered before they are transformed and the long wavelength part is replaced with information from an a-priori gravity field model. This implies that these gradients should not be used for gravity field determination, but can be applied for geophysical or oceanographic interpretation.

The precise orbit is provided based on two different estimation schemes. Positions are provided from a reduced dynamic orbit determination as well as from a pure geometrical kinematic approach. Velocities are solely available from the reduced dynamic orbits. Supporting information in terms of rotation matrices between the Earth-Fixed and Inertial systems as well as covariance matrices for the kinematic positions are additionally included.

The final gravity field product consists of the spherical harmonic series potential coefficients, derived quantities and the full variance-covariance matrix of these coefficients. Derived quantities are provided on regular grids applying some approximations in order to avoid the use of third party information in terms of a topography model. The exact formulation is provided in the Level 2 Product Data Handbook.

This sequence of products represents the baseline for all follow-on applications of GOCE gradiometer data, orbits and gravity fields.

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