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# GOCE High Level Processing Facility

## GOCE Level 2 Data Handbook

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Prepared by: The European GOCE Gravity Consortium  
EGG-C

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				<p>improved.</p> <p>6. Chapter 4.1, page 18: Acronym description for IERS updated.</p> <p>7. Chapter 4.3: Table 4-3: Geoid slopes replaced by deflections of the vertical.</p> <p>8. Chapter 4.4.2: Quaternions description completely updated and interpolation formulas included. Explanation of terms in formulas improved. New reference paper.</p> <p>9. Chapter 4.4.3: Definition of spherical harmonics improved.</p> <p>10. Chapter 5.2: Specification for EGG_NOM_2 product updated.</p>
3.0	A	22/09/2006	Issue for data exploitation AO	<p>Chapter 4.3: Table 4-3 updated. Complete update of chapters 4.4.2 and 4.4.3. Complete update of chapter 5.3 and new chapter 5.4.</p>



## Abbreviations and Acronyms

AD	Applicable Document	ECSS	European Cooperation for Space Standardization
ADD	Architectural Design Document	EFRF	Earth Fixed Reference Frame
ADIR	Architectural Design and Interface Review	EGG	Electrostatic Gravity Gradiometer
ADP	Auxiliary Data Provider	EGG-C	European GOCE Gravity Consortium
AIT	Acceptance, Integration, Test	EM	Engineering Model
ANX	Ascending Equator Crossing Node	EME2000	Equinox and Mean Equator of J2000.0
AO	Announcement of Opportunity	EO	Earth Observation
AR	Acceptance Review	EOEP	Earth Observation Envelope Programme
ARF	Accelerometer Reference Frame	EPAR	Extended mission Product Acceptance Review
AS	Anti-Spoofing	ESA	European Space Agency
ATP	Authorisation To Proceed	FM	Flight Model
ATR	Algorithm Test Review	FOCC	Flight Operations Control Centre
CAB	Change Appeal Board	FOS	Flight Operations Segment
CBCP	Current Baseline Cost Plan	GLONASS	GLObal NAVigation Satellite System
CCN	Contract Change Notice	GOCE	Gravity field and steady-state Ocean Circulation Explorer
CDAF	Command and Data Acquisition Facility	GPS	Global Positioning System
CDP	Configuration and Documentation management Plan	GRACE	Gravity Recovery And Climate Experiment
CDR	Critical Design Review	GRF	Gradiometer Reference Frame
CFI	Customer Furnished Item	GS	Ground Segment
CHAMP	CHALLENGING Minisatellite Payload for geophysical research and application	GSOV	Ground Segment Overall Validation
CMF	Calibration and Monitoring Facility	GSRR	Ground Segment Readiness Review
CNL	Contract change Notices status List	HK	House-Keeping
COP	Commissioning Operations Phase	HOP	Hibernation Operations Phase
COS	Consortium Organisation Structure	HPF	High level Processing Facility
CPF	Central Processing Facility	HW	Hardware
CPR	Cycle Per Revolution	ICD	Interface Control Document
CPS	Company Project Structure	IERS	International Earth Rotation and Reference Systems Service
CR	Change Request	IGS	International GNSS Service
CRB	Change Review Board	ILRS	International Laser Ranging Service
CTRS	Conventional Terrestrial Reference System	IPF1	Instrument Processing Facility level 1
DCN	Document Change Notice	IRF	Inertial Reference Frame
DDP	Design and Development Plan	ISP	Instrument Source Packet
DFACS	Drag-Free and Attitude Control System	ITT	Invitation To Tender
DPA	Data Processing Archive	L	Level, L-band frequency
DPM	Detailed Processing Model	LAN	Local Area Network
DSAT	Development Site Acceptance Test	LEOP	Launch and Early Orbit Phase
DTL	Documentation Tree and status List	LORF	Local Orbital Reference Frame
E2E	End-to-End Simulator	LRR	Laser Retro-Reflector
ECMWF	European Centre for Medium-range Weather Forecast	LTA	Long-Term Archive
ECP	External Calibration Products	MBW	Measurement BandWidth



MOP	Measurement Operational Phase	SLR	Satellite Laser Ranging
MPH	Main Product Header	SMF	Software Maintenance Facility
MPS	Mission Planning System	SOW	Statement Of Work
NA	Not Applicable	SPC	Satellite Prime Contractor
NRT	Near-Real Time	SPF	Sub-Processing Facility
OBCP	On-Board Control Procedures	SPH	Specific Product Header
OBT	On-Board Time	SPR	Software Problem Report
ORR	Operational Readiness Review	SPRL	Software PProblems status List
OSAT	On-Site Acceptance Test	SRD	System Requirements Document
PAR	Product Acceptance Review	SRR	System Requirements Review
PCD	Product Confidence Data	SST	Satellite-to-Satellite Tracking
PDD	Product Definition Document	SSTI	Satellite-to-Satellite Tracking Instrument
PDS	Payload Data Segment	SSTR	Sub-System Test Review
PF	Processing Facility	STP	Software Test Plan
PI	Principal Investigator	SVT	System Validation Test
POD	Precise Orbit Determination	SW	SoftWare
PSD	Packet Structure Definition; Power Spectral Density	SWRD	SoftWare Requirements Document
QL	Quick-Look	TBC	To Be Confirmed
QLP	Quick-Look Products	TBD	To Be Defined
RD	Reference Document	TC	TeleCommand
RERF	Radial Earth-pointing Reference Frame	TM	TeleMetry
RFQ	Request For Quotation	TP	Test Plan
RMS	Root-Mean Square	TR	Test Report
RPF	Reference Planning Facility	USF	User Services Facility
RSS	Root-Sum Square	UTC	Universal Time Coordinated
S/C	Space-Craft	V0/1/2	Version 0/1/2
SCP	Secure Copy (remote file copy program)	VC	Virtual Channel
SDE	Software Development Environment	WAN	Wide Area Network
SFTP	Secure File Transfer Program	WBS	Work Breakdown Structure
SGG	Satellite Gravity Gradiometer	WP	Work Package
		XML	eXtensible Markup Language

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## 1. INTRODUCTION

### 1.1 PURPOSE

The purpose of this document is to provide a detailed description of the GOCE level 2 products generated by the High Level Processing Facility and distributed to the GOCE users. These products include GOCE gravity gradients, GOCE orbit solutions as well as the GOCE gravity field models including supporting information. The document describes everything required to make use of the level 2 products for further processing or application.

### 1.2 APPLICABILITY

This document is part of the Deliverable Items List [AD-3]. The first issue is delivered at CDR and classified for review by the Agency. An update of the document shall be delivered at AR-1 and AR-2 for approval by the Agency. The document applies to the development phase and to the actual implementation and operational phases of the HPF.

### 1.3 DEFINITIONS

The term “Contract” is used to indicate the HPF implementation contract.  
The term “the Contractor” is used to indicate the entity in charge of implementing the HPF.  
The term “Agency” is used to indicate the European Space Agency (ESA).

EGG-C is composed by 10 European institutions. Institutions and team members contributing to the HPF project are defined in Table 1-1.

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**Table 1-1:** EGG-C Team Members in Alphabetical Order

<b>Acronym</b>	<b>Institution</b>	<b>Function</b>	<b>Team Members</b>
AIUB	Astronomical Institute, University of Bern, Switzerland	WP4000 Partner	G. Beutler U. Hugentobler
CNES	Centre National d'Etudes Spatiales, Groupe de Recherche de Géodésie Spatiale, Toulouse, France	WP5000 Manager	G. Balmino S. Bruinsma
FAE/A&S	Faculty of Aerospace Engineering, Astrodynamics & Satellite systems, Delft University of Technology, Delft, The Netherlands	WP 4000 Manager WP 3000 Partner WP 8000 Partner WP 6000 Consultant	P. Visser
GFZ	GeoForschungsZentrum Potsdam, Department 1 Geodesy and Remote Sensing, Potsdam, Germany	WP 5000 Partner	M. Rothacher Ch. Förste
IAPG	Institute of Astronomical and Physical Geodesy, Technical University Munich, Germany	Principal Investigator Management WP 3000 Partner WP 4000 Partner WP 6000 Partner WP 8000 Manager	R. Rummel Th. Gruber J. Flury
ITG	Institute of Theoretical Geodesy, University Bonn, Germany	WP 6000 Partner	W.D. Schuh
POLIMI	DIAR – Sezione Rilevamento, Politecnico di Milano, Italy	WP 7000 Manager	F. Sanso F. Migliaccio
SRON	SRON National Institute for Space Research, Utrecht, The Netherlands	Management WP3000 Manager	R. Koop J. Bouman
TUG	Institute of Navigation and Satellite Geodesy, Graz University of Technology	WP 6000 Manager	H. Sünkel R. Pail
UCPH	Department of Geophysics, University of Copenhagen, Denmark	WP 3000 Partner WP 7000 Partner	Ch. Tscherning

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## 2. APPLICABLE AND REFERENCE DOCUMENTS

### 2.1 APPLICABLE DOCUMENTS

- [AD-1] GO-SW-ESA-GS-0079: GOCE High Level processing Facility, Statement of Work, Issue 2.0, 4. May 2004
- [AD-2] GO-RS-ESA-GS-0080: GOCE High Level processing Facility, Statement of Work Appendix 1, Management Requirements, Issue 2.0, 4. May 2004
- [AD-3] GO-LI-ESA-GS-0081: GOCE High Level Processing Facility, Statement of Work Appendix 2, Deliverable Items List, Issue 2.0, 4. May 2004
- [AD-4] GO-RS-ESA-GS-0082: GOCE High Level Processing Facility, Statement of Work Appendix 3, Technical Requirements Specification, Issue 2.0, 4. May 2004
- [AD-5] GO-LI-ESA-GS-0087: GOCE High Level Processing Facility, Statement of Work Appendix 4, List of CFI, Issue 1.0, 5. December 2003
- [AD-6] GO-TN-ESA-GS-0085: GOCE High Level Processing Facility, Statement of Work Appendix 5, Tailoring of ECSS Standards, Issue 1.0, 5. December 2003
- [AD-7] ECSS-E-40B: Space Engineering, Software Standards, Draft Issue, 28. July 2000
- [AD-8] ECSS-Q-80B: Space Product Assurance, Software Product Assurance, Issue 3. April 2000
- [AD-9] PE-TN-ESA-GS-0001: Earth Explorer Ground Segment File Format Standard, Issue 1.4, 13.6.2003
- [AD-10] GO-ID-ACS-GS-0109: PDS Product Specification Document, Issue 3.0, 20.02.2006
- [AD-11] GO-ID-HPF-GS-0041: Product Specification for L2 Products and Auxiliary Data Products, Issue 5.0, 28.08.2006
- [AD-12] GO-TN-HPF-GS-0111: GOCE Standards, Issue 2.0, 28.08.2006

### 2.2 REFERENCE DOCUMENTS

- [RD-1] ESA-SP-1233(1): Gravity Field and Steady-State Ocean Circulation Mission
  - [RD-2] GO-RS-ESA-SY-0001: GOCE Mission requirements Document
  - [RD-3] GO-TN-ESA-GS-0017: GOCE Ground Segment Concept and Architecture
  - [RD-4] GO-SP-AI-0004: GPS Receiver Ground Processing Algorithms Specification
  - [RD-5] GO-SP-AI-0003: Gradiometer Ground Processing Algorithms Specification
  - [RD-6] GO-TN-AI-0067: Gradiometer Ground Processing Algorithms Documentation
  - [RD-7] GO-TN-AI-0068: Gradiometer Ground processing Analysis
  - [RD-8] GO-PL-AI-0039: Gradiometer Calibration Plan
  - [RD-9] GO-TN-AI-0069: Gradiometer On-Orbit Calibration Procedure Analysis
  - [RD-10] GO-RP-AI-0014: Mission Analysis Report
  - [RD-11] CS-MA-DMS-GS-0001: Earth Explorer Mission Conventions Document
  - [RD-12] GO-MA-AI-0002: GOCE User's Manual
  - [RD-13] GO-TN-AI-0027: Performance Requirements and Budgets for the Gradiometric Mission
  - [RD-14] GO-TN-IAPG-0001: Detailed Processing Model for EGG
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- [RD-15] GO-TN-IAPG-0002: Detailed Processing Model for SSTI
- [RD-16] GO-ID-ESC-FS-5070: FOS/PDS – PDS/SLR: Predicted Orbit File
- [RD-17] GO-RS-ESA-GS-0052: Product Requirement Document
- [RD-18] ECSS-M-00A: Policy Principles
- [RD-19] ECSS-M-10A: Project Breakdown and Structures
- [RD-20] ECSS-M-20A: Project Organization
- [RD-21] ECSS-M-30A: Project Phasing and Planning
- [RD-22] ECSS-M-40A: Configuration Management
- [RD-23] ECSS-M-50A: Information / Documentation Management
- [RD-24] ECSS-M-60A : Cost Schedule Management
- [RD-25] ECSS-M-70A: Integrated Logistics Support
- [RD-26] GO-MI-ESA-0101: Minutes of the HPF Negotiation Meeting
- [RD-27] GO-AI-HPF-GS-0008: Action Item Reply of HPF Negotiation Meeting
- [RD-28] GO-AI-HPF-GS-0013: Action Item Reply of HPF Negotiation Meeting
- [RD-29] GO-ID-ESC-FS-5070: FOS/FDS to PDS/SLR: Predicted Orbit File Interface Control Document
- [RD-30] DTOS-FDOS-FDIS-ICD-0250-TOS-GFM: Flight Dynamics Infrastructure Software Napeos Interface Control Document
- [RD-31] PE-TN-ESA-GS-0001: Earth Explorer Ground Segment File Format Standard
- [RD-32] GO-ID-ESA-GS-0037: GOCE Ground Segment Master ICD

*As a general rule it holds that the latest approved issue of the document is applicable, except if the issue number and the document date is specified.*

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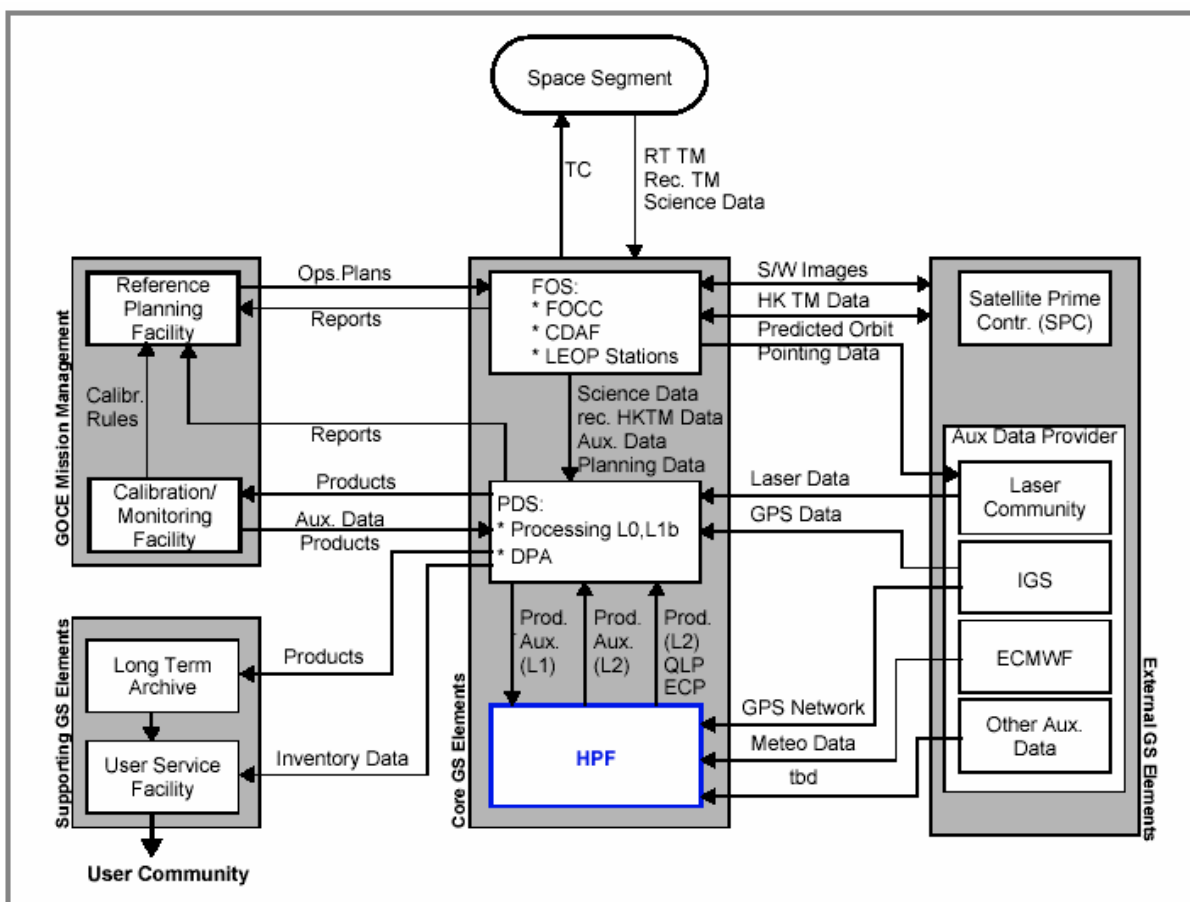


### 3. GOCE GROUND SEGMENT

#### 3.1 OVERVIEW GOCE GROUND SEGMENT

The GOCE ground segment concept and architecture is described in [RD-3]. The following gives a brief summary of all ground segment elements, depicted in Figure 3-1.

Figure 3-1: GOCE Ground System



#### 3.2 HIGH-LEVEL PROCESSING FACILITY

Within the GOCE GS the HPF is one of the Core GS Elements (ESA-controlled), and it is charged with the generation of L2 products and acquisition of the external (auxiliary) data needed to generate these products, the delivery of these products (auxiliary, intermediate and final) to the PDS/DPA and/or the LTA and the generation of Quick-Look Products and External Calibration Products for the purpose of the activities of the CMF.

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## 4. MISSION AND PRODUCTS OVERVIEW

### 4.1 THE GOCE MISSION

#### *Mission Goals*

GOCE is the acronym for „Gravity field and steady-state Ocean Circulation Explorer mission“. It is the first core satellite mission of the newly defined ESA “Living Planet” programme. The objective of GOCE is the determination of the stationary part of the Earth gravity field and geoid with highest possible spatial detail and accuracy. The gravity and geoid model derived from the GOCE mission will serve science and application in the fields of solid earth physics, oceanography, geodesy and glaciology, compare (Johannessen et al, 2003; Rummel et al, 2002).

Two main uses can be distinguished. Firstly, the spatial variations of gravity and geoid are directly related to density anomalies in lithosphere and upper mantle, respectively, and consequently to interior stresses and ultimately to mass motion. In this respect GOCE provides important new information to studies of continental and oceanic lithosphere and upper mantle. Its information is complementary to that of seismic tomography, magnetic field models, geokinematic studies and laboratory results. Secondly, a detailed geoid surface when combined with satellite altimetry yields sea surface topography, the quasi-stationary deviation of the ocean surface from its hypothetical surface of rest. Under the assumption of geostrophic balance ocean topography can be directly translated into a global map of surface ocean circulation. Thus, ocean surface circulation becomes directly measurable, globally and uninterruptedly. In conjunction with higher resolution ocean models and ocean measurements, GOCE is expected to improve significantly estimates of global mass and heat transport in the oceans. Furthermore, the global geoid will permit height systems to be connected globally with almost cm-precision. Sea level variations in Australia, or East Asia will become directly comparable with those measured in Europe or America. These and other expected scientific benefits from GOCE gravity and geoid models demonstrate that this mission represents an important element of global observation of mass anomalies, mass transport and mass exchange. The science goals and the requirements on the mission performance are summarized in Table 4-1.

The science goals as summarized in Table 4-1 can be reached on the condition that GOCE can determine gravity and geoid with a precision of  $10^{-6} \cdot g$  (corresponding to 1 mgal) and 1-2 cm, respectively, with a spatial resolution of better of 100 km half wavelength and that these results are achieved free of long wavelength systematic errors. The mission performance depends on the gravity sensor system on-board GOCE.

**Table 4-1:** Science Goals of the GOCE Mission (ESA, 1999)

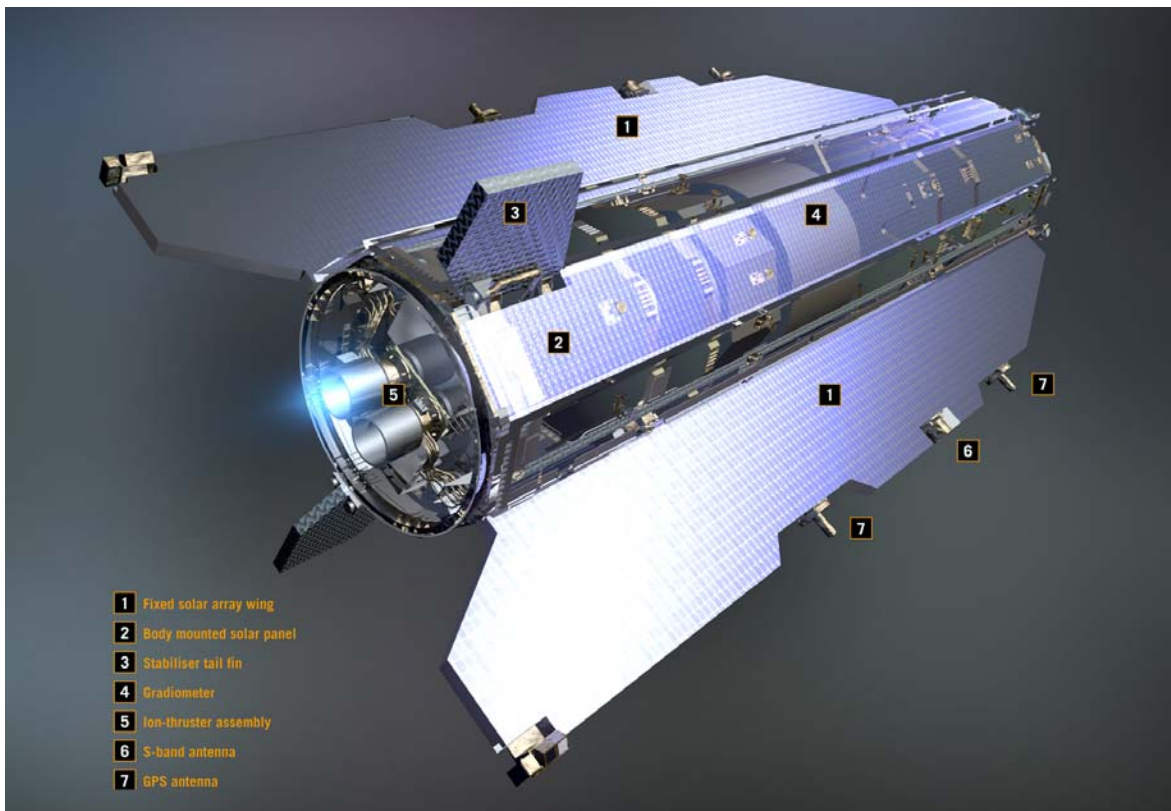
Application	Accuracy		Spatial Resolution (half wavelength – D in km)
	Geoid [cm]	Gravity [mgal]	
SOLID EARTH			
Lithosphere and upper mantle density structure		1-2	100
Continental lithosphere:			
▪ Sedimentary basins		1-2	50-100
▪ Rifts		1-2	20-100
▪ Tectonic motions		1-2	100-500
Seismic hazards		1	100
Ocean lithosphere and interaction with asthenosphere		0.5-1	100-200
OCEANOGRAPHY			
▪ Short scale	1-2		100
	0.2		200
▪ Basin scale	≈0.1		1000
ICE SHEETS			
▪ Rock basement		1-5	50-100
▪ Ice vertical movements	2		100-1000
GEODESY			
▪ Levelling by GPS	1		100-1000
▪ Unification of worldwide height systems	1		100-20000
▪ Inertial navigation system		1-5	100-1000
▪ Orbits		1-3	100-1000
SEA LEVEL CHANGE	Many of the above applications, with their specific requirements, are relevant to studies of sea-level change.		

### ***GOCE Sensor System***

The GOCE satellite and its instruments are shown in Figure 4-1. Core instrument is a three axis gravity gradiometer. It consists of three pairs of orthogonally mounted 3-axis accelerometers, i.e. an orthogonal arrangement of three one-axis gradiometers. The gradiometer baseline of each pair is about 50 cm. The accelerometer precision is  $10^{-12} \frac{m}{s^2} / \sqrt{Hz}$  along two axes with the third axis less sensitive. From the measured gravitational acceleration differences the three main diagonal terms of the gravitational tensor can be determined with high precision. The extremely high gradiometric performance of the instrument is confined to the so-called measurement bandwidth (MBW). In addition, the gradiometer yields the required information of the angular acceleration about the out-of-plane axis of the gradiometer. This information in combination with the angular rates as derived from the star sensor readings is used as control signal for angular control of the spacecraft. The satellite has to be guided well controlled and smoothly around the Earth in an Earth pointing mode, i.e. with one full revolution per orbit revolution. Angular control is attained via magnetic torquers. This implies that active angular motion is possible only over part of each orbit revolution. In order to prevent non-gravitational forces to “sneak” into the measured differential accelerations as secondary effect, the satellite is kept “drag-free” in along track direction by means of a pair of ion thrusters. The necessary control signal is

derived from the available “common-mode” accelerations (=mean accelerations) along the three orthogonal axes of the accelerometer pairs of the gradiometer. The gradiometric and angular signal part of the common mode acceleration, which is a result of the imperfect symmetry of the gradiometer relative to the spacecraft centre of mass, has to be modelled.

The second gravity sensor device is a newly developed GPS receiver. From its measurements the orbit trajectory is computed to within a few centimetres, either purely geometrically, a so-called kinematic orbit, or by the method of reduced dynamic orbit determination. As the spacecraft is kept in an almost drag-free mode (at least along track and within an extended measurement bandwidth) the orbit motion is purely gravitational. The observations from the GPS receiver are complementary to those of the gravity gradiometer. They provide high quality information about the long wavelength gravity field, which is outside the measurement bandwidth of the gradiometer. By a joint analysis of data from both gravity field sensors the final GOCE gravity field models are determined.



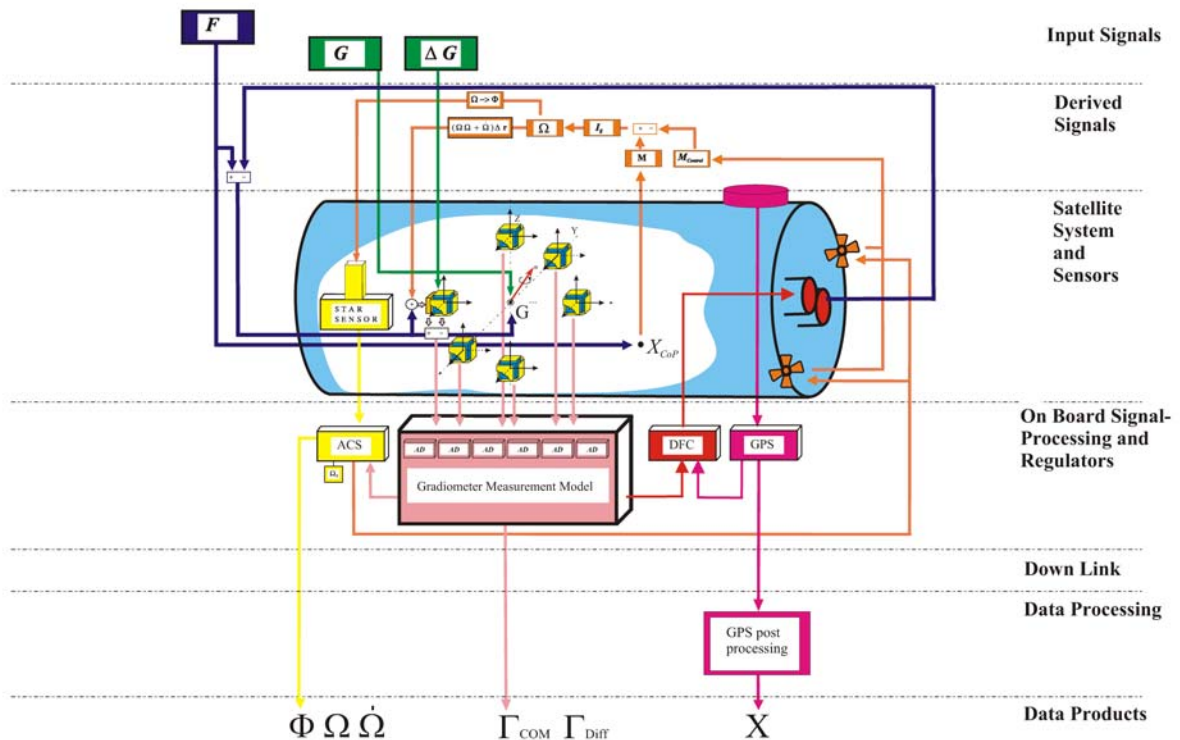
**Figure 4-1:** The GOCE Satellite and its Instruments

In summary, GOCE is a technologically very complex and demanding mission. The gravitational field sensor system consists of a three-axis gravitational gradiometer and GPS receiver as core instruments. Orientation in inertial space is derived from star sensors. Common mode mode accelerations from the gradiometer and orbit positions from GPS are used together with ion thrusters for drag-free control and with magneto-torquers for angular

control. The principle of the system is shown in Figure 4-2 and, the system elements are summarized in Table 4-2.

**Table 4-2:** Elements of the Gravity Sensor System of GOCE

Element	Purpose
3-axis gravity gradiometer	Measures diagonal gravity gradients $\Gamma_{xx}$ , $\Gamma_{yy}$ , $\Gamma_{zz}$ and off-diagonal gravity gradients $\Gamma_{xy}$ , $\Gamma_{xz}$ , $\Gamma_{yz}$ in instrument system and in MBW (measurement bandwidth) Measures angular accelerations (highly accurate around y-axis, less accurate around x, z axes) Measures common mode accelerations
Star sensors	Measure high rate and high precision inertial orientation
GPS receiver	Measures orbit trajectory with cm-precision
Drag control with 2 ion thrusters	Control signal from common mode accelerations from gradiometer
Angular control with magnetic torquer	Based on angular rates from star sensors and gradiometer
Internal gradiometer calibration and quadratic factors determination	With cold gas thrusters (random pulses) and sinusoidal motion of test masses of accelerometers, respectively



**Figure 4-2:** The GOCE Sensor System

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## 4.2 GOCE DATA PROCESSING OVERVIEW

### *Operational Ground Segment Elements*

The European Space Agency has defined a ground system, which will prepare and process the GOCE observations up to so-called level 2 products. Level 2 products will be precise orbits and the GOCE gravity field models as well as quality indicators associated to them. These level 2 products will be available to the users in solid Earth physics, oceanography, geodesy and others. Figure 3-1 shows the structure of the ESA GOCE ground system elements and their interrelations.

- FOS: The Flight Operation System controls the satellite and receives the raw telemetry data on ground.
- PDS: The Payload Data System processes from raw observations (level 0) corrected and internally calibrated instrumental data sets with physical meaning (e.g. GPS range and phase observations, gravity gradients)( level 1B).
- CMF: The Calibration and Monitoring Facility permanently monitors the quality of the level 1B data by applying dedicated test algorithms.
- HPF: The High level Processing Facility generates from level 1B data the final GOCE orbit and gravity field products in different quality levels (level 2).

Supporting elements to these four kernel elements are the satellite prime contractor providing support on the instrument performance analysis, the auxiliary data providers providing supporting data sets to perform the processing tasks and the long-term archive and user service facility providing finally the GOCE products to the user community.

### *The GOCE High Level Processing Facility (HPF)*

The HPF is as a distributed system developed and operated by the European GOCE Gravity Consortium (EGG-C). In order to fulfil the mission objectives, a dedicated scientific data analysis and processing system is implemented (Rummel et al, 2004). The major processing tasks of the HPF are as follows:

- The generation of level 2 products (orbits and gravity fields) from level 1b products generated by the PDS (nominal and calibrated products from the gradiometer and the GPS-receiver): The level 1b products consist mainly of gravity gradients in the gradiometer reference frame and pseudo-ranges and phases from the GPS receiver. They require a comprehensive scientific data processing before they can be used to compute satellite positions and velocities and gravity information in terms of a set of spherical harmonic coefficients (including their estimated full variance-covariance matrix), geoid heights, geoid height errors, geoid slopes and gravity anomalies. These are the main products expected by the scientific users.
- The generation of GOCE calibration and validation products (external calibration of gradiometer data, quick-look gravity field and orbit solutions for data validation): The level 1b gradiometer products are already internally calibrated. This means that

calibration parameters are applied and non-linearity is corrected for. The former are derived from a dedicated data analysis from observations taken during satellite and electronic shaking manoeuvres. At this point the relationship between the observed gravity gradients and real gravity field is still to be established. In order to do so an external scientific calibration of the gravity gradients is performed by comparison with existing gravity information. Furthermore level 1b products from both sensors, SST and SGG, have to be validated in order to warrant a continuously high quality data flow, which is required to meet the mission objectives. For this reason the HPF implements several validation tools, which permanently monitor the quality of the level 1b products by derivation of so-called quick-look or rapid products on a level 2 basis. This means orbit and gravity field solutions are systematically generated from partial data sets of new GOCE observations with latencies of a few days. These solutions are further evaluated in order to find out whether the mission performance requirements are met.

- The acquisition of auxiliary data needed for level 2 products generation: The most important are Earth rotation parameters from the International Earth Rotation and Reference Systems Service (IERS), GPS orbit, clock and ground station data from the International GNSS Service (IGS), satellite laser ranging data from the International Laser Ranging Service (ILRS) and atmospheric parameters from the European Centre for Medium Range Weather Forecast (ECMWF). Apart from this a variety of supporting data like planetary ephemerides, solar flux, geomagnetic indices, tide models, digital terrain models, external gravity field information and others have to be acquired. The HPF will acquire all ancillary data, check their quality and store them in a local HPF processing archive as well as in the long term GOCE archive, in case they are required for reprocessing purposes.

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

### 4.3 GOCE LEVEL 2 PRODUCTS SUMMARY

During the level 2 processing various intermediate level 2 products are generated. They contain intermediate results necessary for the next processing step in sequence. These products are not foreseen to be provided as standard GOCE products to the users. Final level 2 products, which will be available to the GOCE user community are listed in Table 4-3. The latencies of the final products are related to data availability of the level 1b products from the PDS. Pre-processed and calibrated gradiometer data and precise science orbits will be available with a latency of two weeks. Both products represent the main input to the gravity field processors. The final gravity field solution, will be available about 9 months after completion of each measurement operations phase. The transformed gravity gradients in an Earth fixed frame will be available after approximately 6 months. In order to reduce the transformation errors as much as possible, which are propagated from the less sensitive

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accelerometer axes of the gradiometer to the transformed gravity gradients in the Earth fixed frame, several months of data will run through that procedure simultaneously.

All GOCE level 2 products are available to the user community via the ESA GOCE user service interface. The products are provided in XML format in order to enhance the products readability and the in-file data definitions (see chapter 5.3).

**Table 4-3:** List of GOCE Level-2 End User Data Products.

Product Name	Product Definition	Remarks
<b>Gravity Gradients</b>		
EGG_NOM_2_	L2 gravity gradients in GRF with corrections: <ul style="list-style-type: none"> <li>Externally calibrated and corrected gravity gradients</li> <li>Corrections to gravity gradients due to temporal gravity variations</li> <li>Flags for outliers, fill-in gravity gradients for data gaps with flags</li> <li>Gravity gradient error estimates</li> </ul>	Latency 2 weeks
EGG_TRF_2_	L2 gravity gradients in LNOF (see chapter 4.4.1) with corrections: <ul style="list-style-type: none"> <li>Externally calibrated gravity gradients in local north oriented frame including corrections to gravity gradients due to temporal gravity variations</li> <li>Flags for outliers, fill-in gravity gradients for data gaps with flags</li> <li>Gravity gradient error estimates</li> </ul>	Latency 1 month,
<b>GOCE Orbits</b>		
SST_PSO_2_	Precise science orbits <ul style="list-style-type: none"> <li>Reduced-dynamic and kinematic precise science orbits</li> <li>Rotation matrices between IRF and EFRF</li> <li>Variance-covariance information for kinematic positions</li> <li>Quality report for precise orbits</li> </ul>	Latency 2 weeks
<b>GOCE Gravity Fields</b>		
EGM_GOC_2_	Final GOCE gravity field model <ul style="list-style-type: none"> <li>Spherical harmonic series including error estimates</li> <li>Grids of geoid heights, gravity anomalies and deflections of the vertical</li> <li>Propagated error estimates in terms of geoid heights</li> <li>Quality report for GOCE gravity field model</li> </ul>	Latency 9 months
EGM_GVC_2_	Variance-covariance matrix for the final gravity field in terms of spherical harmonic series	Latency 9 months, Only on physical media

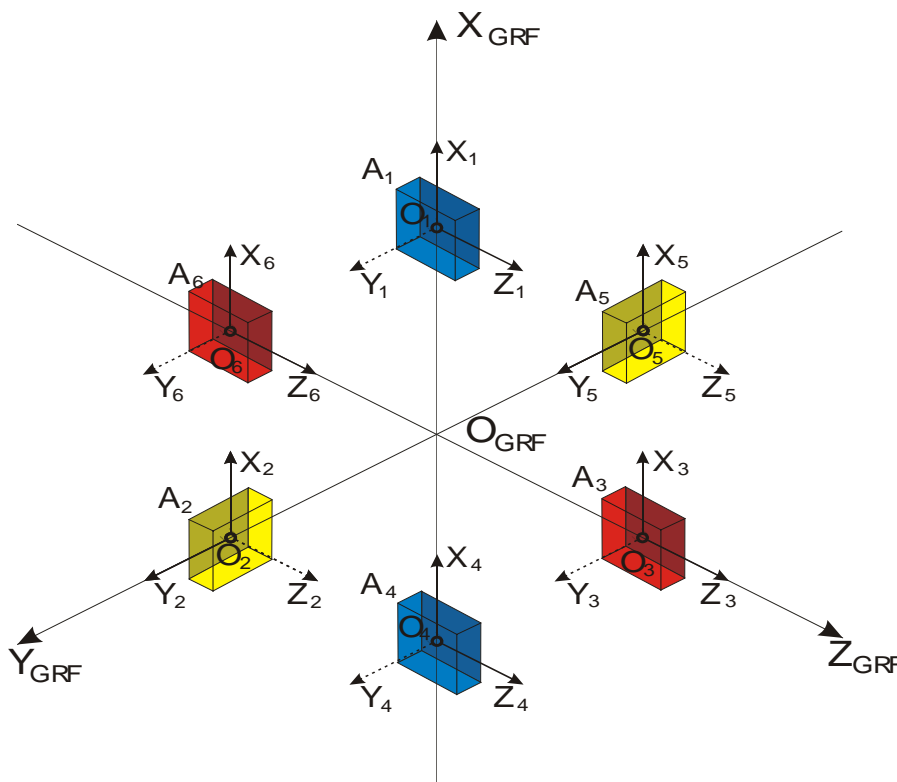
## 4.4 GENERAL DEFINITIONS AND CONVENTIONS

All details about general definitions and conventions applied for level 2 data processing are specified in [AD-12]. In the following a short summary describing the most essential definitions and conventions is provided.

#### 4.4.1 Reference Frames and Time System

##### *GRF - Gradiometer Reference Frame & ARF – Accelerometer Reference Frame*

GRF is the coordinate system in which the components of the gravity gradient tensor are measured by GOCE (see Figure 4-3). The GRF represents the Three-Axis Gradiometer common reference for the mutual positioning and alignment of the three One Axis Gradiometers and for the positioning and orientation of the whole instrument with respect to external reference frames. Nominally the origins of all one-axis gradiometer reference frames (OAGRF) coincide in one intersection point. The corresponding axes of each of the 3 OAGRF's are parallel and point in the same directions. The corresponding 6 accelerometer reference frames (ARF) are parallel and point in the same direction.



**Figure 4-3:** : Notation and location of the 6 accelerometers of the GOCE gradiometer in the GRF and with all 6 ARF's. The axes of the ARF shown by solid arrows are aligned with ultra sensitive axes of the accelerometer. The axes of the ARF shown by dashed arrows are aligned to the less sensitive axes of the accelerometer. Each colour represents a one-axis gradiometer. The shadowed surfaces represent the locations of the lower plates (and the sole plates).

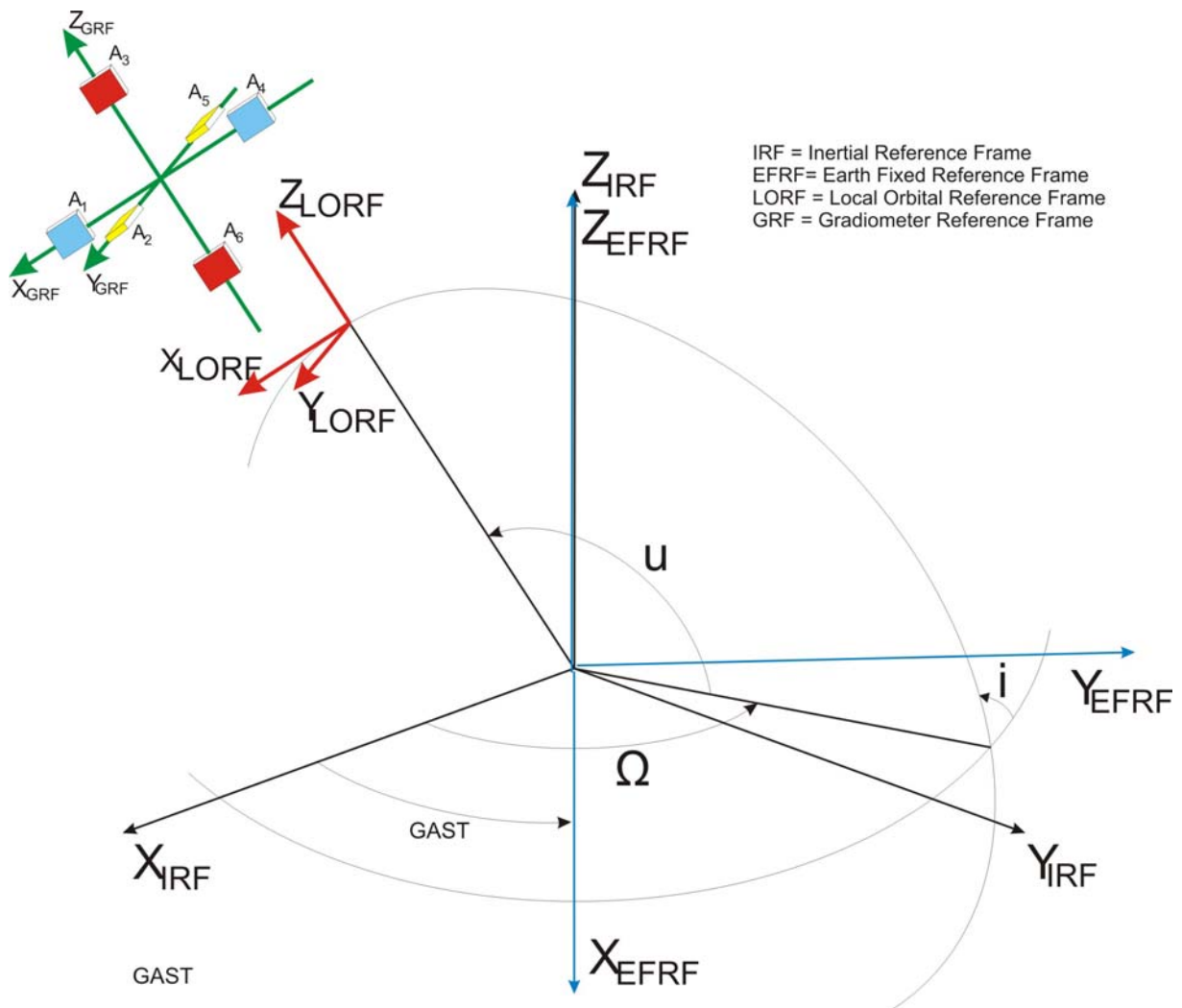
##### *LORF – Local Orbital Reference Frame*

The origin  $O_{LORF}$  is located at the actual satellite centre of mass;  $X_{LORF}$  axis (roll) is parallel to instantaneous direction of the orbital velocity vector ( $\underline{V}$ ) with the same sign as this vector.

$Y_{LORF}$  axis (pitch) is parallel to instantaneous direction of the orbital angular momentum ( $\underline{N}$ ), with the same sign as  $\underline{N}$  ( $\underline{V}$  and  $\underline{N}$  are orthogonal by definition, since  $\underline{N} = \underline{R} \times \underline{V}$ , where  $\underline{R}$  is the vector from the Earth centre to the origin). The  $Z_{LORF}$  (yaw) axis is parallel to  $\underline{V} \times \underline{N}$ , with the same sign as  $\underline{V} \times \underline{N}$

**Orientation of GRF/LORF in Space**

Figure 4-4 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 magnetorquers over the poles. Since the magnetorquers can only operate close to the pole, the yaw steering mode allows the roll angle to accumulate at the equator by a few degrees. The maximum yaw angle value of  $3.5^\circ$  is reached at the equator due to out-of-plane forces caused by Earth rotation. Thus the satellite will be yaw steered to within  $\pm 3.5^\circ$  (with respect to the LORF) in order to minimise lateral forces and torques.



**Figure 4-4:** Definition of fundamental Reference Systems for GOCE

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### ***Earth-Fixed Reference Frame (EFRF)***

The Earth-Fixed Reference System (EFRF) is a spatial reference system co-rotating with the Earth in its diurnal motion in space. The EFRF is an orthogonal, right-handed system. Its origin is at the Earth's center of mass (geocenter), the orientation is equatorial (z-axis is the direction of the pole). The x-axis is fixed in the equatorial plane in direction to the Greenwich meridian. The angle between the x-axis of the inertial reference frame (defined by the vernal equinox) and the Greenwich meridian is the Greenwich Apparent Sideral Time (GAST).

### ***Local North Oriented Frame (LNOF)***

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 calibrated gravity gradients of the EGG\_TRF\_2 products are provided in this system.

- The origin  $O_{LNOF}$  is located at the nominal satellite centre of mass
- $Z_{LNOF}$  is defined as the vector from the geocenter to the origin  $O_{LNOF}$ , pointing radially outward,
- $Y_{LNOF}$  is parallel to the normal vector to the plane of the geocentric meridian of the satellite center of mass, pointing westward,
- $X_{LNOF}$  is parallel to the normal vector to the plane defined by  $Y_{LNOF}$  and  $Z_{LNOF}$ .

In geocentric latitude and East longitude ( $\varphi$ ,  $\lambda$ ) of the GOCE center of mass in the CTRS the 3 axes are defined as follows:

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

### ***Time System***

All GOCE products are time-tagged in GPS-time. This time will be derived by correlating the on-board time with the GPS time. In case no GPS time is available (due to receiver outage) the GPS time is automatically determined by correlating the on-board time with UTC and applying the constant and leap second time shift.

## **4.4.2 Mathematical Conventions**

### **4.4.2.1 Earth Orientation Quaternions**

The rotation matrix provided together with the precise science orbit is defined in terms of quaternions. Earth Orientation Quaternions (EOQ) define the rotation between Earth-Fixed

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Reference Frame (EFRF) and Inertial Reference Frame (IRF) and are provided for every integer second of GPS time. Quaternions are used in the following way e.g. for a rotation of a vector from EFRF to IRF.

The quaternion  $q$  is defined in terms of Euler symmetric parameters  $q_1, q_2, q_3, q_0$ :

$$q = q_0 + iq_1 + jq_2 + kq_3 \quad (4.1)$$

$$q_1 = e_1 \sin \frac{\Phi}{2}, \quad q_2 = e_2 \sin \frac{\Phi}{2}, \quad q_3 = e_3 \sin \frac{\Phi}{2}, \quad q_0 = \cos \frac{\Phi}{2}$$

where  $e_1, e_2, e_3$  are components of the Euler axis and  $\Phi$  is the corresponding rotation angle (the angle of the frame rotation around the axis defined by the unit vector  $(e_1, e_2, e_3)$ ). The quantity  $q_0$  is the real or scalar part of the quaternion and  $iq_1 + jq_2 + kq_3$  is the imaginary or vector part. The  $i, j, k$  are the hyperimaginary numbers satisfying the conditions:

$$\begin{aligned} i^2 &= j^2 = k^2 = -1 \\ ij &= -ji = k \\ jk &= -kj = i \\ ki &= -ik = j \end{aligned} \quad (4.2)$$

Transformation of the orbit position and velocity given in the Earth-Fixed Reference Frame (EFRF) into Inertial Reference Frame (IRF) is defined as:

$$X_{\text{IRF}} = R X_{\text{EFRF}} \quad (4.3)$$

$$\dot{X}_{\text{IRF}} = R \dot{X}_{\text{EFRF}} + \dot{R} X_{\text{EFRF}}$$

$$\dot{X}_{\text{IRF}} = R \dot{X}_{\text{EFRF}} + \Omega R X_{\text{EFRF}}$$

where the rotation matrix  $R$  is computed by:

$$R = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_0^2 & 2(q_1 q_2 + q_3 q_0) & 2(q_1 q_3 - q_2 q_0) \\ 2(q_1 q_2 - q_3 q_0) & -q_1^2 + q_2^2 - q_3^2 + q_0^2 & 2(q_2 q_3 + q_1 q_0) \\ 2(q_1 q_3 + q_2 q_0) & 2(q_2 q_3 - q_1 q_0) & -q_1^2 - q_2^2 + q_3^2 + q_0^2 \end{bmatrix} \quad (4.4)$$

The skew-symmetric matrix  $\Omega$  can be with sufficient accuracy approximated by:

$$\Omega = \begin{bmatrix} 0 & \omega_3 & -\omega_2 \\ -\omega_3 & 0 & \omega_1 \\ \omega_2 & -\omega_1 & 0 \end{bmatrix} \approx \begin{bmatrix} 0 & \omega_3 & 0 \\ -\omega_3 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (4.5)$$

$$\omega_3 = -7292115.1567 \cdot 10^{-11} \text{ rad/s}$$

Where  $(\omega_1, \omega_2, \omega_3)$  are components of the instantaneous Earth rotation velocity in IRF.

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Using quaternions, computation of the rotation matrix can be avoided and the transformation can be replaced by the multiplication:

$$X_{\text{IRF}} = q^* X_{\text{EFRF}} q \quad (4.6)$$

where  $q^*$  denotes the conjugate or inverse quaternion  $q^*$  defined as

$$q^* = q_0 - iq_1 - jq_2 - kq_3 \quad (4.7)$$

and  $X_{\text{EFRF}}$  position vector written in the form of a quaternion (scalar part is zero).

Transformation from the Earth-fixed reference frame (EFRF) into inertial reference frame (IRF) can be then computed as follows:

$$\begin{bmatrix} 0 \\ X_{\text{IRF}} \\ Y_{\text{IRF}} \\ Z_{\text{IRF}} \end{bmatrix} = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \\ -q_1 & q_0 & q_3 & -q_2 \\ -q_2 & -q_3 & q_0 & q_1 \\ -q_3 & q_2 & -q_1 & q_0 \end{bmatrix} \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & q_3 & -q_2 \\ q_2 & -q_3 & q_0 & q_1 \\ q_3 & q_2 & -q_1 & q_0 \end{bmatrix} \begin{bmatrix} 0 \\ X_{\text{EFRF}} \\ Y_{\text{EFRF}} \\ Z_{\text{EFRF}} \end{bmatrix} \quad (4.8)$$

The Earth orientation quaternion is provided for every integer second ( $t_0$ ) of GPS time together with the orbit product. To get quaternion information for the actual epoch time  $t_{\text{epo}}$ , kinematic equation can be used to propagate quaternion information from the nearest integer second  $q_{4 \times 1}(t_0)$ :

$$q_{4 \times 1}(t_{\text{epo}}) = S_{4 \times 4} q_{4 \times 1}(t_0)$$

$$\Delta t = t_{\text{epo}} - t_0 \quad [s] \quad \omega = -7292115.1567 \cdot 10^{-11} \quad [\text{rad/s}]$$

$$S_{4 \times 4} = \begin{bmatrix} \cos\left(\frac{1}{2} \omega \Delta t\right) & -\sin\left(\frac{1}{2} \omega \Delta t\right) & 0 & 0 \\ \sin\left(\frac{1}{2} \omega \Delta t\right) & \cos\left(\frac{1}{2} \omega \Delta t\right) & 0 & 0 \\ 0 & 0 & \cos\left(\frac{1}{2} \omega \Delta t\right) & -\sin\left(\frac{1}{2} \omega \Delta t\right) \\ 0 & 0 & \sin\left(\frac{1}{2} \omega \Delta t\right) & \cos\left(\frac{1}{2} \omega \Delta t\right) \end{bmatrix} \quad (4.9)$$

#### 4.4.2.2 Spherical Harmonic Series

The GOCE gravity field models are provided in terms of a set of dimensionless coefficients of a spherical harmonic series up to a maximum degree of the gravity potential. These coefficients are the result of the gravity field determination process. All other quantities

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delivered together with the products are derived from these coefficients. The variance-covariance matrix product consists of the variances and covariances of and between all individual coefficients of the spherical harmonic series.

The gravitational potential spherical harmonic series is defined by (see e.g. Torge, 2001, p. 70 or Heiskanen/Moritz, 1967, p.59):

$$\begin{aligned}
 V(r, \theta, \lambda) &= W(r, \theta, \lambda) - Z(r, \theta, \lambda) = \\
 &= \frac{GM}{r} \sum_{n=0}^{N_{\max}} \left(\frac{a}{r}\right)^n \sum_{m=0}^n (\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta)
 \end{aligned} \tag{4.10}$$

where:	V	gravitational potential at computation point
	W	Earth's gravity potential (incl. centrifugal potential)
	Z	centrifugal potential
	GM	gravity constant times total mass of Earth (solid Earth, atmosphere, ocean) (Note: The factor GM is provided together with the spherical harmonic series)
	a	equatorial radius of the Earth ellipsoid used for the determination of the harmonic coefficients ( $\bar{C}_{nm}, \bar{S}_{nm}$ ); (Note: This value is provided together with the spherical harmonic series)
	n	degree of spherical harmonic coefficient
	$N_{\max}$	maximum degree of spherical harmonic series
	m	order of spherical harmonic coefficient
	r	radial distance of computation point from geocenter
	$\theta$	geocentric co-latitude of computation point
	$\lambda$	(geocentric) longitude of computation point
	$\bar{P}_{nm}$	normalized associated Legendre functions of degree n and order m
	$\bar{C}_{nm}, \bar{S}_{nm}$	coefficients of spherical harmonic series (normalized and dimensionless)

The coefficients of the spherical harmonic series are normalized. The following convention is used (Heiskanen/ Moritz, 1967, p.32; Torge, 2001, p.72):

$$\begin{aligned}
 \bar{C}_{n0} &= \frac{1}{\sqrt{2n+1}} C_{n0}, & \bar{P}_{n0}(\cos \theta) &= \sqrt{2n+1} \cdot P_{n0}(\cos \theta), \\
 \left\{ \begin{array}{c} \bar{C}_{nm} \\ \bar{S}_{nm} \end{array} \right\} &= \sqrt{\frac{(n+m)!}{2(2n+1)(n-m)!}} \cdot \left\{ \begin{array}{c} C_{nm} \\ S_{nm} \end{array} \right\}, & \bar{P}_{nm}(\cos \theta) &= \sqrt{\frac{2(2n+1)(n-m)!}{(n+m)!}} \cdot P_{nm}(\cos \theta),
 \end{aligned} \tag{4.11}$$

where:	$C_{nm}, S_{nm}$	unnormalized coefficients of spherical harmonic series
	$P_{nm}$	unnormalized associated Legendre functions of degree n and order m

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The set of coefficients  $C_{nm}, S_{nm}$  or  $\bar{C}_{nm}, \bar{S}_{nm}$  together with the chosen value GM and a form the spherical harmonic set.

#### 4.4.2.3 Error Propagation

Together with the coefficients of the spherical harmonic series the variance-covariance matrix for the estimated coefficients is available. Error propagation from the spherical harmonic coefficients variance-covariance matrix to that of the observations is performed by:

$$Q_{ll} = A Q_{xx} A^T \quad (4.12)$$

- with
- $Q_{ll}$  Variance-covariance matrix of the observations
  - $A$  Coefficient matrix (partial derivatives of observation equation) connecting the parameters with the observations
  - $Q_{xx}$  Variance-covariance matrix of the parameters

#### 4.4.3 Geophysical Conventions

The gravity potential expressed by the spherical harmonic series represents the total effect of the solid Earth mass, the atmospheric and the oceanic masses. The constants of the spherical harmonic series GM (gravitational constant times mass) and  $a$  (equatorial radius of the Earth) are provided together with the model coefficients. The atmosphere is assumed to be condensed at the surface of the sphere with radius  $a$ . All time variable mass variations are subtracted by models during the estimation procedure. This includes direct tides from Sun, Moon and planets, solid Earth tides, ocean tides and solid Earth pole tides. The product information includes an indicator whether permanent tides are included in the model (zero-tide) or not (tide free). Also non-tidal mass variations in the atmosphere and the oceans are taken into account by using an atmospheric and oceanic model. Details about the correction models and how they are applied are described in [AD-12].

From the gravity potential derived gravity quantities such as geoid heights, gravity anomalies and deflections of the vertical are directly computed using the spherical harmonic series and subtracting the spherical harmonic coefficients of the adopted reference potential. Before subtraction, the gravity field spherical harmonic series has to be scaled to the constants of the reference potential (see (4.13)). This includes the coefficient  $\bar{C}_{00}$  representing the zero-order part of the gravitational potential. The name of the adopted reference potential is provided in the header of the product files. When computing the derived gravity quantities the following pre-computations and assumptions are made:

In order to take into account the constant potential difference between the GOCE derived and the reference potential all coefficients are transformed to the constants of the reference potential. Equation (4.13) is based on the assumption that at any point above the Earth's surface the gravity potential  $W$  is constant and does not change due to the coefficients

transformation. (The superscript “REF” indicates a constant taken from the adopted reference potential, “GOCE” means the constant is part of the gravity potential spherical harmonic solution).

$$\begin{Bmatrix} \bar{C}_{nm}^{REF} \\ \bar{S}_{nm}^{REF} \end{Bmatrix} = \left( \frac{GM^{GOCE}}{GM^{REF}} \right) \left( \frac{a^{GOCE}}{a^{REF}} \right)^n \begin{Bmatrix} \bar{C}_{nm}^{GOCE} \\ \bar{S}_{nm}^{GOCE} \end{Bmatrix} \quad (4.13)$$

- with
- $GM^{REF}$  Factor GM for the reference ellipsoid potential
  - $GM^{GOCE}$  Factor GM for the GOCE gravity spherical harmonic series
  - $a^{REF}$  Equatorial radius for the reference ellipsoid
  - $a^{GOCE}$  Equatorial radius for the GOCE gravity spherical harmonic series
  - $\bar{C}_{nm}^{REF}, \bar{S}_{nm}^{REF}$  Normalized spherical harmonic coefficients referring to the constants of the reference ellipsoid
  - $\bar{C}_{nm}^{GOCE}, \bar{S}_{nm}^{GOCE}$  Normalized spherical harmonic coefficients referring to the constants of the GOCE gravity spherical harmonic series

After rescaling the spherical harmonic coefficients to the set of constants of the reference potential the disturbing potential at a point P can be computed by (see for example Torge, 2001, p. 214, Heiskanen/Moritz, 1967, p.82):

$$T_p = W_p - U_p \quad (4.14)$$

- with
- $W_p$  gravity potential at point P (including centrifugal potential)
  - $U_p$  normal potential of reference ellipsoid at point P (including centrifugal potential)
  - $T_p$  disturbing potential at point P

By subtracting the normal potential from the gravity potential the centrifugal potential drops out. As the gravitational potential (see (4.10)) also the normal potential can be expanded into a spherical harmonic series (compare Torge, 2001, p. 107):

$$U(r, \theta, \lambda) - Z(r, \theta, \lambda) = \frac{GM^{REF}}{r} \left( 1 + \sum_{n=2(2)}^{\infty} \left( \frac{a^{REF}}{r} \right)^n \tilde{C}_n^{REF} \bar{P}_n(\cos \theta) \right) \quad (4.15)$$

- with
- $\tilde{C}_n^{REF}$  normalized coefficient of spherical harmonic series of the reference ellipsoid of degree n and order 0
  - $\bar{P}_n$  normalized Legendre polynomial of degree n

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The normalized coefficients of the spherical harmonic series of the reference ellipsoid are computed by:

$$\tilde{C}_{2k}^{REF} = (-1)^k \frac{3(e^{REF})^{2k}}{(2k+3)(2k+1)\sqrt{4k+1}} \left[ 1 + \frac{2}{3}k \left( 1 - \frac{m_\gamma e'^{REF}}{q_0} \right) \right] \quad (4.16)$$

The series is rapidly convergent and in practical computations it can be truncated at  $k=4$  without losing accuracy.

with  $n=2k, (k=1,2,3,4)$   
 $e^{REF}$  as defined in (4.18)  
 $e'^{REF}, m_\gamma, q_0$  as defined in (4.26) and follow-on equations

The spherical harmonic series of the disturbing potential for the point P with the coordinates  $r, \theta, \lambda$  then becomes:

$$T(r, \theta, \lambda) = \frac{GM^{REF}}{r} \sum_{n=0}^{N_{max}} \left( \frac{a^{REF}}{r} \right)^n \sum_{m=0}^n (\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \quad (4.17)$$

with  $\Delta \bar{C}_{nm}, \Delta \bar{S}_{nm}$  residual coefficients of the spherical harmonic series after subtracting the coefficients of the normal potential from the gravitational potential.

Employing an ellipsoidal reference field (e.g. wgs84, grs80) this means for all residual coefficients except for degrees 0,2,4,6,8 and zero order that the following relation holds:

$$\Delta \bar{C}_{nm} = \bar{C}_{nm}^{REF} ; \Delta \bar{S}_{nm} = \bar{S}_{nm}^{REF}$$

For the coefficients of degree  $n=2,4,6,8$  and zero order the residual coefficients are defined by:

$$\Delta \bar{C}_{n0} = \bar{C}_{n0}^{REF} - \tilde{C}_n^{REF}$$

And for the degree 0 term the residual coefficient is defined by:

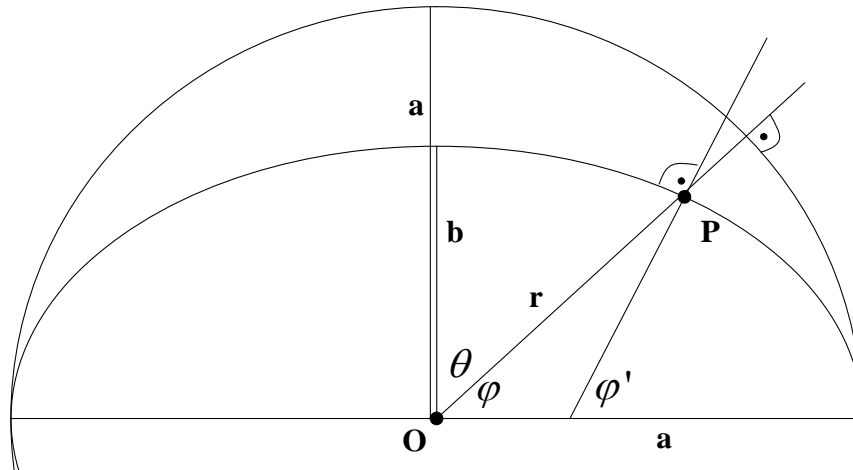
$$\Delta \bar{C}_{00} = \bar{C}_{00}^{REF} - 1$$

#### 4.4.3.1 Approximations for Derived Quantities

The series expansion of the normal potential (see equation (4.15)) is truncated at  $n=8$ . This means that for the normal potential only the spherical harmonic coefficients  $\tilde{C}_0^{REF}, \tilde{C}_2^{REF}, \tilde{C}_4^{REF}, \tilde{C}_6^{REF}, \tilde{C}_8^{REF}$  are taken into account (with  $\tilde{C}_0^{REF} = 1$ ).

In order to obtain approximate gravity field quantities like geoid heights, gravity anomalies and deflections of the vertical from the GOCE gravity potential harmonic series some approximations are introduced. In the following it is described how these derived products are

computed and what approximations are applied. Caution: These gridded quantities provide a good overall impression of the characteristics of these gravity quantities and are sufficiently accurate for global graphical representation. For real data analysis they are only suited in ocean areas or in low land continental areas. For a rigorous formulation see chapter 4.4.3.2.



**Figure 4-5:** Geometry of the ellipsoid (the ellipsoidal longitude  $\lambda'$  and geocentric longitude  $\lambda$  are identical. It holds for all points P:  $\lambda = \lambda'$ )

Note: the coordinates of the grid data files described in chapter 5.3 are given as geodetic (ellipsoidal) latitude and longitude.

The computation points P for the derived quantities are located on the reference ellipsoid (see Figure 4-5). Each point on the ellipsoid is defined by the set of geodetic (ellipsoidal) coordinates  $(\varphi', \lambda', r)$  (see Figure 4-5). The radial distance  $r$  from the geocenter to the computation point P is computed for each given geocentric latitude  $\varphi$  (or co-latitude  $\theta$ ). First the geodetic (ellipsoidal) latitude  $\varphi'$  is transformed to the corresponding geocentric value  $\varphi$  applying formula (4.19) (see Torge, 2001, equations 4.1b and 4.11a).

$$\frac{b^{REF}}{a^{REF}} = \sqrt{1 - (e^{REF})^2} ; e^{REF} = \frac{\sqrt{(a^{REF})^2 - (b^{REF})^2}}{a^{REF}} \quad (4.18)$$

$$\tan \varphi = (1 - (e^{REF})^2) \tan \varphi' \quad (4.19)$$

where:  $\varphi'$  geodetic (ellipsoidal) latitude  
 $\varphi$  geocentric latitude  
 $a$  semi major axis of the reference ellipsoid  
 $b$  semi minor axis of the reference ellipsoid  
 $e^{REF}$  first eccentricity of the reference ellipsoid

The geocentric distance of the computation point P running on the reference ellipsoid can be calculated as a function of the geodetic latitude by the following formulas (compare Torge, 2001, equations 4.6, 4.8, 4.9):

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$$r = \sqrt{p^2 + \bar{Z}^2} \quad (4.20)$$

$$p = \sqrt{\bar{X}^2 + \bar{Y}^2}$$

$$\bar{X} = \frac{(a^{REF})^2 \cos \varphi' \cos \lambda'}{\sqrt{(a^{REF})^2 \cos^2 \varphi' + (b^{REF})^2 \sin^2 \varphi'}} \quad (4.21)$$

$$\bar{Y} = \frac{(a^{REF})^2 \cos \varphi' \sin \lambda'}{\sqrt{(a^{REF})^2 \cos^2 \varphi' + (b^{REF})^2 \sin^2 \varphi'}}$$

$$\bar{Z} = \frac{(b^{REF})^2 \sin \varphi'}{\sqrt{(a^{REF})^2 \cos^2 \varphi' + (b^{REF})^2 \sin^2 \varphi'}}$$

Alternatively one can compute it as a function of the geocentric latitude as:

$$r = a^{REF} \sqrt{\frac{1 - (e^{REF})^2}{1 - (e^{REF} \cos \varphi)^2}} \quad (4.22)$$

For evaluating equation (4.17) the geocentric co-latitude  $\theta$ , the longitude  $\lambda$  and the geocentric distance  $r$  is used. As the geocentric distance ( $r$ ) is always equal or less than the semi major axis of the reference ellipsoid ( $a$ ) formula (4.17) is evaluated on or inside the sphere with radius  $a$ . Over the oceans the computation points  $P$  are always close to the real ocean surface, while over continental areas they refer to points that are in reality be located inside the continental masses. They have to be regarded as downward continued (to the ellipsoid) mathematical values. For any geophysical interpretation of these derived quantities this fact must be taken into account. (Note: in case of evaluation of equation (4.17) for an equi-angular grid on the reference ellipsoid the degree dependent term as well as the associated Legendre polynomials only have to be recomputed once for each parallel).

The geoid height is defined as the distance between the ellipsoid and the geoid. The geoid is defined by the condition that its potential equals to the constant normal potential of the corresponding point on the reference ellipsoid. By applying Bruns formula to equation (4.17) we get the relation between geoid heights and the disturbing potential ((Heiskanen / Moritz, 1967, p. 85, Torge, 2001, p. 258).

$$N = \frac{T}{\gamma_0} \quad (4.23)$$

where: N        geoid height  
 T        disturbing potential on the geoid  
 $\gamma_0$        normal gravity at reference ellipsoid

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The normal gravity at the reference ellipsoid is computed by the formula of Somigliana (see Torge, 2001, p. 106, equation 4.41b):

$$\gamma_0(\varphi') = \gamma_a \frac{1 + k \sin^2 \varphi'}{\sqrt{1 - (e^{REF})^2 \sin^2 \varphi'}} ; k = \frac{b^{REF} \gamma_b}{a^{REF} \gamma_a} - 1 \quad (4.24)$$

with:  $\gamma_a$  normal gravity at the equator  
 $\gamma_b$  normal gravity at the pole

The normal gravity at the equator and at the poles are computed by (see Heiskanen / Moritz, 1967, p. 69, equations 2-73 and 2-74):

$$\gamma_a = \frac{GM^{REF}}{a^{REF} b^{REF}} \left( 1 - m_\gamma - \frac{m_\gamma e'^{REF} q'_0}{6} \right) \quad (4.25)$$

$$\gamma_b = \frac{GM^{REF}}{(a^{REF})^2} \left( 1 + \frac{m_\gamma e'^{REF} q'_0}{3} \right)$$

with  $m_\gamma = \frac{(\omega^{REF})^2 (a^{REF})^2 b^{REF}}{GM^{REF}} \quad (4.26)$

$\omega^{REF}$  rotational velocity of reference ellipsoid (provided together with ellipsoid parameters)

$$e'^{REF} = \frac{\sqrt{(a^{REF})^2 - (b^{REF})^2}}{b^{REF}} \quad \text{second eccentricity of ellipsoid}$$

$$q_0 = \frac{1}{2} \left[ \left( 1 + \frac{3}{(e'^{REF})^2} \right) \tan^{-1} e'^{REF} - \frac{3}{e'^{REF}} \right]$$

$$q'_0 = 3 \left( 1 + \frac{1}{(e'^{REF})^2} \right) \left( 1 - \frac{\tan^{-1} e'^{REF}}{e'^{REF}} \right) - 1$$

By applying equation (4.23) to equation (4.17) the geoid heights as defined above can be written as a spherical harmonic series.

$$N(r, \theta, \lambda) = \frac{GM^{REF}}{r \gamma_0} \sum_{n=0}^N \left( \frac{a^{REF}}{r} \right)^n \sum_{m=0}^n (\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \quad (4.27)$$

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Gravity anomalies are derived from the fundamental equation of physical geodesy introducing the derivatives along the plumb line of the disturbing potential and the normal gravity (see Heiskanen / Moritz, 1967, p.86).

$$\Delta g = g_P - \gamma_0 = -\frac{\partial T}{\partial h} + \frac{1}{\gamma_0} \frac{\partial \gamma}{\partial h} T \quad (4.28)$$

with  $g_P$  magnitude of gravity at the geoid

In spherical approximation (by approximating the real plumb line with the geocentric vector) it becomes (Heiskanen / Moritz, 1967, p. 88):

$$\Delta g = -\frac{\partial T}{\partial r} - \frac{2}{a^{REF}} T \quad (4.29)$$

By applying the spherical approximation of (4.29) to equation (4.17) we get the spherical harmonic series for the gravity anomalies:

$$\Delta g(r, \theta, \lambda) = \frac{GM^{REF}}{r^2} \sum_{n=0}^N (n-1) \left( \frac{a^{REF}}{r} \right)^n \sum_{m=0}^n (\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \quad (4.30)$$

The above formulas are given in spherical approximation. Their accuracy is sufficient in ocean areas and for applications where the effect of topographic masses on gravity quantities can be disregarded.

In a similar way the deflections of the vertical are defined in spherical approximation as (see Heiskanen / Moritz, 1967, p. 112, equation 2-204):

$$\xi = -\frac{1}{a^{REF}} \frac{\partial N}{\partial \varphi} ; \quad \eta = -\frac{1}{a^{REF} \cos \varphi} \frac{\partial N}{\partial \lambda} \quad (4.31)$$

where  $\xi$  North-South deflection of the vertical at computation point  
 positive towards North  
 $\eta$  East-West deflection of the vertical at computation point  
 positive towards East

By applying the formulas (4.31) to (4.27) we get the spherical harmonic series expansions for both components of the vertical deflections.

$$\xi(r, \theta, \lambda) = -\frac{GM^{REF}}{a^{REF} r \gamma_0} \sum_{n=0}^N \left( \frac{a^{REF}}{r} \right)^n \sum_{m=0}^n (\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda) \frac{\partial \bar{P}_{nm}(\cos \theta)}{\partial \theta} \quad (4.32)$$

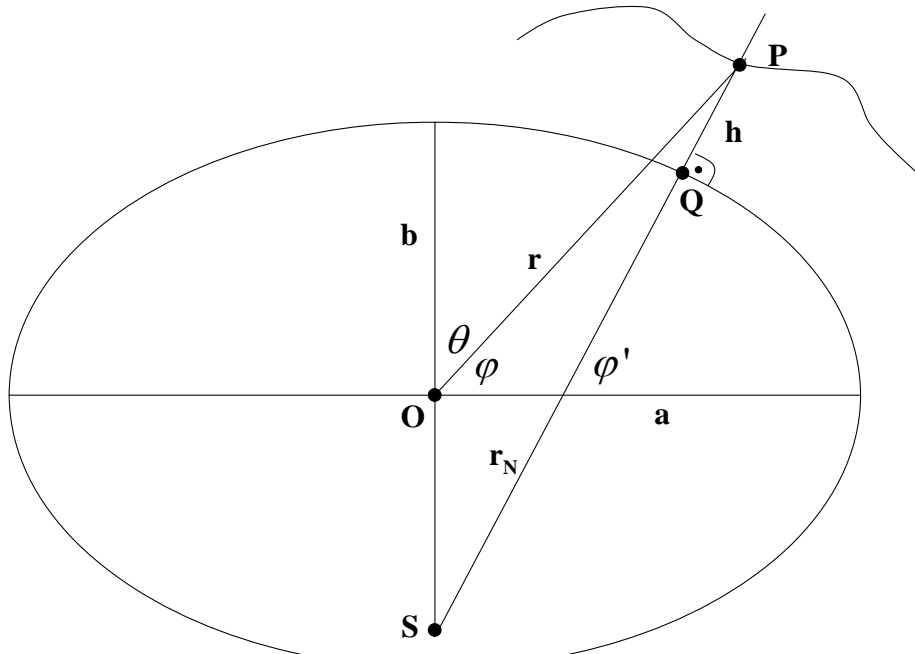
$$\eta(r, \theta, \lambda) = \frac{GM^{\text{REF}}}{a^{\text{REF}} r \gamma_0 \sin \theta} \sum_{n=0}^N \left( \frac{a^{\text{REF}}}{r} \right)^n \sum_{m=0}^n \left( -m \Delta \bar{C}_{nm} \sin m\lambda + m \Delta \bar{S}_{nm} \cos m\lambda \right) \bar{P}_{nm}(\cos \theta) \quad (4.33)$$

The derivative of the associated Legendre functions can be computed with the following formula (see Kautzleben, 1965):

$$2 \frac{\partial \bar{P}_{n,m}(\cos \theta)}{\partial \theta} = \begin{cases} -\sqrt{2n(n+1)} \bar{P}_{n,1}(\cos \theta) & (m=0) \\ \sqrt{2n(n+1)} \bar{P}_{n,0}(\cos \theta) - \sqrt{(n-1)(n+1)} \bar{P}_{n,2}(\cos \theta) & (m=1) \\ \sqrt{(n+m)(n-m+1)} \bar{P}_{n,m-1}(\cos \theta) - \sqrt{(n-m)(n+m+1)} \bar{P}_{n,m+1}(\cos \theta) & (m > 1) \end{cases} \quad (4.34)$$

#### 4.4.3.2 More Accurate Formulations for Derived Quantities

In order to avoid downward continuation inside the masses to the reference ellipsoid, Molodensky introduced the Earth surface as boundary surface, where the spherical harmonic series is evaluated. This implies that several approximations introduced before are not applicable anymore and a more rigorous formulation has to be applied.



**Figure 4-6:** Geometry for a point P on the Earth's surface and the ellipsoid. (the ellipsoidal longitude  $\lambda'$  and geocentric longitude  $\lambda$  are identical. It holds for all points P:  $\lambda = \lambda'$ )

The computation points P for the derived quantities are located on the Earth's surface (see Figure 4-6). As for the case when P is located on the ellipsoid the radial distance  $r$  from the geocenter to the computation point P is computed for each given geocentric latitude  $\phi$  (or co-latitude  $\theta$ ) and for the height  $h$  of the point above the ellipsoid (distance point Q-P).

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First, the radius of the curvature  $r_N$  (distance point S-Q) is computed by (see Torge, 2001, p. 96, equation 4-15) (with  $e^{REF}$  defined by equation (4.18)):

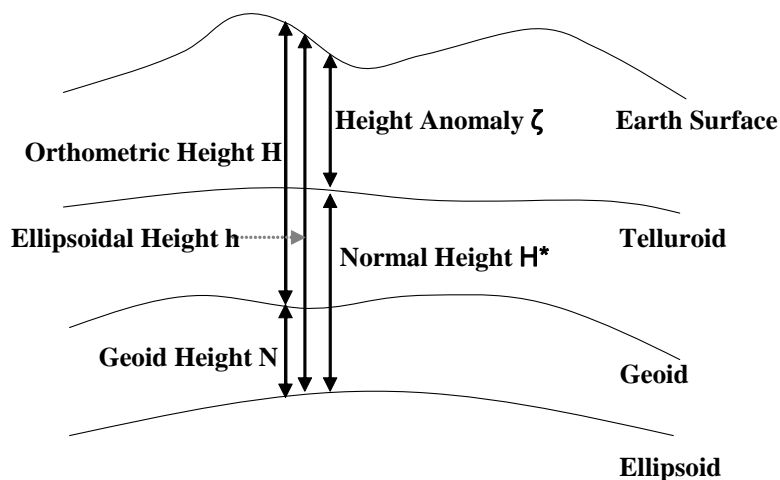
$$r_N = \frac{a^{REF}}{\sqrt{1 - (e^{REF})^2 \sin^2 \varphi'}} \quad (4.35)$$

The geocentric latitude and the radial distance are computed by (Torge, 2001, p. 100, equation 4-27):

$$\begin{aligned} \bar{X} &= (r_N + h) \cos \varphi' \cos \lambda' \\ \bar{Y} &= (r_N + h) \cos \varphi' \sin \lambda' \\ \bar{Z} &= \left( (1 - (e^{REF})^2) r_N + h \right) \sin \varphi' \\ \varphi &= \arctan \frac{\bar{Z}}{\sqrt{\bar{X}^2 + \bar{Y}^2}} ; \theta = 90^\circ - \varphi \\ \lambda &= \arctan \frac{\bar{Y}}{\bar{X}} \\ r &= \sqrt{\bar{X}^2 + \bar{Y}^2 + \bar{Z}^2} \end{aligned} \quad (4.36)$$

The height  $h$  of the surface point has to be taken from observations or from a topography model, e.g. that was derived by the SRTM mission. In order to compute the disturbing potential at the Earth's surface, equation (4.17) is evaluated using the geocentric co-latitude  $\theta$ , the longitude  $\lambda$  and the geocentric distance  $r$  as they are defined in equations (4.36). This means that for each point on the Earth's surface the degree dependent term in equation (4.17)  $(a/r)^n$  as well as the normalized associated Legendre polynomials  $\bar{P}_{nm}(\cos \theta)$  have to be recomputed, because  $\varphi$  and  $r$  are dependent on the height  $h$  of each point. (Note: in case of evaluation of equation (4.17) for an equi-angular grid on the reference ellipsoid the degree dependent term as well as the associated Legendre polynomials only have to be recomputed once for each parallel).

Before gravity quantities derived from the disturbing potential can be computed, the different height systems have to be introduced (see Figure 4-7).



**Figure 4-7:** Definition of Height Systems

The height anomaly is defined as the distance between the telluroid and the Earth's surface. The telluroid is defined by the condition that the normal potential at the telluroid point equals to the gravity potential of the corresponding point on the Earth's surface. By applying Bruns formula to equation (4.17) for the disturbing potential on the Earth's surface we get the relation between height anomalies and the disturbing potential ((Heiskanen / Moritz, 1967, p. 293, equation 8-10).

$$\zeta = \frac{T}{\gamma} \quad (4.37)$$

where:  $\zeta$  height anomaly  
 $T$  disturbing potential on the Earth's surface  
 $\gamma$  normal gravity acceleration at telluroid

By applying equation (4.37) to equation (4.17) the height anomalies as defined above are written as a spherical harmonic series:

$$\zeta(r, \theta, \lambda) = \frac{GM^{REF}}{r\gamma} \sum_{n=0}^N \left( \frac{a^{REF}}{r} \right)^n \sum_{m=0}^n (\Delta\bar{C}_{nm} \cos m\lambda + \Delta\bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \quad (4.38)$$

where  $r$  now is the distance from the geocenter to the point on the Earth's surface (compare Figure 4-6) and where  $\gamma$  is computed at topographic height  $H^*$  (see Heiskanen / Moritz, p. 79, equation 2-123):

$$\gamma = \gamma_0 \left( 1 - \frac{2}{a^{REF}} (1 + f^{REF} + m_\gamma - 2f^{REF} \sin^2 \varphi') H^* + \frac{3}{a^{REF}} H^{*2} \right) \quad (4.39)$$

with  $\gamma_0$  normal gravity on the reference ellipsoid (see equation (4.24))

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- $f^{REF}$  flattening of the ellipsoid  $f^{REF} = \frac{a^{REF} - b^{REF}}{a^{REF}}$   
 $m_\gamma$  centrifugal force at equator divided by centrifugal acceleration at the equator (see equation (4.26))  
 $H^*$  normal height

In order to compute height anomalies from a spherical harmonic series of the disturbing potential we have to know the normal heights of the telluroid points. As not for all areas in the world normal heights are available (depending on the height system used in each country) they could be approximated by orthometric heights, which are also often used as height system. The difference between the normal and orthometric heights is equal to the difference between height anomalies and geoid heights (see Heiskanen / Moritz, 1967, page 327, equation 8-102). They can reach up to a few decimeters in mountainous areas (e.g. 0.5 meters for Mont Blanc with an elevation of 4807 meters).

Free-air gravity anomalies (referring to ground level) are defined by the difference of the scalar gravity on the surface of the Earth and the normal gravity on the telluroid (see Heiskanen / Moritz, 1967, p.293, equation 8-7).

$$\Delta g = g_p - \gamma \quad (4.40)$$

- with  $g_p$  magnitude of gravity at Earth' surface  
 $\gamma$  magnitude of normal gravity at telluroid

In order to avoid spherical approximation (as in equation (4.29)) the magnitudes of both vectors are computed by the gradients of the gravitational potential and the normal potential, respectively, applying the following local right handed rectangular coordinate system: x positive towards the North, y positive towards the East, z: positive towards the geocenter.

$$g_p = |\text{grad } W_p| = \sqrt{\left(\frac{\partial W}{\partial x}\right)_P^2 + \left(\frac{\partial W}{\partial y}\right)_P^2 + \left(\frac{\partial W}{\partial z}\right)_P^2} \quad (4.41)$$

$$\gamma = |\text{grad } U| = \sqrt{\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial z}\right)^2}$$

from (4.10), after transformation of the coefficients to the constants of the reference ellipsoid applying equation (4.13) and from (4.15), after some rearrangement and introduction of geocentric spherical coordinates, the gravity and normal potentials are defined as spherical harmonic series including the centrifugal potential by (see Torge, 2001, p. 55, equation 3.38 for the centrifugal potential):

$$W(r, \theta, \lambda) = \frac{GM^{REF}}{a^{REF}} \sum_{n=0}^{N_{max}} \left(\frac{a^{REF}}{r}\right)^{n+1} \sum_{m=0}^n (\bar{C}_{nm}^{REF} \cos m\lambda + \bar{S}_{nm}^{REF} \sin m\lambda) \bar{P}_{nm}(\cos \theta) + \frac{1}{2} (\omega^{REF})^2 r^2 \sin^2 \theta \quad (4.42)$$

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$$U(r, \theta, \lambda) = \frac{GM^{\text{REF}}}{a^{\text{REF}}} \left( 1 + \sum_{n=2(2)}^8 \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \tilde{C}_n^{\text{REF}} \bar{P}_n(\cos \theta) \right) + \frac{1}{2} (\omega^{\text{REF}})^2 r^2 \sin^2 \theta \quad (4.43)$$

The derivatives of the gravity potential, after introducing spherical coordinates for equation (4.41), then are computed by (compare to equations (4.32) and (4.33)):

$$\begin{aligned} \frac{\partial W}{\partial x} &= \frac{\partial W}{r \partial \varphi} = -\frac{GM^{\text{REF}}}{ra^{\text{REF}}} \sum_{n=0}^{N_{\text{max}}} \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \sum_{m=0}^n (\bar{C}_{nm}^{\text{REF}} \cos m\lambda + \bar{S}_{nm}^{\text{REF}} \sin m\lambda) \frac{\partial \bar{P}_{nm}(\cos \theta)}{\partial \theta} + \\ &\quad + (\omega^{\text{REF}})^2 r \sin \theta \cos \theta \\ \frac{\partial W}{\partial y} &= \frac{\partial W}{r \cos \varphi \partial \lambda} = \frac{GM^{\text{REF}}}{r \cos \varphi a^{\text{REF}}} \sum_{n=0}^{N_{\text{max}}} \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \sum_{m=0}^n (-m \bar{C}_{nm}^{\text{REF}} \sin m\lambda + m \bar{S}_{nm}^{\text{REF}} \cos m\lambda) \bar{P}_{nm}(\cos \theta) \\ \frac{\partial W}{\partial z} &= \frac{\partial W}{\partial r} = -\frac{GM^{\text{REF}}}{ra^{\text{REF}}} \sum_{n=0}^{N_{\text{max}}} (n+1) \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \sum_{m=0}^n (\bar{C}_{nm}^{\text{REF}} \cos m\lambda + \bar{S}_{nm}^{\text{REF}} \sin m\lambda) \bar{P}_{nm}(\cos \theta) + \\ &\quad + (\omega^{\text{REF}})^2 r \sin^2 \theta \end{aligned} \quad (4.44)$$

In analogy the derivatives of the normal potential can be computed.

$$\begin{aligned} \frac{\partial U}{\partial x} &= \frac{\partial U}{r \partial \varphi} = -\frac{GM^{\text{REF}}}{ra^{\text{REF}}} \sum_{n=2(2)}^8 \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \tilde{C}_n^{\text{REF}} \frac{\partial \bar{P}_n(\cos \theta)}{\partial \theta} + (\omega^{\text{REF}})^2 r \sin \theta \cos \theta \\ \frac{\partial U}{\partial y} &= \frac{\partial U}{r \cos \varphi \partial \lambda} = 0 \\ \frac{\partial U}{\partial z} &= \frac{\partial U}{\partial r} = -\frac{GM^{\text{REF}}}{ra^{\text{REF}}} \sum_{n=2(2)}^{N_{\text{max}}} (n+1) \left( \frac{a^{\text{REF}}}{r} \right)^{n+1} \tilde{C}_n^{\text{REF}} \bar{P}_n(\cos \theta) + (\omega^{\text{REF}})^2 r \sin^2 \theta \end{aligned} \quad (4.45)$$

The deflection of the vertical is defined as the angle between the real plumb line direction and the ellipsoidal normal vector for a point on the Earth surface. The two components of the deflection of the vertical are computed by the following formulas (see Heiskanen / Moritz, 1967, p. 83, equation 2-140):

$$\xi = \Phi - \varphi' ; \quad \eta = (\Lambda - \lambda) \cos \Phi \quad (4.46)$$

where  $\xi$  North-South deflection of the vertical at computation point positive towards North  
 $\eta$  East-West deflection of the vertical at computation point positive towards East  
 $\Phi, \Lambda$  Astronomical coordinates representing the real plumb line

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$\varphi', \lambda$  Ellipsoidal coordinates representing the ellipsoid normal

The astronomical coordinates are related to the gravity potential at the surface of the Earth by the following relations (see Heiskanen / Moritz, 1967, p. 57, equation 2.29). As for equation (4.41) the same local orthogonal right handed coordinate system is applied (x positive towards the North, y positive towards the East, r: positive towards the geocenter).

$$\Phi = \arctan \left( \frac{-\frac{\partial W}{\partial z}}{\sqrt{\left(\frac{\partial W}{\partial x}\right)^2 + \left(\frac{\partial W}{\partial y}\right)^2}} \right); \Lambda = \arctan \left( \frac{\frac{\partial W}{\partial y}}{\frac{\partial W}{\partial x}} \right) \quad (4.47)$$

In analogy the ellipsoidal coordinates are related to the normal potential by the following formulas:

$$\varphi' = \arctan \left( \frac{-\frac{\partial U}{\partial z}}{\sqrt{\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2}} \right); \lambda' = \arctan \left( \frac{\frac{\partial U}{\partial y}}{\frac{\partial U}{\partial x}} \right) \quad (4.48)$$

The derivatives of the gravity potential and the normal potential are computed by equations (4.44) and (4.45). After solving equations (4.47) and (4.48) finally the deflections of the vertical are computed by equations (4.46).

Remark: Sometimes the anomalous quantities like  $\zeta$ ,  $\Delta g$ ,  $\xi$  and  $\eta$  have to be computed at points with known ellipsoidal heights, other times at points with known orthometric heights and one might wonder whether the choice of one or the other can make any significant difference. As a matter of fact this is not the case, because one can easily see that moving  $\zeta$  for 100 m along the vertical in an area of 100 mGal anomaly (which is an extreme case) can induce a change in  $\zeta$  of 1 cm; analogously moving up  $\Delta g$  by 100 m on the Earth surface can produce a change of 1 mGal in an area of 100 EU, i.e. under extreme geophysical conditions.

## 5. LEVEL-2 PRODUCT DEFINITIONS

### 5.1 PRODUCT IDENTIFIER

The product file names within the GOCE project follow the Earth Explorer standard [AD-9]. Each product file name is composed of the following components:

MM\_CCCC\_TTTTTTTTTT\_yyyymmddThhmmss\_YYYYMMDDTHHMSS\_vvvv.XXX

The meaning of these components is:

MM	Mission identifier: GO for GOCE
CCCC	File class: CONS for final products
TTTTTTTTTT	File type (see Table 4-3): e.g. EGG_NOM_2_, EGM_GOC_2_, SST_PSO_2_
vvvv	Version number
xxx	File extension: e.g. HDR for XML header file, DBL for XML data block
yyymmddThhmmss	Product validity start time in year, month, day and time in hours, minutes, seconds [UTC]
YYYYMMDDTHHMSS	Product validity stop time in year, month, day and time in hours, minutes, seconds [UTC]

### 5.2 PRODUCT DESCRIPTIONS

Product Name	EGG_NOM_2_
Product Description	Gravity Gradients in the Gradiometer Reference Frame (GRF) (see 4.4.1) corrected for temporal gravity field variations, outliers, data gaps and externally calibrated
Representation	Time series
Reference Frame	GRF (HPF GOCE standards apply, see chapter 4.4.1)
Time System	GPS time (HPF GOCE standards apply, see chapter 4.4.1)
Spatial Coverage	N/A
Temporal Coverage	1 day
Spatial Resolution	≈ 8 km along-track
Temporal Resolution	1 s
Input Data	<ol style="list-style-type: none"> <li>Internally calibrated gravity gradients from the PDS (EGG_NOM_1b product)</li> <li>GRF to IRF rotation matrix (from EGG_NOM_1b, EGG_IAQ_1b measurement data set)</li> <li>Gravity gradient external calibration parameters (HPF)</li> <li>GOCE precise science orbit &amp; EFRF to IRF rotation matrix (HPF)</li> <li>A priori gravity gradient error model (HPF)</li> <li>A priori gravity field model which is used in the outlier detection and the external calibration (external, e.g. GRACE)</li> <li>Indirectly: GOCE SST, terrestrial gravity data</li> </ol>

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Output Data	<ol style="list-style-type: none"> <li>1. Externally calibrated gravity gradients in GRF and GG calibration corrections</li> <li>2. Corrections to gravity gradients due to temporal gravity field variations</li> <li>3. Flags for outliers, fill-in gravity gradients for data gaps with flags</li> <li>4. Gravity gradient error estimates</li> </ol>
Units	S.I. ( $1/s^2$ for the gravity gradients and the corrections)
Data Format	See chapter 5.3
Latency	2 weeks
Volume	230 MB uncompressed, 22 MB compressed
Remarks	<p>In order to identify the orientation of the gradients (GRF) wrt to the inertial frame the measurement data set EGG_IAQ_1b of product EGG_NOM_1b has to be used.</p> <p>In order to spatially correlate the gradients and to identify the orientation of the inertial frame wrt the Earth fixed frame the product SST_PSO_2 has to be used.</p>

Product Name	EGG TRF 2
Product Description	Gravity Gradients in Local North-Oriented reference Frame (LNOF) (see chapter 4.4.1) corrected for temporal gravity field variations, outliers, data gaps and externally calibrated
Representation	Time series
Reference Frame	LNOF: Local north-oriented reference frame (HPF GOCE standards apply, see chapter 4.4.1)
Time System	GPS time (HPF GOCE standards apply)
Spatial Coverage	Global coverage without polar caps (depends on inclination of GOCE orbit)
Temporal Coverage	1 month
Spatial Resolution	$\approx 8$ km along-track
Temporal Resolution	1 s
Input Data	<ol style="list-style-type: none"> <li>1. GRF to IRF rotation matrix (GOCE)</li> <li>2. Externally calibrated gravity gradients in GRF (EGG_NOM_2_)</li> <li>3. GOCE precise science orbit &amp; EFRF to IRF rotation matrix (HPF)</li> <li>4. A priori gravity field model which is used in the outlier detection and the external calibration (external, e.g. GRACE)</li> </ol>
Output Data	<ol style="list-style-type: none"> <li>1. Externally calibrated gravity gradients in LNOF</li> <li>2. Flags for outliers, fill-in gravity gradients for data gaps with flags</li> <li>3. Gravity gradient error estimates</li> </ol>
Units	S.I. ( $1/s^2$ for the gravity gradients)
Data Format	See chapter 5.3
Latency	1 month
Volume	2.3 GB uncompressed, 140 MB compressed
Remarks	<p>Least-squares collocation is used to predict all 6 gravity gradients in the LNOF – <math>V_{XX}</math>, <math>V_{XY}</math>, <math>V_{XZ}</math>, <math>V_{YY}</math>, <math>V_{YZ}</math>, <math>V_{ZZ}</math> – using the 4 accurate gravity gradients in the GRF – <math>V_{XX}</math>, <math>V_{XZ}</math>, <math>V_{YY}</math>, <math>V_{ZZ}</math> – as input (EGG_NOM_2_). To this end the earth is divided in regular blocks and in each block the GRF to LNOF transformation is done using the data in that block with some overlap. In each block a pre-determined scaling of the signal covariance function is used. Because EGG_NOM_2 has large errors at long wavelengths, it is not possible to directly use these gravity gradients. The long wavelength errors would lead to large discontinuities between blocks after the transformation. Therefore, EGG_NOM_2 is high-pass filtered and the complementary part of model gravity gradients, e.g. from a GRACE model, is added. In addition, EGG_NOM_2 is also low-pass filtered, that is, the noise above the MBW is suppressed. Before the gravity gradients are used in GEOCOL, reference gravity gradients are subtracted (gravity gradient anomalies are computed). Finally, gravity gradients in the LNOF are computed using GEOCOL and the reference field in the LNOF is restored.</p>

Product Name	SST PSO 2
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Product Description	Precise science orbits from reduced dynamic approach (positions and velocities) and kinematic approach (positions), both in EFRF (see section 4.4.1). Additionally included is variance-covariance information for the kinematic orbits (over 9 epochs) and the rotation matrix for each epoch from the EFRF to the IRF in terms of quaternions according to section 4.4.2.1. Furthermore a quality report based on the daily orbit solutions is included in the product.
Representation	Orbits, variance-covariance matrices and rotation matrices are provided as time series, the quality report in PDF format.
Reference Frame	EFRF
Time System	GPS time
Reference System	Not applicable
Spatial Coverage	Global along satellite tracks
Temporal Coverage	1 day
Spatial Resolution	Not applicable
Temporal Resolution	1 sec
Input Data	GPS data; Ancillary data from several sources (e.g. Earth rotation parameters)
Output Data	Several sub-product files to be combined to one product
Units	Positions [m], velocities [m/s], rotation angles [dimensionless]
Data Format	See chapter 5.3
Latency	4 weeks
Volume	480 MB uncompressed, 21 MB compressed
Remarks	-

Product Name	EGM_GOC_2
Product Description	<p>GOCE gravity field model:  The coefficients of the spherical harmonic series of the gravitational potential are provided as defined in equation (4.10).  As derived quantities grids of geoid heights, gravity anomalies and deflections of the vertical are additionally included in the product. These quantities are defined as follows:  Geoid heights are defined according to equation (4.27).  Gravity anomalies are defined according to equation (4.30)  Deflections of the vertical are defined according to equations (4.32) and (4.33)  Errors are provided as variances and covariances of the coefficients of the spherical harmonic series of the gravitational potential (see also product EGM_GVC_2). The full variance-covariance matrix (product EGM_GVC_2) of the coefficients is propagated to geoid height errors on a grid applying equation (4.12).  Further on a quality report based on an extensive product validation is included in the product.</p>
Representation	The gravity field is provided as spherical harmonic series up to a specific degree and order. Derived quantities are provided on equi-angular grids. The quality report is provided in PDF format.
Reference Frame	EFRF
Time System	Not applicable
Reference System	WGS84 reference ellipsoid for geoid heights, gravity anomalies and deflections of the vertical.
Spatial Coverage	Spherical harmonic series: global per definition Grids: limited by GOCE inclination ( $\pm 82^\circ$ latitude)
Temporal Coverage	At least 1 measurement operational phase. It is planned to release one GOCE gravity field model for each measurement operational phase and the final model based on all GOCE data.
Spatial Resolution	Not applicable for spherical harmonic series. Derived quantities will be provided as $30' \times 30'$ equi-angular grids.
Temporal Resolution	Not applicable

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Input Data	GOCE gradiometer and GPS data; Ancillary data from different sources.
Output Data	Several sub-product files to be combined to one product
Units	Spherical harmonic coefficients are dimensionless, Geoid heights and errors in [m], Gravity anomalies in [m/s], Deflections of the vertical in [arc sec].
Data Format	See chapter 5.3
Latency	9 months after completion of each measurement operational phase
Volume	144 MB uncompressed, 33 MB compressed
Remarks	-

Product Name	EGM GVC 2
Product Description	Variance-covariance matrix for the coefficients of the spherical harmonic series of the GOCE gravity field model EGM_GOC_2_. The product contains the full variance and covariance information for each model.
Representation	The matrix is provided for the complete spherical harmonic series.
Reference Frame	EFRF
Time System	Not applicable
Reference System	Not applicable
Spatial Coverage	Spherical harmonic series: global per definition
Temporal Coverage	At least 1 measurement operational phase. The variance-covariance matrix is released each time a new GOCE gravity field product is finalized.
Spatial Resolution	Not applicable for spherical harmonic series.
Temporal Resolution	Not applicable
Input Data	GOCE gradiometer and GPS data; Ancillary data from different sources.
Output Data	Full variance-covariance matrix
Units	Variances and covariances of spherical harmonic coefficients are dimensionless.
Data Format	See chapter 5.4
Latency	9 months after completion of each measurement operational phase
Volume	Several GB
Remarks	The variance-covariance matrix will be distributed on DVD

## 5.3 XML PRODUCT FORMATS

This chapter contains the description of the XML format of all level 2 products except for the variance-covariance matrix product EGM\_GVC\_2, which are generated by the HPF for the GOCE mission. The description of the EGM\_GVC\_2 format is provided in chapter 5.4. The purpose of the chapter is to define the product structure and content of each level 2 product generated in the HPF identifying for each data section and field the meaning and the format to be used for its representation.

### 5.3.1 File Structure

The file structure of any Level 2 file produced by the HPF must follow the requirements of the [AD-9].

Each level 2 product is composed by two files:

- XML Header file, with extension “.HDR”
- XML Product file, with extension “.DBL”.

Both files are packed using tar/gzip for distribution, with extension “.TGZ”.

The XML Header file is an auxiliary ASCII file that users can easily access for identifying the product without needs to look inside the XML Product file.

The XML Product file is the real product containing meaningful instrument's data and ASCII header used by ad hoc development standard tools for inspecting the product's content.

### 5.3.2 XML Header File

The XML Header file contains information identifying the product and is easy to read as based on a standard syntax accessed by common tools available for visualizing its content.

The XML Header file is composed by:

- A Fixed Header
- A Variable Header

The Fixed Header (hereafter called Standard GOCE Header) is the common header for all files produced by the HPF. The Variable Header (hereafter called Product Header) is the header with the format and content depending on the file type and kind of product.

#### *Fixed Header*

The standard GOCE header is completely ASCII and based on XML and conventions proposed in [AD-9].

The fixed header fields are specified in the following table:

Tag Name	Type	Comment
File_Name	string	file name without extension
File_Description	string	restricted number of possible values
Notes	string	reserved for future use
Mission	string	shall always be "GOCE"
File_Class	string	
File_Type	string	
Validity_Period	structure	
+ Validity_Start	string	UTC=yyyy-mm-ddThh:mm:ss
+ Validity_Stop	string	UTC=yyyy-mm-ddThh:mm:ss
File_Version	integer	
Source	structure	
+ System	string	"GOCE High Level Processing Facility (HPF)"
+ Creator	string	"HPF's Central Processing Facility (CPF) using cpf_eef_create.pl"
+ Creator_Version	string	version of the creator tool
+ Creation_Date	string	UTC=yyyy-mm-ddThh:mm:ss

#### *Variable Header*

The Product Header for level 2 products is composed by:

- a XML Main Product Header (XML MPH)

- a XML Specific Product Header (XML SPH) which includes Data Set Descriptors for reference to external input files and Measurement Data of the Product.

### *XML Main Product Header (XML MPH)*

Tag Name	Type	Comment
Product	string	file name without extension
Ref_Doc	string	shall always be "GO-ID-HPF-GS-0041"
Acquisition_Station	empty	
Processor	structure	
+ Proc_Stage	character	ENUM('O','T','R','C')
+ Proc_Center	string	"HPF" for L2, else Workpackage/Institute
+ Proc_Time	string	UTC=yyyy-mm-ddThh:mm:ss
+ Software_Ver	string	Processorname/VV.rr
Time_Information	structure	
+ Sensing	structure	
++ Start	string	UTC=yyyy-mm-ddThh:mm:ss
++ Stop	string	UTC=yyyy-mm-ddThh:mm:ss
+ Abs_Orbit	structure	
++ Start	integer	
++ Stop	integer	
Phase	character	not used, set to 'X'
Cycle	integer	not used, set to zero
Rel_Orbit	integer	not used, set to zero
Abs_Orbit	integer	not used, set to zero
State_Vector_Time	empty	
X_Position	float	not used, set to '0.000'
Y_Position	float	not used, set to '0.000'
Z_Position	float	not used, set to '0.000'
X_Velocity	float	not used, set to '0.000000'
Y_Velocity	float	not used, set to '0.000000'
Z_Velocity	float	not used, set to '0.000000'
Vector_Source	empty	
Product_Err	integer	0: no errors; 1 errors have been reported
DBL_Size	integer	format='(013d)'
HDR_Size	integer	format='(011d)'
Num_DSD	integer	
Num_Data_Sets	integer	number of DSDs with Dta_Set_Type='O'
CRC	integer	not used, set to '-1'

### *XML Specific Header (XML SPH)*

Tag Name	Type	Comment
SPH_descriptor	string	equal to File_Type (see fixed header)
Original_Source	structure	
+ Product	string	Prod. name of orig. src. in HPF format
Time_Information	structure	
+ GPS_Time	structure	
++ Start	string	format='(%20.9f)'
++ Stop	string	format='(%20.9f)'
+ Abs_Orbit	structure	
++ Start	integer	



++ Stop	integer	
productID	structure	product identifier
<i>Product Specific tags are included here</i>		
DSDs	structure	
+ List of DSDs	structure	attribute: 'count'
++ Data Set Descriptor	structure	repeated 'count' times
+++ Data Set Name	string	
+++ Data Set Type	character	ENUM('I','O','S')
+++ File Name	string	name of Reference File
+++ Num Epochs	integer	
+++ MD5	string	

### 5.3.2.1 SPH product specific tags: EGG\_NOM\_2

Tag Name	Type	Comment
Original_Source	structure	
+Format	structure	
++Name	string	'GG_time'
++Version	string	
Product_Type	string	"quick_look" or "final"
Input	structure	
+L1	string	"fast", "consolidated", or "recomputed"
+L2	string	"quick_look" or "precise"
Reference_System	string	shall always be "GRF"
Tide_System	string	"zero_tide", "tide_free" or "unknown"
Gravity_Model	string	reference gravity model used
Errors	string	"formal" or "calibrated"

### 5.3.2.2 SPH product specific tags: EGG\_TRF\_2

Tag Name	Type	Comment
Original Source	structure	
+Format	structure	
++Name	string	'GG spatial'
++Version	string	
Product_Type	string	shall always be "final"
Input	structure	
+L1	string	"consolidated", or "recomputed"
+L2	string	shall always be "precise"
Reference_System	string	shall always be "TRF"
Tide_System	string	"zero_tide", "tide_free" or "unknown"
Gravity_Model	string	reference gravity model used
Errors	string	"formal" or "calibrated"

### 5.3.2.3 SPH product specific tags: SST\_PSO\_2

Tag Name	Type	Comment
SST_PRP_2	structure	<i>sub-product</i>
+Original_Source	structure	



++Format	structure	
+++Name	string	'PDF'
+++Version	string	
SST_PKI_2	structure	<i>sub-product</i>
+Original_Source	structure	
++Format	structure	
+++Name	string	'Sp3c'
+++Version	string	
+++Type	character	
+Pos_or_Vel	character	"P" or "V"
+Time_Information	structure	
++System	structure	
++GPS_Time	structure	
+++Start	structure	
++++GPS	structure	
+++++Week	integer	
+++++Seconds_of_week	float	
+++++Mod_Jul_day	structure	
+++++Day	integer	
+++++Fractional_Day	float	
++++Gregorian	structure	
+++++Year	integer	
+++++Month	integer	
+++++Day_of_Month	integer	
+++++Hour	integer	
+++++Minute	integer	
+++++Second	float	
+Epoch_Information	structure	
++Num_Epochs	integer	
++Interval	float	
+Data_Used	string	
+Coordinate_Sys	string	
+Orbit_Type	string	
+Agency	string	
+List_of_Satellite_Descriptors	structure	attribute: 'count'
++Satellite_Descriptor	structure	repeated 'count' times
+++Satellite_ID	string	
+++Accuracy	string	
+Base_for_Pos_or_Vel	float	
+Base_for_Clk_or_Rate	float	
+Comments	string	
SST_PCV_2	structure	<i>sub-product</i>
+Original_Source	structure	
++System	string	
++Creator	string	
++Creator_Version	string	
++Creation_Date	string	yyyy-mm-dd hh:mm:ss
++Format	structure	
+++Name	string	'Covariance'
+++Version	string	
+Var_Cov_Matrix	structure	
++File_Name	string	
+Corresponding_Kinematic_Orbit	structure	



++File_Name	string	
+Time_Information	structure	
++System	string	
++Time_Step_Size	integer	attribute: 'unit'
++GPS_Time	structure	
+++Start	structure	
++++Gregorian	structure	
+++++Year	integer	
+++++Month	integer	
+++++Day_of_Month	integer	
+++++Hour	integer	
+++++Minute	integer	
+++++Second	float	
+++Stop	structure	
+RMS_Of_Unit_Weight	float	
+Parameters	string	
SST_PRD_2	structure	<i>sub-product</i>
+Original_Source	structure	
++Format	structure	
+++Name	string	'Sp3c'
+++Version	string	
+++Type	character	
+Pos_or_Vel	character	
+Time_Information	structure	
++System	structure	
++GPS_Time	structure	
+++Start	structure	
++++GPS	structure	
+++++Week	integer	
+++++Seconds_of_week	float	
+++++Mod_Jul_day	structure	
+++++Day	integer	
+++++Fractional_Day	float	
+++++Gregorian	structure	
+++++Year	integer	
+++++Month	integer	
+++++Day_of_Month	integer	
+++++Hour	integer	
+++++Minute	integer	
+++++Second	float	
+Epoch_Information	structure	
++Num_Epochs	integer	
++Interval	float	
+Data_Used	string	
+Coordinate_Sys	string	
+Orbit_Type	string	
+Agency	string	
+Satellites	structure	attribute: 'count'
++Satellite_Descriptor	structure	attribute: 'id'; repeated 'count' times
+++Accuracy	string	
++Base_for_Pos_or_Vel	float	
++Base_for_Clk_or_Rate	float	
+Comments	string	



SST_PRM_2	structure	<i>sub-product</i>
+Original_Source	structure	
++System	string	
++Creator	string	
++Creator_Version	string	
++Creation_Date	string	yyyy-mm-dd hh:mm:ss
++Format	structure	
+++Name	string	'Rotation'
+++Version	string	
+Transformation	structure	
++File_Name	string	
+Time_Information	structure	
++System	string	
++GPS_Time	structure	
+++Start	structure	
++++Gregorian	structure	
+++++Year	integer	
+++++Month	integer	
+++++Day_of_Month	integer	
+++++Hour	integer	
+++++Minute	integer	
+++++Second	float	
+++Stop	structure	
+Epoch_Information	structure	
++Reference	string	
+Transformation	structure	
++Direction	string	
+Pole_File	string	
+Nutation	structure	
++Model	string	
++Offset	string	
+Subdaily_Model	string	

### 5.3.2.4 SPH product specific tags: EGM\_GOC\_2

Tag Name	Type	Comment
EGM_GAN_2	structure	<i>sub-product</i>
+Original_Source	structure	
++Format	structure	
+++Name	string	'Grid'
+++Version	string	
+++C_sprintf Notation	string	
+Data_Information	structure	
++Dataset_Name	string	
++Description	string	
++Unit	string	
+Coordinate_Information	structure	attribute: count'
++Latitude	structure	repeated 'count' times
+++Northern Border	float	attribute: 'unit'
+++Southern Border	float	attribute: 'unit'
+++Cell_Information	structure	
++++Number_of_Cells	integer	



++++Size	float	
++Longitude	structure	repeated 'count' times
+++Western Border	float	attribute: 'unit'
+++Eastern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
+Flags	structure	
++Mean or Point Values	string	"mean" or "point"
++Geocentric or Geodetic Latitudes	string	"geocentric" or "geodetic"
+Reference Ellipsoid	string	
+Gap Value	float	
EGM_GRP_2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'PDF'
+++Version	string	
EGM_GEO_2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'Grid'
+++Version	string	
+++C sprintf Notation	string	
+Data Information	structure	
++Dataset Name	string	
++Description	string	
++Unit	string	
+Coordinate Information	structure	attribute: count'
++Latitude	structure	repeated 'count' times
+++Northern Border	float	attribute: 'unit'
+++Southern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
++Longitude	structure	repeated 'count' times
+++Western Border	float	attribute: 'unit'
+++Eastern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
+Flags	structure	
++Mean or Point Values	string	"mean" or "point"
++Geocentric or Geodetic Latitudes	string	"geocentric" or "geodetic"
+Reference Ellipsoid	string	
+Gap Value	float	
EGM_GVN_2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'Grid'
+++Version	string	
+++C sprintf Notation	string	
+Data Information	structure	
++Dataset Name	string	
++Description	string	



++Unit	string	
+Coordinate Information	structure	attribute: 'count'
++Latitude	structure	repeated 'count' times
+++Northern Border	float	attribute: 'unit'
+++Southern Border	float	attribute: 'unit'
+++Cell information	structure	
++++Number of Cells	integer	
++++Size	float	
++Longitude	structure	repeated 'count' times
+++Western Border	float	attribute: 'unit'
+++Eastern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
+Flags	structure	
++Mean or Point Values	string	"mean" or "point"
++Geocentric or Geodetic Latitudes	string	"geocentric" or "geodetic"
+Reference Ellipsoid	string	
+Gap Value	float	
EGM_GVE_2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'Grid'
+++Version	string	
+++C_sprintf Notation	string	
+Data Information	structure	
++Dataset Name	string	
++Description	string	
++Unit	string	
+Coordinate Information	structure	attribute: 'count'
++Latitude	structure	repeated 'count' times
+++Northern Border	float	attribute: 'unit'
+++Southern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
++Longitude	structure	repeated 'count' times
+++Western Border	float	attribute: 'unit'
+++Eastern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
+Flags	structure	
++Mean or Point Values	string	"mean" or "point"
++Geocentric or Geodetic Latitudes	string	"geocentric" or "geodetic"
+Reference Ellipsoid	string	
+Gap Value	float	
EGM_GCF_2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'ICGEM'
+++Version	string	
+Product Type	string	



+Model Name	string	
+Earth Gravity Constant	float	
+Spherical Harmonic Development	structure	
++Radius	float	
++Max Degree	integer	
+Errors	string	
+Normalization	string	
+Tide System	string	
+Comments	string	
EGM GER 2	structure	<i>sub-product</i>
+Original Source	structure	
++Format	structure	
+++Name	string	'+'
+++Version	string	
+++C sprintf Notation	string	
+Data Information	structure	
++Dataset Name	string	
++Description	string	
++Unit	string	
+Coordinate Information	structure	attribute: 'count'
++Latitude	structure	repeated 'count' times
+++Northern Border	float	attribute: 'unit'
+++Southern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
++Longitude	structure	
+++Western Border	float	attribute: 'unit'
+++Eastern Border	float	attribute: 'unit'
+++Cell Information	structure	
++++Number of Cells	integer	
++++Size	float	
+Flags	structure	
++Mean or Point Values	string	"mean" or "point"
++Geocentric or Geodetic Latitudes	string	"geocentric" or "geodetic"
+Reference Ellipsoid	string	
+Gap Value	float	

### 5.3.3 XML Data Block File

This section contains the XML ASCII file syntax definition of the Data Block files of the L2 products send to the PDS/LTA by the HPF.

#### 5.3.3.1 EGG\_NOM\_2

Tag Name	Type	Comment
List_of_GG_time_Records	structure	attribute: 'count'
+ GG_time	structure	repeated 'count' times
++ Time Information	structure	
+++ GPS_Time	string	attribute: 'unit'
++ Gravity Gradients	structure	attribute: 'unit'



+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	
++ Sigmas	structure	attribute: 'unit'
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	
++ Flags	structure	
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	
++ Corrections	structure	attribute: 'unit'
++ Temporal	structure	
+++ Tidal	structure	
++++ Direct Tides	structure	
+++++ XX	string	
+++++ YY	string	
+++++ ZZ	string	
+++++ XY	string	
+++++ XZ	string	
+++++ YZ	string	
++++ Solid Earth	structure	
+++++ XX	string	
+++++ YY	string	
+++++ ZZ	string	
+++++ XY	string	
+++++ XZ	string	
+++++ YZ	string	
++++ Ocean Tides	structure	
+++++ XX	string	
+++++ YY	string	
+++++ ZZ	string	
+++++ XY	string	
+++++ XZ	string	
+++++ YZ	string	
++++ Pole Tides	structure	
+++++ XX	string	
+++++ YY	string	
+++++ ZZ	string	
+++++ XY	string	
+++++ XZ	string	
+++++ YZ	string	
+++ Non-Tidal	structure	
+++++ XX	string	
+++++ YY	string	



+++++ ZZ	string	
+++++ XY	string	
+++++ XZ	string	
+++++ YZ	string	
++ Calibration	structure	
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	

### 5.3.3.2 EGG\_TRF\_2

Tag Name	Type	Comment
List of GG_spatial_Records	structure	attribute: 'count'
+ GG_spatial	structure	repeated 'count' times
++ Time_Information	structure	
+++ GPS_Time	string	attribute: 'unit'
++Position	structure	
+++Height	float	attribute: 'unit'
+++Phi	float	attribute: 'unit'
+++Lambda	float	attribute: 'unit'
++ Gravity_Gradients	structure	attribute: 'unit'
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	
++ Sigmas	structure	attribute: 'unit'
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	
++ Flags	structure	
+++ XX	string	
+++ YY	string	
+++ ZZ	string	
+++ XY	string	
+++ XZ	string	
+++ YZ	string	

### 5.3.3.3 SST\_PSO\_2

Tag Name	Type	Comment
SST_PRP_2	structure	sub-product
+PDF	string	attribute: 'encoding'
+List_of_Covariance_Records	structure	attribute: 'count'



++Covariance	float	attribute: 'row' and 'column'
SST_PKI_2	structure	<i>sub-product</i>
+List_of_SP3c_Records	structure	attribute: 'count'
++SP3c	structure	repeated 'count' times
+++Time_Information	structure	
++++GPS_Time	structure	
+++++Start	structure	
++++++Gregorian	structure	
+++++++Year	integer	
+++++++Month	integer	
+++++++Day_of_Month	integer	
+++++++Hour	integer	
+++++++Minute	integer	
+++++++Second	float	
+++List_of_Satellite_IDs	structure	
++++<satID>	structure	ID of Satellite (see header)
+++++Position	structure	attribute: 'unit'
+++++X	float	
+++++Y	float	
+++++Z	float	
+++++Clock	float	attribute: 'unit'
+++++Standard_Deviation	structure	
+++++Position	float	attribute: 'unit'
+++++Clock	float	attribute: 'unit'
SST_PRD_2	structure	<i>sub-product</i>
+List_of_SP3c_Records	structure	attribute: 'count'
++SP3c	structure	repeated 'count' times
+++Time_Information	structure	
++++GPS_Time	structure	
+++++Start	structure	
++++++Gregorian	structure	
+++++++Year	integer	
+++++++Month	integer	
+++++++Day_of_Month	integer	
+++++++Hour	integer	
+++++++Minute	integer	
+++++++Second	float	
+++List_of_Satellite_IDs	structure	
++++<satID>	structure	ID of Satellite (see header)
+++++Position	structure	attribute: 'unit'
+++++X	float	
+++++Y	float	
+++++Z	float	
+++++Clock	float	attribute: 'unit'
+++++Standard_Deviation	structure	
+++++Position	float	attribute: 'unit'
+++++Clock	float	attribute: 'unit'
SST_PRM_2	structure	<i>sub-product</i>
+List_of_Rotation_Records	structure	attribute: 'count'
++Rotation	structure	repeated 'count' times
+++Time_Information	structure	
++++Time_Since_Reference_Epoch	float	attribute: 'unit'
+++Quaternions	structure	
++++Q1	float	

++++Q2	float	
++++Q3	float	
++++Q4	float	

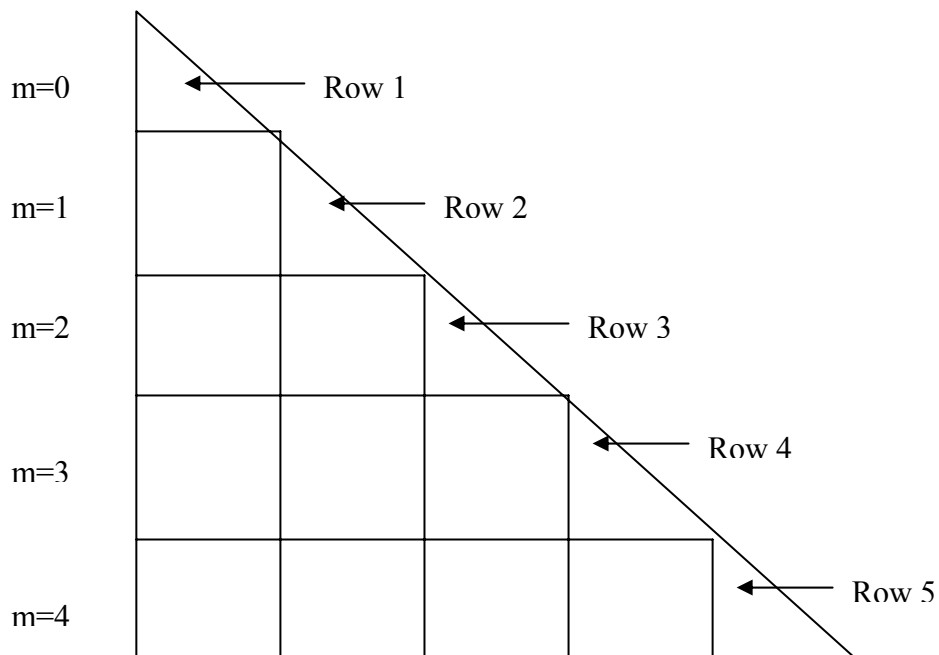
### 5.3.3.4 EGM\_GOC\_2\_

Tag Name	Type	Comment
EGM_GAN_2	structure	<i>sub-product</i>
+List_of_Latitudes	structure	attribute: 'count'
++Latitude	structure	attribute: 'degree'; repeated 'count' times
+++List_of_Longitudes	structure	attribute: 'count'
++++Longitude	structure	repeated 'count' times
+++++Value	float	attribute: 'unit'
EGM_GCF_2	structure	<i>sub-product</i>
+List_of_ICGEM_Records	structure	attribute: 'count'
++<keyword>	structure	Earth Gravity Field: "gfc", "gfct", or "dot", Ocean/Atmosphere: "lovr", "ocs", "acs", "ccs", 'oap', 'aap', 'cap'; repeated 'count' times
+++Degree	integer	[all]
+++Order	integer	[all, except 'lovr', ]
+++Clm	float	[all, except 'dot', 'oap', 'aap', 'cap']
+++Slm	float	[all, except 'dot', 'oap', 'aap', 'cap']
+++Sigmas	structure	[all, except errors="no"]
++++C	float	
++++S	float	
EGM_GEO_2	structure	<i>sub-product</i>
+List_of_Latitudes	structure	attribute: 'count'
++Latitude	structure	attribute: 'degree'; repeated 'count' times
+++List_of_Longitudes	structure	attribute: 'count'
++++Longitude	structure	repeated 'count' times
+++++Value	float	attribute: 'unit'
EGM_GER_2	structure	<i>sub-product</i>
+List_of_Latitudes	structure	attribute: 'count'
++Latitude	structure	attribute: 'degree'; repeated 'count' times
+++List_of_Longitudes	structure	attribute: 'count'
++++Longitude	structure	repeated 'count' times
+++++Value	float	attribute: 'unit'
EGM_GRP_2	structure	<i>sub-product</i>
+PDF	string	attribute: 'encoding'
EGM_GVE_2	structure	<i>sub-product</i>
+List_of_Latitudes	structure	attribute: 'count'
++Latitude	structure	attribute: 'degree'; repeated 'count' times
+++List_of_Longitudes	structure	attribute: 'count'
++++Longitude	structure	repeated 'count' times
+++++Value	float	attribute: 'unit'
EGM_GVN_2	structure	<i>sub-product</i>
+List_of_Latitudes	structure	attribute: 'count'
++Latitude	structure	attribute: 'degree'; repeated 'count' times
+++List_of_Longitudes	structure	attribute: 'count'
++++Longitude	structure	repeated 'count' times
+++++Value	float	attribute: 'unit'

## 5.4 EGM\_GVC\_2\_ FORMAT

Due to the size of the variance-covariance product it is not stored in XML format, but in a specific ASCII format specified below (TBC). This product is not distributed by on-line access, but only via DVD copies.

Due to a maximum file size of 2 GB for some operating systems the matrix is distributed among several files. The splitting of the lower triangle shall be done row-wise (in order to facilitate the handling of block-diagonal approximations). The matrix entries of each harmonic order  $m$  is stored in a separate file. The numbering of the files is done by a consecutive numbering scheme in the file name. The following figure illustrates the file splitting.



The set of files is complemented by a general-meta data ASCII file describing the whole file sequence. This general meta-data file contains all information what is required to identify and read the subsequent data files of the variance-covariance matrix. The following list shows the entries provided in the general meta-data file. Each keyword has to be read with a fixed length of 30 characters, while the maximum length for the related parameter is fixed to 70 characters.

### Meta Data File:

<b>Keyword</b> [30 characters fixed length, filled with blanks]	<b>Meaning of parameters</b> [<70 characters]
product_type	Variance-covariance matrix
modelname	Name of the model

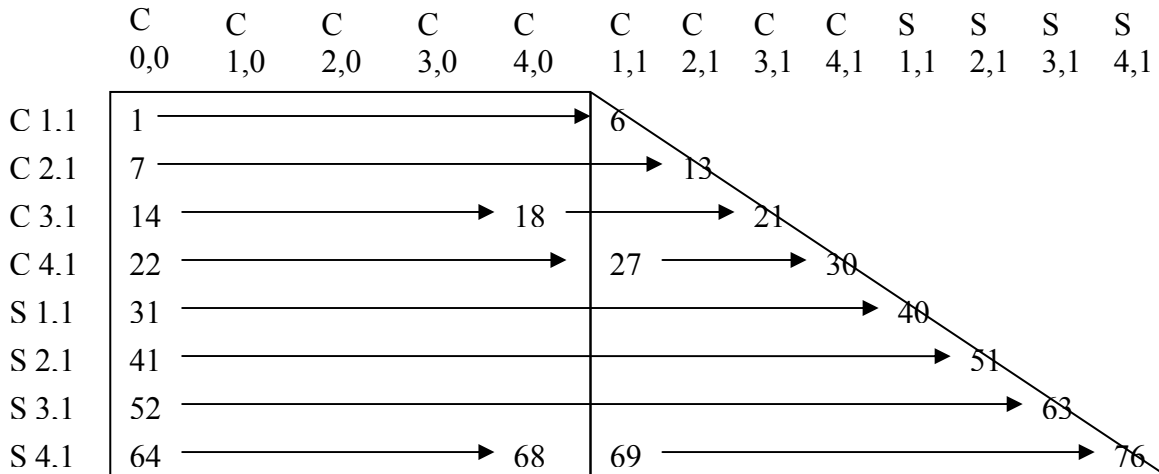
earth_gravity_constant	Earth gravity constant multiplied by mass, which has been used for the gravity field model (GM). This value might be required for error propagation.
radius	Radius of sphere which has been used for the gravity field model. This value might be required for error propagation.
max_degree	Maximum degree of the spherical harmonic series
errors	Must be set to: "formal", "calibrated" or "calibrated_and_formal" depending on the type of the errors
covariance_matrix_type	Covariance file type: "full" or "block" Full means a full wsystem, block means a block-diagonal system.
sequence_number_entries	Number of coefficients in the matrix. After this entry the sequence of the coefficients is provided. Each coefficient is described in one line
[C,S] nnn_mmm	Coefficient description
sequence_number_files	Number of files that belong to the variance-covariance matrix file. Each file name is then provided in a subsequent record. Files are stored per harmonic order.
	List of file names (each in a new record without keyword)

The data files themselves are stored in ASCII and include in the first lines the following meta data. Each keyword has to be written with a fixed length of 30 characters, while the maximum length for the related parameter is fixed to 70 characters.

Data File:

<b>Keyword</b> [30 characters fixed length, filled with blanks]	<b>Meaning of parameters</b> [<70 characters]
meta_data_file_name	Name of the meta data file
order	Harmonic order of the file
number_entries	Total number of data values in the file (for control information)
begin_data	Keyword indicating where the data section starts
end_data	Keyword indicating where the data section ends.

The data files are stored in row-wise order (one entry per line free ASCII formatted in order to avoid problems with the record length). The sequence for order 1 in the file according to the previous figure is shown in the following figure. The numbers in the drawing indicate the sequence how the elements are stored in the file.



Estimation of file sizes: The maximum number of elements in a file for a maximum degree of 250 is 12173185 (at order 106) and 20993274 for maximum degree of 300 (at order 127). Under the assumption that we need not more than 20 bytes for 1 elements this sums up to a maximum file size of about 250 MB (for a maximum degree 250) and to 420 MB (for a maximum degree 300). These files can be easily handled by all computer systems.

**Example**

Below an example for the general or master meta-file and the sub-files for a maximum degree of 4 is provided. The meta-file is similar to the HPF spherical harmonic series file format.

```

product_type          variance-covariance matrix
modelname            EXAMPLE-MODEL
earth_gravity_constant 0.3986004415E+15
radius              0.6378136460E+07
max_degree          4
errors              formal
covariance_matrix_type full
sequence_number_entries 25
                    C_000_000
                    C_001_000
                    C_002_000
                    C_003_000
                    C_004_000
                    C_001_001
                    C_002_001
                    C_003_001
                    C_004_001
                    S_001_001
                    S_002_001
                    S_003_001
                    S_004_001
                    C_002_002
                    C_003_002
                    C_004_002
                    S_002_002
                    S_003_002
                    S_004_002

```

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```

C_003_003
C_004_003
S_003_003
S_004_003
C_004_004
S_004_004
sequence_number_files      5
data_file_000
data_file_001
data_file_002
data_file_003
data_file_004

```

Below a sample file for a subsequent data file is provided (the sample file is related to the figure above):

```

meta_data_file_name      main_file
order                    1
number_entries           76
begin_data
-0.7657887654320E-09
...
...
...
...      (all together 76 numbers in ASCII format)
...
...
+1.0567758766890E-14
end_data

```

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