GeoGravGOCE

Geoid and Gravity Field Modelling by GOCE Satellite Gradients and Terrestrial Data

WP 2: Satellite and local Data collection
TSK2100: GOCE SGG data collection

DELIVERABLE
DL2110: Report on the data collected for GeoGravGOCE realization

H.F.R.I. Hellenic Foundation for Research & Innovation
GSRT GENERAL SECRETARIAT FOR RESEARCH AND TECHNOLOGY

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Abstract

The present deliverable describes the collection of all terrestrial and satellite data needed for the Greece-wide geoid evaluation. These data sets refer to free-air gravity anomalies over Greece (local gravity data), GOCE and GOCE/GRACE derived GGMs (Global Geopotential Models), Digital Terrain Models and Digital Bathymetry Models for the evaluation of topographic effects (topography/bathymetry models) and GOCE SGG observations (GOCE raw data). All these data sets are collected, validated and archived into a geodatabase.

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Acronyms

DL	Deliverable
EFRF	Earth Fixed Reference Frame
ES	Earth Surface
FIR	Finite Impulse Response
GGMs	Global Geopotential Models
GRF	Gradiometer Reference Frame
GSRT	General Secretariat for Research and Technology
HFRI	Hellenic Foundation for Research and Innovation
IIR	Infinite Impulse Response
IRF	Inertial Reference Frame
LNOF	Local North Oriented Frame
LS	Least Squares
LSC	Least Squares Collocation
MC	Monte Carlo
MIMOST	Multiple Input Multiple Output System Theory
MO	Mean Orbit
MRA	Multi-Resolution Approximation
PSD	Power Spectral Density
RTM	Residual Terrain Model
SA	Simulated Annealing
SGG	Satellite Gravity Gradiometry
SISOS	Single Input Single Output System
TSK	Task
WL	Wavelet
WP	Work Package
WPS	Work Package Structure
w.r.t.	with respect to

1.

Report on the data collected for GeoGravGOCE realization

1.1 Outline of the deliverable

The present deliverable describes the collection of all terrestrial and satellite data needed for the Greece-wide geoid evaluation. These data sets refer to free-air gravity anomalies over Greece (local gravity data), GOCE and GOCE/GRACE derived GGMs (Global Geopotential Models), Digital Terrain Models and Digital Bathymetry Models for the evaluation of topographic effects (topography/bathymetry models) and GOCE SGG observations (GOCE raw data). All these data sets are collected, validated and archived into a geodatabase.

1.2 Local Gravity data

The gravity data that will be used in the frame of the GeoGravGOCE project originate from the database compiled by Grigoriadis (2009). The total amount of free-air gravity anomalies is 294777 irregularly distributed point values. In Figure 1 the free-air gravity anomaly field is shown, while in Table 1 the corresponding statistical results are summarized.

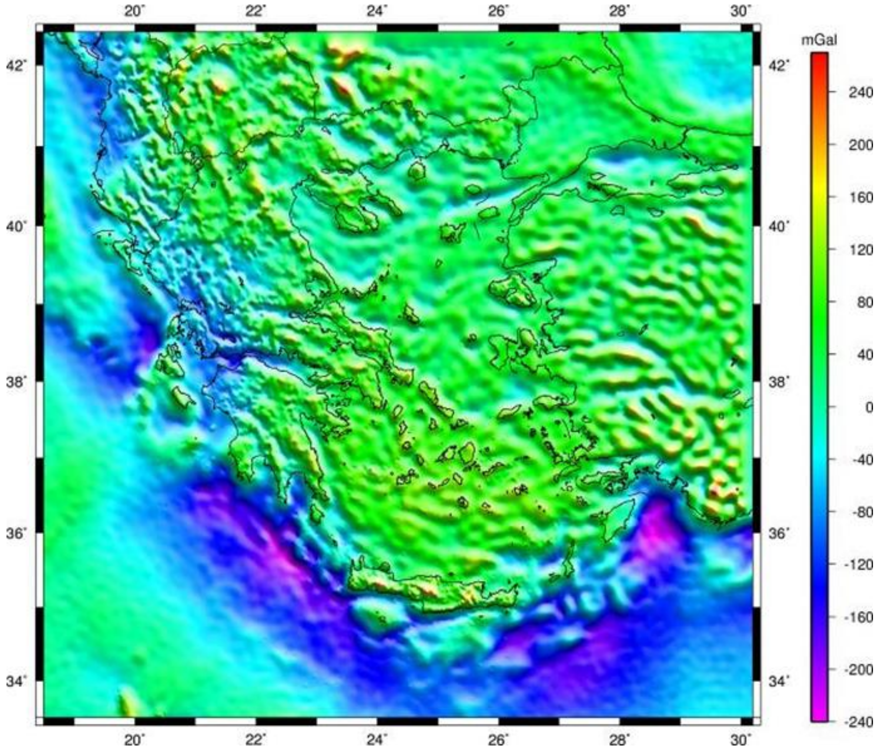

Figure 1: The available free-air gravity anomaly field [mGal].

Table 1: Statistics of the free-air gravity anomaly field [mGal].

	max	min	mean	std
Δg_{FA}	269.93	-236.10	-22.73	±74.11

1.3 GGM availability

Since GOCE launch in 2009, and depending on the releases of GOCE gradients, various solutions became available, which can be distinguished in a) Release 1 based on two months of GOCE data (R1), b) Release 2 based on eight months of data (R2) c) Release 3 based on twelve months of data (R3) models, d) Release 4 based on 27 months of data (R4) models, e) Release 5 based on 42 months of data (R5) models and f) Release 6 based on 48 months of data (R6) models. Note that the data coverage period refers to the effective data covered by the available GOCE data. Depending on the processing strategy four classes of models can be distinguished as a) the TIM models using the time-wise approach (Pail et al. 2011), b) the DIR models using the direct approach (Bruinsma et al. 2010), c) the SPW models using the space-wise approach (Migliaccio et al. 2010) and d) combined models (GOCO0xs) where both and GOCE and GRACE data are used (Goiginger et al. 2011; Mayer-Gürr et al. 2012; Pail et al. 2010). Table 1 summarizes the models to be used and their maximum d/o of expansion. Apart from the aforementioned ones, EGM2008 (Pavlis et al. 2012) and XGM2019e_2159 (Zingerle et al. 2019), will be used as well. The GGMs that will be used within GeoGravGOCE and are already archived in the dedicated project server.

Within the GeoGravGOCE project all GGMs are collected from the International Centre for Global Earth Models (ICGEM), which belongs to the International Association of Geodesy (IAG) International Gravity Field Service (IGFS). ICGEM provides the latest GOCE GGMs, along with the generating agencies, in a unified format and a single collection point, therefore it was selected to be the one, where all GGMs will be collected from. As far as the GGM models are concerned, these are available in the standard ICGEM format, i.e., with a header describing the model, tide conventions, the period covered and then the harmonic coefficients with their errors per order. This format is summarized in Table 3, where the main information provided is summarized as a) the maximum d/o of expansion, b) the data used, c) the tide-convention, d) error modelling is reported as formal or calibrated and e) the normal field used is outlined as well (GOCO06s is reported in that Table). Within GeoGravGOCE, all available past and future models generated during the project duration will be evaluated.

Table 2 : GOCE/GRACE GGMs to be used within the GeoGravGOCE project.

Models	*n max*	*Data*	*Reference*
EGM2008	2190	S(GRACE), G, A	Pavlis et al., 2008
XGM2019e_2159	2190	A, G, S(GOCO06s), T	Zingerle, P. et al, 2019
GOCO06S	300	S	Kvas et al., 2019
DIR_R6	300	S	Brockmann, J. M. et al, 2014
TIM_R6	300	S(GOCE)	Pail et al., 2010
SPW_R5	330	S(GOCE)	Gatti, A. et al, 2016

(Data: S = Satellite Tracking Data, G = Gravity Data, A = Altimetry Data
GRACE (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment)

CHAMP (**CHA**llenging **M**ini-satellite **P**ayload)
GOCE (**G**ravity field and steady state **O**cean **C**irculation **E**xplorer)
LAGEOS (**La**ser G**EO**dynamics **S**atellite)
SLR (**S**atellite **L**aser **R**anking)

GOCO (Combination of GOCE data with complementary gravity field information) is a project initiative with the objective to compute high-accuracy and high-resolution static global gravity field models based on data of the satellite gravity missions CHAMP, GRACE, and GOCE, satellite altimetry, and SLR data. The satellite-only model GOCO06S based on GOCE and GRACE was computed with the complete mission of GOCE and 15.5 years of GRACE (Kvas et al. 2019).

Table 3: GGM format from ICGEM (GOCO06S is reported here).

```
The 6th release of the GOCE gravity field model by means of the time-wise approach
================================================================================
Brockmann, Jan Martin (1); Schubert, Till (1); Mayer-Gürr, Torsten (2); Schuh,
Wolf-Dieter (1)
(1) Institute of Geodesy and Geoinformation, Theoretical Geodesy Group, University of Bonn, Germany
(2) Institute of Geodesy, Theoretical Geodesy and Satellite Geodesy Group, TU Graz, Austria

These data are freely available under the Creative Commons Attribution 4.0 International
Licence (CC BY 4.0). When using the data please cite:

Brockmann, Jan Martin; Schubert, Till; Mayer-Gürr, Torsten; Schuh,
Wolf-Dieter (2019): The Earth's gravity field as seen by the GOCE satellite
- an improved sixth release derived with the time-wise approach. GFZ Data Services.
http://doi.org/10.5880/ICGEM.2019.003

GOCE Input Data:
- Gradients: EGG_NOM_2 (re-calibration, released 2018, version 0202)
- Orbits: SST_PKI (kinematic orbits); SST_PCV (variance information of kinematic orbit positions),
        SST_RNX (original RINEX orbit data)
- Attitude: EGG_IAQ_2C
- Non-conservative accelerations: EGG_CCD_2C
- Data period: 09/10/2009 - 20/10/2013

No static a-priori gravity field information applied (neither as reference model, nor for
constraining the solution)

Processing procedures:
- Gravity from orbits (SST):
  - short-arc integral method applied to kinematic orbits, up to degree/order 150
  - orbit variance information included as part of the stochastic model, it is refined by empirical
    covariance functions
- Gravity from gradients (SGG):
  - parameterization up to degree/order 300
  - observations used: Vxx, Vyy, Vzz and Vxz in the Gradiometer Reference Frame (GRF)
  - realistic stochastic modelling by applying digital decorrelation filters to the observation
    equations; estimated separately for individual data segments applying a robust procedure
- Combined solution:
  - addition of normal equations (SST D/O 150, SGG D/O 300)
```

- Constraints:
  - * Kaula-regularization applied to coefficients of degrees/orders 201 - 300 (constrained towards zero)
  - * observation equations for zero gravity anomaly observations in polar regions (>83°) to constrain polar gaps towards zero (degree 11 to 300)
- Optimum weighting (SST, SGG, constraints) based on variance component estimation

Specific features of resulting gravity field:
- Gravity field solution is independent of any other gravity field information
- Constraint towards zero starting from degree/order 201 to improve signal-to-noise ratio
- Related variance-covariance information represents very well the true errors of the coefficients
- Solution can be used for independent comparison and combination on normal equation level with other satellite-only models (e.g. GRACE), terrestrial gravity data, and altimetry
- Since in the low degrees the solution is based solely on GOCE orbits, it is not competitive with a GRACE model in this spectral region
- The reference epoch is 2010-01-01 (MJD 55197).

Further processing details can be found in:

Brockmann, J. M. 2014. “On High Performance Computing in Geodesy -- Applications in Global Gravity Field Determination.” Phd thesis, Bonn, Germany: Institute of Geodesy and Geoinformation, University of Bonn. http://nbn-resolving.de/urn:nbn:de:hbz:5n-38608.

Brockmann, J. M., N. Zehentner, E. Höck, R. Pail, I. Loth, T. Mayer-Gürr, and W.-D. Schuh. 2014. “EGM_TIM_RL05: An Independent Geoid with Centimeter Accuracy Purely Based on the GOCE Mission.” Geophysical Research Letters 41 (22): 8089–99. 10.1002/2014GL061904.

Pail, R., S. Bruinsma, F. Migliaccio, C. Förste, H. Goiginger, W.-D. Schuh, E. Höck, et al. 2011. “First GOCE Gravity Field Models Derived by Three Different Approaches.” Journal of Geodesy 85 (11): 819. 10.1007/s00190-011-0467-x.

Mayer-Gürr, T., K. H. Ilk, A. Eicker, and M. Feuchtinger. 2005. “ITG-CHAMP01: A CHAMP Gravity Field Model from Short Kinematic Arcs over a One-Year Observation Period.” Journal of Geodesy 78 (7–8): 462–80. 10.1007/s00190-004-0413-2.

```
begin_of_head ======================================
product_type         gravity_field
modelname            GO_CONS_EGM_GOC_2__20091009T000000_20131021T000000_0201
earth_gravity_constant 3.986004415e+14
radius               6378136.46
max_degree           300
errors               formal
norm                 fully_normalized
tide_system          zero_tide

key    L     M  C                     S                    sigma C                sigma S
end_of_head
================================================================================
==============
gfc     0     0  1.000000000000000000000e+00  0.000000000000000000000e+00
0.000000000000000000000e+00  0.000000000000000000000e+00
```

```
gfc     1      0  0.00000000000000000000e+00  0.00000000000000000000e+00
0.00000000000000000000e+00  0.00000000000000000000e+00
gfc     1      1  0.00000000000000000000e+00  0.00000000000000000000e+00
0.00000000000000000000e+00  0.00000000000000000000e+00
gfc     2      0  -4.84169852633576757849e-04  0.00000000000000000000e+00  5.49100060369365413041e-
12  0.00000000000000000000e+00
gfc     2      1  -2.70219049431657054102e-10  1.44715732876258504770e-09  5.31290543857086488938e-
12  5.37000026430665584794e-12
……………………………………………………………………………………………………………………………………………………………
```

EGM2008 is a spherical harmonic model of the Earth's gravitational potential complete to degree and order 2159 with some additional coefficients up to degree 2190 and order 2159. EGM2008 is a model that combines the ITG-GRACE03S gravitational model with free-air gravity anomalies defined on a 5 arc-minute equiangular grid. This grid was formed by merging terrestrial, altimetry-derived, and airborne gravity data (Pavlis et al. 2012). Finally, XGM2019e is a combined global gravity field model represented through spheroidal harmonics up to d/o 5399, corresponding to a spatial resolution of 2' (~4 km). As data sources it includes the satellite model GOCO06s in the longer wavelength area combined with terrestrial measurements for the shorter wavelengths. The terrestrial data itself consists over land and ocean of gravity anomalies provided by courtesy of NGA (identical to XGM2016, having a resolution of 15') augmented with topographically derived gravity over land (EARTH2014). Over the oceans, gravity anomalies derived from satellite altimetry are used (DTU13, in consistency with the NGA dataset) (Zingerle et al. 2019).

1.4 Digital Terrain Models and Digital Bathymetry Models

Two DTBMs are used in GeoGravGoce , the detailed DTBM that was used has a resolution of 3 arcsec Grigoriadis (2009) and was computed by combining SRTM3 v2 (Farr et al. 2007) and SRTM30-plus v4 (Smith and Sandwell 1997). It covers the area bounded by $30.5^o \leq \phi \leq 44.5^o$ and $16.5^o \leq \lambda \leq 33.0^o$, which is more than sufficient with respect to the available gravity data. On the other hand, the reference DTBM has a resolution of 12 arcmin and has been derived by averaging the 3 arcsec DTBM. Due to the large amount of values in the detailed DTBM the model was confined to the area bounded by $33.0^o \leq \phi \leq 43.0^o$ and $18.0^o \leq \lambda \leq 31.0^o$. Still though, the number of available values was large (~190 million), so it was decided to split the model in two parts (see Figure 2). The limits of the first tile are $33.0^o \leq \phi \leq 39.0^o$ and $18.0^o \leq \lambda \leq 31.0^o$ (Tile 1-1), while the second lies between $37.0^o \leq \phi \leq 43.0^o$ and $18.0^o \leq \lambda \leq 31.0^o$ (Tile 2-1). Note that the two tiles have an overlap of 1 degree, while there is a 1 degree extent in all directions (WESN) with respect to the gravity data coverage. This extent ensures that any edge effects will be eliminated.

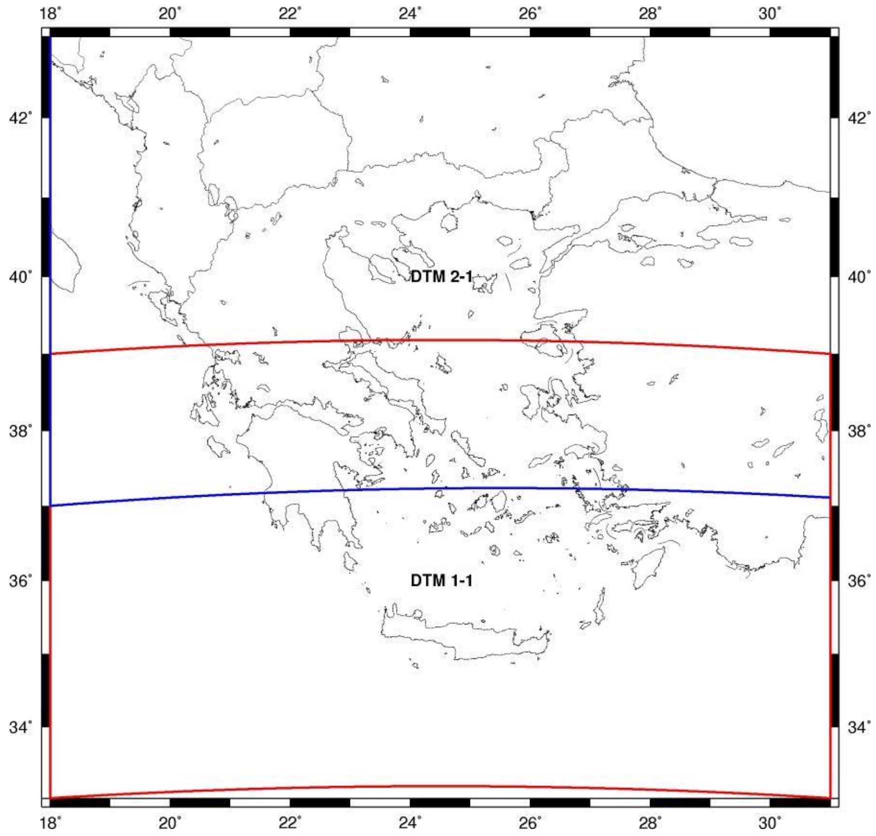

Figure 2: The detailed DTBM distribution for the computation of RTM effects

1.5 GOCE SGG observations

With GOCE having completed its mission at the end of October 2013, there still exists a wide range of applications that GOCE-derived products can have a significant contribution too. The abundance of gravity data for the oceans, apart from a high-accuracy static gravity field, can offer unique insights to oceanographic, engineering and geophysical applications. Given the availability of recent GGMs from of GOCE, the latest GGMs from GOCE and GRACE data, DIR-R6, TIM-R6, GOCO06s, EGM2008 will be used to determine the contribution of GOCE SGG data to improving the geoid over the Hellenic area. The time interval covered refers to the entire period of GOCE mission. The data type refers to the EGG_NOM_2 product delivered by the GOCE HLPF and ESA/ESRIN.

- ***GOCE data availability and conventions***

Within the GeoGravGOCE project, the data needed will be the Level 2 (GO-MA-HPF-GS-0110, 2008) processed second order derivatives (gravity gradients) of the gravity potential in a local North-East-Up Earth Fixed Reference Frame. GOCE Level 1b and Level 2 data access has been granted to the project during a successful GOCE AO proposal with reference nr. 4299 "*Comparison of GOCE data with gradiometric observations, gravity anomalies and satellite altimetry data at various altitudes for precise geoid and gravity field approximation in Europe*". Therefore, all GOCE gradiometric observations have been downloaded from the GOCE Virtual on-line Archive (http://eo-virtual-archive1.esa.int/Index.html), where the necessary quality reports are available as well.

GOCE Level1b and Level 2 data are provided by ESA in EEF format, which is based on XML. Since the entire processing within GEOGRAVGOCE will be performed with existing and newly developed software either in Fortran, Matlab, C and .NET, it is necessary to translate the native EEF format to a classic ASCII or netcdf format so that they can be further processed. To achieve that, the GOCE XML parser will be used, which is a program that takes input in the form of sequential instructions, tags (or any other defined sequence of tokens), and breaks them up into easily manageable parts. The GOCE XML parser is designed to read and, in a sense, interpret XML documents (GO-TN-HPF-GS-0192, 2012), so that they can be transformed to an easily interpreted format by other software. Finally, GOCE observations are provided in the GRF, in order to be used for gravity field modelling and combined with other data, e.g., altimetric SSHs, GRACE EWT and mass changes, local gravity and GPS/Leveling observations, they need to be transformed in an EFRF or better in a LNOF one. The details on GOCE data conventions, data format, data parsing and transformations needed are provided in the sequel.

- *GOCE EGG_NOM_2 data conventions*

GOCE gradiometric observations are provided as a Level2 product, resulting from the Level1b measurements of the gradiometer after applying various corrections (direct tides, solid earth tides, ocean tides, pole tides and non-tidal temporal corrections), quality checks and flags. The Level2 gradiometric observations are provided in the products **EGG_NOM_2** and results from the calibrated and corrected GOCE gravity gradients in the products **EGG_NOM_1b**. EGG_NOM_2 GOCE GGs are given in daily files with a latency of two weeks and they refer to the GRF. Even though a TRF product is available (**EGG_TRF_2**) with the GOCE GGs in a LNOF, they include information from an external spherical harmonics GGM, so they will not be used in GeoGravGOCE. Therefore, for each GOCE GG dataset, the naming convention used depicts the day that the product refers to and contains two files, a header file (**HDR**) and a data file (**DBL**) both in XML format. The naming convention is as follows:

Table 4: GOCE EGG_NOM_2 naming conventions

GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002.HDR
Header (HDR) file with begin date and time (2009/11/02 at 0:00:00) and end date and time (2009/11/02 23:59:59) and version (0002).

GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002.DBL
Data block file (DBL) with begin date and time (2009/11/02 at 0:00:00) and end date and time (2009/11/02 23:59:59) and version (0002).

The header file contains specific information for the time reference, generation, corrections and data count in terms of epochs of the EGG_NOM_2 product. Its structure for the GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002.HDR product is presented in Table 5. Of importance in the HDR file are the GPS times of the first and last recording (mark in red in Table 5) which will be used for the time-tagging correlation of the GOCE GGs with the orbit elements of the satellite. It should be noted that the products summarized in the following tables are the ones that result after the use of the GOCE XML parser in ASCII format, so that their contents can be presented here easily.

Table 5: GOCE EGG_NOM_2 HDR content

```
GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002      |L2 gravity gradients in GRF with
corrections                                    |GOCE|CONS|EGG_NOM_2_|UTC=2009-11-02T00:00:00|UTC=2009-
11-02T23:59:59|0002|HPF|CPF       |2.4.1|UTC=2010-05-31T12:52:54|GO-MA-HPF-GS-0110    |      282

EGG_NOM_2                |O|GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002       |
86400|0941155215.394921899|0941241614.378060818|X|    0|    0
AUX_EPH                    |I|GO_CONS_AUX_EPH____20000101T000000_20010101T000000_0001        |
0|0000000000.000000000|9999999999.999999999|X|    0|    0
ANC_TID_2I                   |I|GO_CONS_ANC_TID_2I_FES2004__________________________0001        |
0|0000000000.000000000|9999999999.999999999|X|    0|    0
ANC_ICGEM                  |I|GO_CONS_ANC_ICGEM__EIGEN_5C__________________________0002       |
0|0000000000.000000000|9999999999.999999999|X|    0|    0
……………………………………………………………………………………………………………………………………………………

++ data products used for the generation of the EGG_NOM_2.DBL file
```

As far as the data block product is concerned, this contains the GOCE GGs, their error estimates, quality flags and the tidal and non-tidal corrections used. Its structure for the GO_CONS_EGG_NOM_2__20091102T000000_20091102T235959_0002.DBL product is presented in Table **6**. Of importance in the DBL file, as far as the GeoGravGOCE project is concerned, is the GPS timing of each observation, the GOCE GGs, their errors, the quality flags and finally the inertial attitude quaternions that will be used for the transformation from GRF to IRF (all marked in red in Table **6** for the GOCE GG record). It should be noted that the errors reported for all GOCE GGs are the formal ones without any calibration. Figure 3 provides the data structure of the EGG_NOM_2_xxx.DBL file and **Figure** 4 a summary table of its contents.

Table 6: GOCE EGG_NOM_2 DBL content

```
final     |consolidated|precise   |GRF |unknown  |EIGEN_5C                                   |formal

 941155215.394921899    -8.14178034E-07    -2.77319373E-06    +2.50889719E-06    -1.57440230E-06    -
6.48349371E-08 -2.82662198E-05 +6.13131200E-11 +3.77393176E-11 +5.05282691E-11 +3.19812326E-10
+5.07038259E-11  +4.71298768E-10  2  2  2  2  2  2  -1.21794345E-13  +2.18354154E-13  -9.66458509E-14  -
4.53333451E-14 -1.33443206E-14 +9.69694893E-14 +3.17127543E-14 +1.18735329E-13 -1.50451546E-13 -
1.06406304E-14 +1.39372151E-14 -9.23707019E-14 -1.11722929E-14 -6.34275553E-15 +1.75205001E-14 -
3.43281525E-14  -4.98199155E-14  -2.69970453E-14  +2.65586519E-16  -3.73097799E-16  +1.07511287E-16
+1.10491401E-15 +3.42600063E-15 -4.92400272E-16 +2.48547290E-16 -2.42094489E-15 +2.17239759E-15
+5.01463018E-15 -2.09978747E-15 -1.16301860E-15 +0.00000000E+00 +0.00000000E+00 +0.00000000E+00
+0.00000000E+00  +0.00000000E+00  +0.00000000E+00  +3.20703846e-01  +6.30748328e-01  -2.21155062e-
01 +6.71115511e-01

 941155216.394921660    -8.14151366E-07    -2.77318225E-06    +2.50886541E-06    -1.57431142E-06    -
6.48859013E-08 -2.82664700E-05 +6.13131200E-11 +3.77393176E-11 +5.05282691E-11 +3.19812326E-10
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4.52310473E-14 -1.33205816E-14 +9.70348398E-14 +3.16824619E-14 +1.18705471E-13 -1.50394332E-13 -
1.06135087E-14 +1.39147567E-14 -9.24381966E-14 -1.07105503E-14 -5.72316156E-15 +1.64390788E-14 -
3.39679187E-14  -4.94039635E-14  -2.71737615E-14  +2.58424669E-16  -3.78126251E-16  +1.19701591E-16
+1.10496740E-15 +3.42751146E-15 -4.87200517E-16 +2.28348948E-16 -2.49804662E-15 +2.26969767E-15
+4.93025423E-15 -2.20204980E-15 -1.11496662E-15 +0.00000000E+00 +0.00000000E+00 +0.00000000E+00
+0.00000000E+00  +0.00000000E+00  +0.00000000E+00  +3.20554273e-01  +6.30368037e-01  -2.21330661e-
01 +6.71486288e-01
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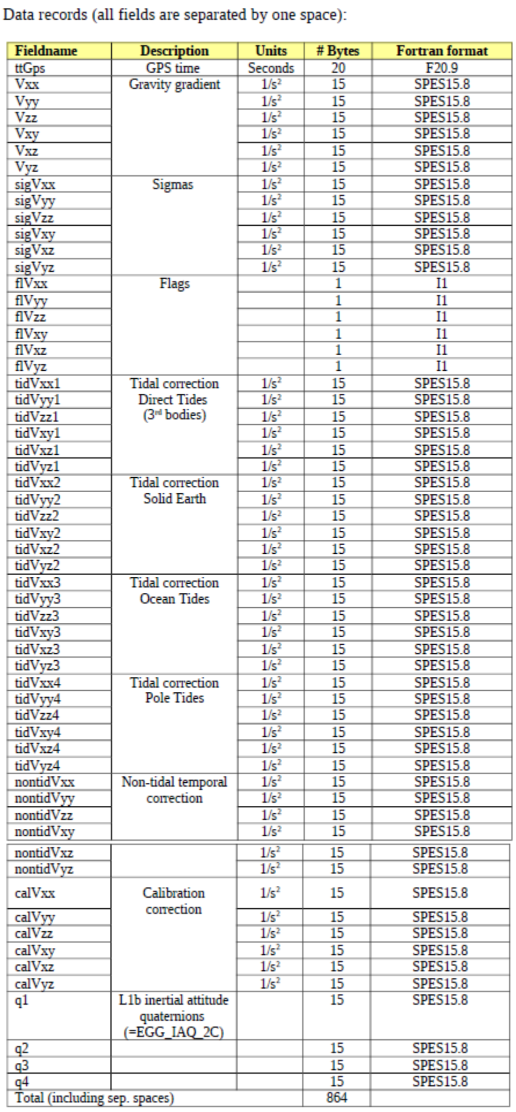


Data records (all fields are separated by one space):

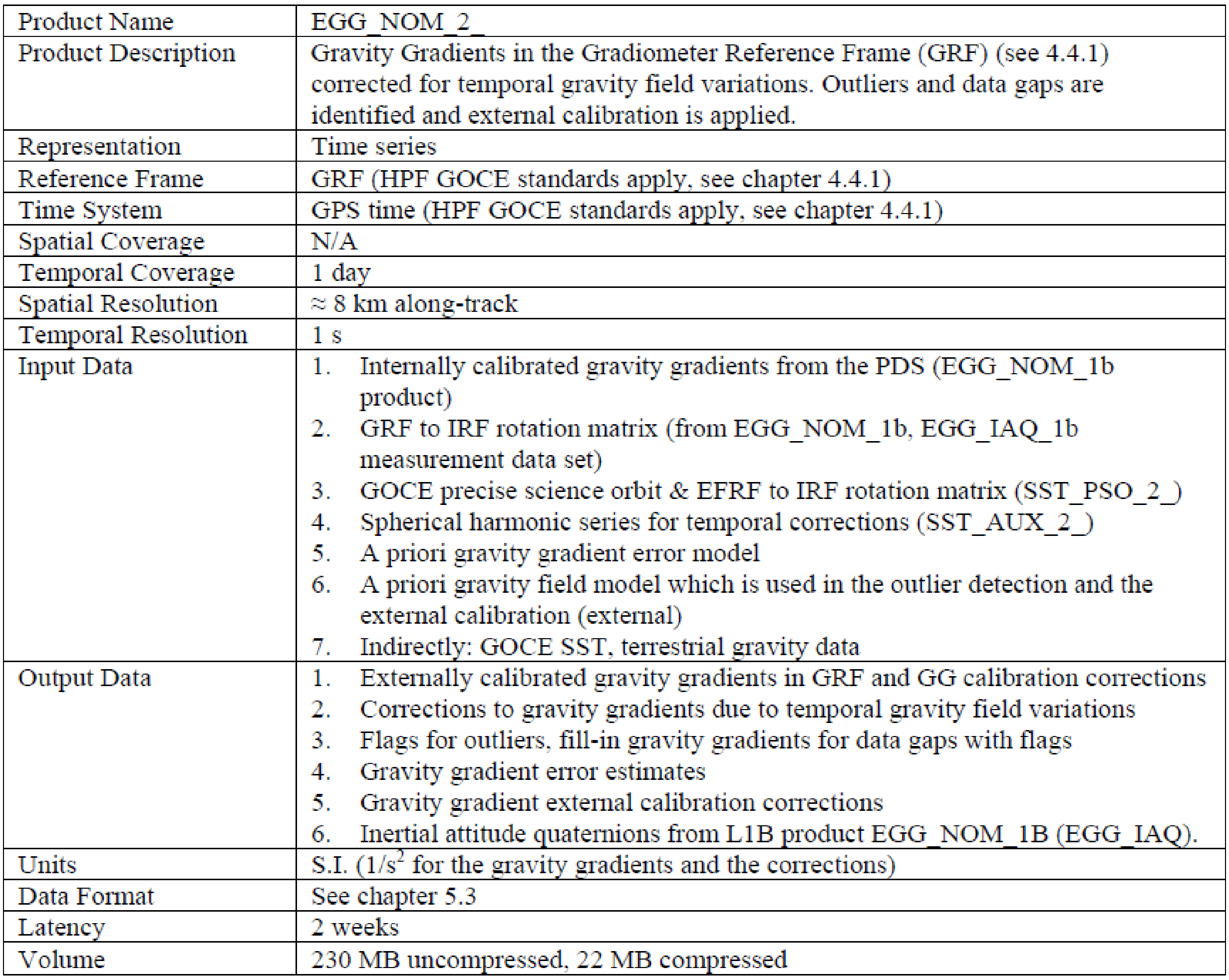
Fieldname	Description	Units	# Bytes	Fortran format
ttGps	GPS time	Seconds	20	F20.9
Vxx	Gravity gradient	$1/s^2$	15	SPES15.8
Vyy		$1/s^2$	15	SPES15.8
Vzz		$1/s^2$	15	SPES15.8
Vxy		$1/s^2$	15	SPES15.8
Vxz		$1/s^2$	15	SPES15.8
Vyz		$1/s^2$	15	SPES15.8
sigVxx	Sigmas	$1/s^2$	15	SPES15.8
sigVyy		$1/s^2$	15	SPES15.8
sigVzz		$1/s^2$	15	SPES15.8
sigVxy		$1/s^2$	15	SPES15.8
sigVxz		$1/s^2$	15	SPES15.8
sigVyz		$1/s^2$	15	SPES15.8
flVxx	Flags		1	I1
flVyy			1	I1
flVzz			1	I1
flVxy			1	I1
flVxz			1	I1
flVyz			1	I1
tidVxx1	Tidal correction Direct Tides (3rd bodies)	$1/s^2$	15	SPES15.8
tidVyy1		$1/s^2$	15	SPES15.8
tidVzz1		$1/s^2$	15	SPES15.8
tidVxy1		$1/s^2$	15	SPES15.8
tidVxz1		$1/s^2$	15	SPES15.8
tidVyz1		$1/s^2$	15	SPES15.8
tidVxx2	Tidal correction Solid Earth	$1/s^2$	15	SPES15.8
tidVyy2		$1/s^2$	15	SPES15.8
tidVzz2		$1/s^2$	15	SPES15.8
tidVxy2		$1/s^2$	15	SPES15.8
tidVxz2		$1/s^2$	15	SPES15.8
tidVyz2		$1/s^2$	15	SPES15.8
tidVxx3	Tidal correction Ocean Tides	$1/s^2$	15	SPES15.8
tidVyy3		$1/s^2$	15	SPES15.8
tidVzz3		$1/s^2$	15	SPES15.8
tidVxy3		$1/s^2$	15	SPES15.8
tidVxz3		$1/s^2$	15	SPES15.8
tidVyz3		$1/s^2$	15	SPES15.8
tidVxx4	Tidal correction Pole Tides	$1/s^2$	15	SPES15.8
tidVyy4		$1/s^2$	15	SPES15.8
tidVzz4		$1/s^2$	15	SPES15.8
tidVxy4		$1/s^2$	15	SPES15.8
tidVxz4		$1/s^2$	15	SPES15.8
tidVyz4		$1/s^2$	15	SPES15.8
nontidVxx	Non-tidal temporal correction	$1/s^2$	15	SPES15.8
nontidVyy		$1/s^2$	15	SPES15.8
nontidVzz		$1/s^2$	15	SPES15.8
nontidVxy		$1/s^2$	15	SPES15.8
nontidVxz		$1/s^2$	15	SPES15.8
nontidVyz		$1/s^2$	15	SPES15.8
calVxx	Calibration correction	$1/s^2$	15	SPES15.8
calVyy		$1/s^2$	15	SPES15.8
calVzz		$1/s^2$	15	SPES15.8
calVxy		$1/s^2$	15	SPES15.8
calVxz		$1/s^2$	15	SPES15.8
calVyz		$1/s^2$	15	SPES15.8
q1	L1b inertial attitude quaternions (=EGG_IAQ_2C)		15	SPES15.8
q2			15	SPES15.8
q3			15	SPES15.8
q4			15	SPES15.8
Total (including sep. spaces)			864	

Figure 3: Data structure of the EGG_NOM_2.DBL file (GO-TN-HPF-GS-0192, 2012)

- *GOCE SST_PSO_2 data conventions*

GOCE gradiometric observations mentioned earlier are tagged only with their GPS time of acquisition and refer to the GRF. Therefore, a transformation from GRF to IRF and from IRF to EFRF is needed, with all detailed information provided in the **SST_PSO_2** product. The main components of the SST_PSO_2 product are:

- two different orbits (reduced-dynamic and kinematic) in the EFRF, named as GO_CONS_SST_PRD_2__20091101T235945_20091102T235944_0001.EDF (reduced-dynamic) and GO_CONS_SST_PKI_2__20091101T235945_20091102T235944_0001.EDF (kinematic),



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 and data gaps are identified and external calibration is applied.
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	1. Internally calibrated gravity gradients from the PDS (EGG_NOM_1b product) 2. GRF to IRF rotation matrix (from EGG_NOM_1b, EGG_IAQ_1b measurement data set) 3. GOCE precise science orbit & EFRF to IRF rotation matrix (SST_PSO_2_) 4. Spherical harmonic series for temporal corrections (SST_AUX_2_) 5. A priori gravity gradient error model 6. A priori gravity field model which is used in the outlier detection and the external calibration (external) 7. Indirectly: GOCE SST, terrestrial gravity data
Output Data	1. Externally calibrated gravity gradients in GRF and GG calibration corrections 2. Corrections to gravity gradients due to temporal gravity field variations 3. Flags for outliers, fill-in gravity gradients for data gaps with flags 4. Gravity gradient error estimates 5. Gravity gradient external calibration corrections 6. Inertial attitude quaternions from L1B product EGG_NOM_1B (EGG_IAQ).
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

Figure 4: Summary table of the EGG_NOM_2 product (GO-MA-HPF-GS-0110, 2009)

- a rotation matrix in terms of quaternions for the transformation from EFRF to IRF named as GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001.EDF
- and a quality report of the orbital elements provided, given in PDF format and named as GO_CONS_SST_PRP_2__20091101T235945_20091102T235944_0001.EDF

As far as the SST_PSO_2 HDR file is concerned, this contains vital information as well. The header file contains specific information for the period and time reference of the provided quaternions for the rotations, the period and time reference of the provided reduced-dynamic and kinematic orbit solutions, and the Level1b products used for its generation. Its structure for the GO_CONS_SST_PSO_2__20091101T235945_20091102T235944_0001.HDR product is presented in **Table 7**. As mentioned, of importance are the timing conventions for the rotation matrix and the orbital elements, which in the SST_PSO_2 are provided in UTC time and not GPS time. This means that the GPS time of the GOCE GGs in EGG_NOM_2 should be correlated with the UTC provided in the SST_PSO_2 taking into account that there are is a leap second difference between the two of 15 s (this holds for 2009 that the data presented refer to). This is shown in **Table 7** where the reference start of the UTC time is 2009-11-01 at 23:59:45, while in **Table 5** the respective reference start for the GOCE GGs is is 2009-11-02 at 00:00:00. It should be noted that again the products summarized in the following tables are the ones that result after the use of the GOCE XML parser in ASCII format, so that their contents can be presented here easily.

Table 7: GOCE SST_PSO_2 HDR content

```
GO_CONS_SST_PSO_2__20091101T235945_20091102T235944_0001       |Precise Science Orbit for GOCE
|GOCE|CONS|SST_PSO_2_|UTC=2009-11-01T23:59:45|UTC=2009-11-02T23:59:44|0001|HPF|CPF
|2.4.1|UTC=2010-05-31T13:02:01|GO-MA-HPF-GS-0110     |      46
Quality report              |O|GO_CONS_SST_PRP_2__20091101T235945_20091102T235944_0001         |
0|0941155200.000000000|0941241599.000000000|X|    0|    0
Reduced dynamic orbit       |O|GO_CONS_SST_PRD_2__20091101T235945_20091102T235944_0001        |
8640|0941155200.000000000|0941241599.000000000|X|    0|    0
Kinematic orbit             |O|GO_CONS_SST_PKI_2__20091101T235945_20091102T235944_0001         |
86343|0941155200.000000000|0941241599.000000000|X|    0|    0
Covariance matrix, kinematic|O|GO_CONS_SST_PCV_2__20091101T235945_20091102T235944_0001       |
86343|0941155200.000000000|0941241599.000000000|X|    0|    0
Rotation matrix             |O|GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001        |
86400|0941155200.000000000|0941241599.000000000|X|    0|    0
.................................................................................................
```

As far as the SST_PSO_2 DBL file is concerned, this contains, among others, the following files: GO_CONS_SST_PRD_2__20091101T235945_20091102T235944_0001.EDF (reduced-dynamic orbit), GO_CONS_SST_PKI_2__20091101T235945_20091102T235944_0001.EDF (kinematic), GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001.EDF (rotation matrix) and GO_CONS_SST_PRP_2__20091101T235945_20091102T235944_0001.EDF (quality report of orbital solutions).

The **rotation matrix** (GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001.EDF) provides, in terms of quaternions, the necessary rotations in order to transform from the EFRF to the IRF, meaning that for the GOCE GGs, where the transformation from the IRF to the EFRF is needed, the provided values should be applied in the opposite direction. More important is the fact that the rotations refer to the UTC time provided in the SST_PSO_2 header (see above) and they are provided for every second. This means that given the GOCE GGs which have a frequency higher than 1 s, interpolation in the given quaternions values should be performed. Within GeoGravGOCE, the processing strategy will be to use the SST_PSO_2 HDR file, get the starting GPS time from that for the SST_PRM_2 product (see **Table 7**, with start time of 0941155200.000000000), apply it to the first column of the rotation matrix in SST_PRM_2 DBL by adding the seconds that the quaternions refer to, so that the processed record will now contain GPS time as do the GOCE GGs. Note that due to the 15s difference between UTC and GPS times, some GOCE GGs form the EGG_NOM_2 DBL that are taken during the last 15s of the day will not have a corresponding time with rotation quaternions. For that reason, in order to process one day of GOCE GGs, two consecutive SST_RPM_2 files will be merged. Finally, the interpolation of quaternions will be performed as described in section 4.4.2.2 of the GOCE Level 2 Product Handbook (GO-MA-HPF-GS-0110, 2008).

The **kinematic orbit** (GO_CONS_SST_PKI_2__20091101T235945_20091102T235944_0001.EDF) solution provides the necessary orbital elements of the satellite so that the already transformed GOCE GGs to the EFRF can be translated with the GPS time tag to Cartesian coordinates X, Y, Z. The same convention of UTC time holds for the orbital elements as well. Therefore, the orbital elements refer to the UTC time provided in the SST_PSO_2 header (see above) and they are provided for every second (for the kinematic orbits). This means that given the GOCE GGs which have a frequency higher than 1 s (now referring to the EFRF), interpolation in the given orbital elements (X, Y, Z) should be performed. Within GEOGRAVGOCE, the processing strategy will be to use the SST_PSO_2 HDR

Table 8: GOCE SST_PRM_2 DBL content

```
#TRANSFORMATION:             GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001.IDF
# Program that created the file: BERNESE/ROTMAT
# Date of creation:           2010-02-05 12:31:19
# Reference epoch:             2009-11-02 00:00:00 GPS
# First epoch:              2009-11-02 00:00:00 GPS
# Transformation direction:     Earth-fixed to inertial
# Pole file:                 G3_09306
# Nutation model:             IAU2000
# Nutation offsets:           not applied
# Subdaily model:             IERS2000
# End of header
      0 -0.0001637471514849 -0.0004621638507369 -0.3519297831131093  0.9360262749246993
      1 -0.0001637640590101 -0.0004621578532122 -0.3519639109355404  0.9360134427402280
      2 -0.0001637809663178 -0.0004621518550730 -0.3519980382900739  0.9360006093114475
      3 -0.0001637978734076 -0.0004621458563192 -0.3520321651766815  0.9359877746383684
      4    -0.0001638147802798    -0.0004621398569509    -0.3520662915953013       0.9359749387210141
……………………………………………………………………………………………………………………………………………………
```

file, get the starting GPS time from that for the SST_PRM_2 product (see Table 7, with start time of 0941155200.000000000), apply it to the respective time of each satellite position (see Table 9, marked with red) in SST_PKI_2 DBL by adding the seconds that the position refers to, so that the processed record will now contain GPS time as do the GOCE GGs. Note that due to the 15s difference between UTC and GPS times, some GOCE GGs form the EGG_NOM_2 DBL that are taken during the last 15s of the day will not have a corresponding time with orbital elements. For that reason, in order to process one day of GOCE GGs, two consecutive SST_PKI_2 files will be merged. Finally, the interpolation of orbital elements will be performed using a simple linear interpolation between the two consecutive X,Y,Z pairs that the GOCE GGs fall in. Note that the SST_PRD_2 data are provided in the standard sp3c format (ftp://igscb.jpl.nasa.gov/igscb /data/format/sp3c.txt) so that the position is given in km.

Table 9: GOCE SST_PKI_2 DBL content.

```
#cP2009 11  2  0  0  0.80680000   86343 ZERO  IGS05 KIN AIUB
## 1556  86400.80680000     1.00000000 55137 0.0000093379630
+   1   L15  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
%c L  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
```

```
%i   0   0   0   0    0    0    0    0      0
%i   0   0   0   0    0    0    0    0      0
/* GOCE Precise Science Orbit
/* Kinematic orbit, day 306, year 2009
/* IAPG/AIUB
*  2009 11  2  0  0  0.80678020
PL15   -390.612059   6623.987679    73.104149 193219.797196
*  2009 11  2  0  0  1.80678020
PL15   -389.240315   6624.166512    65.402457 193219.799413
*                   2009          11                  2                  0                  0                  2.80678020
……………………………………………………………………………………………………………………………………………………
```

The **reduced-dynamic orbit** (GO_CONS_SST_PRD_2__20091101T235945_20091102T235944 _0001.EDF) solution provides the necessary orbital elements of the satellite so that the already transformed GOCE GGs to the EFRF can be translated with the GPS time tag to Cartesian coordinates X, Y, Z. The same convention of UTC time holds for the orbital elements as well. Therefore, the orbital elements refer to the UTC time provided in the SST_PSO_2 header (see above) and they are provided for every **10 seconds** (for the reduced-dynamic orbits). This means that given the GOCE GGs which have a frequency higher than 1 s (now referring to the EFRF), interpolation in the given orbital elements (X, Y, Z) should be performed. Note that within the 10s gap, many GOCE GG observations will fall, therefore, the first step needed will be the interpolation of the 10 s orbital elements to 1 s. Various options, such as Lagrange polynomials, splines, etc., can be used to fit the satellite arc. Within GeoGravGOCE, the reduced-dynamic orbits will not be used in order to avoid any interpolation errors. The processing strategy if reduced-dynamic orbits were to be used, would be to first interpolate the 10 s orbital elements to 1 s bins by Lagrange polynomials in order to fit the GOCE satellite arc. With that operation, the new interpolated reduced-dynamic orbits would be available with 1 s sampling, so that then the SST_PSO_2 HDR file would be used, to get the starting GPS time from that for the SST_PRM_2 product (see Table 7, with start time of 0941155200.000000000), apply it to the respective time of each satellite position (see **Table 10**, marked with red) in SST_PRD_2 DBL by adding the seconds that the position refers to, so that the processed record will now contain GPS time as do the GOCE GGs. Note that due to the 15s difference between UTC and GPS times, some GOCE GGs form the EGG_NOM_2 DBL that are taken during the last 15s of the day will not have a corresponding time with orbital elements. For that reason, in order to process one day of GOCE GGs, two consecutive SST_PRD_2 files will be merged. Finally, the interpolation of orbital elements will be performed using a simple linear interpolation between the two consecutive 1 s X, Y, Z pairs that the GOCE GGs fall in. Note that the SST_PRD_2 data are provided in the standard sp3c format (ftp://igscb.jpl.nasa.gov/igscb /data/format/sp3c.txt) so that the position is given in km.

Table 10: GOCE SST_PRD_2 DBL content

```
#cV2009 11  2  0  0  0.00000000    8640 u     IGS05 FIT AIUB
## 1556  86400.00000000    10.00000000 55137 0.0000000000000
+    1   L15  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

```
++       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
%c L  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i   0    0    0    0     0     0     0     0       0
%i   0    0    0    0     0     0     0     0       0
/* GOCE Precise Science Orbit
/* Reduced-dynamic orbit, day 306, year 2009
/* IAPG/AIUB
/*
*  2009 11  2  0  0  0.00000000
PL15   -391.718353   6623.836682    79.317661 999999.999999
VL15  13710.157683   1908.731015 -77015.601314 999999.999999
*  2009 11  2  0  0 10.00000000
PL15   -377.980705   6625.284690     2.298385 999999.999999
VL15  13764.602016    987.250587 -77021.193676 999999.999999
……………………………………………………………………………………………………………………………………
```

- *GOCE GGs reference system transformations GRF, IRF, EFRF, LNOF*

GOCE gradiometric observations described in the previous section need to be transformed from the given GRF to IRF, then from IRF to EFRF and finally from EFRF to LNOEF, so that they can be combined with other data (altimetry, local gravity and GPS/Leveling, GGMs, topography/bathymetry, etc.) and be presented in a more meaningful from the GRF earth-based reference system. The first transformation to be performed is from the GRF to the IRF, using the GOCE GGs and the provided quaternions as outlined in **Table 6** (product **EGG_NOM_2**). Given the availability of the quaternions q_1, q_2, q_3 and q_4 the rotation matrix can be formed as (see also section 4.4.2.1 in GO-MA-HPF-GS-0110, 2008):

$$\boldsymbol{R}=\begin{bmatrix} q_1^2-q_2^2-q_3^2+q_4^2 & 2\left(q_1q_2+q_3q_4\right) & 2\left(q_1q_3-q_2q_4\right) \\ 2\left(q_1q_2-q_3q_4\right) & -q_1^2+q_2^2-q_3^2+q_4^2 & 2\left(q_2q_3+q_1q_4\right) \\ 2\left(q_1q_3+q_2q_4\right) & 2\left(q_2q_3-q_1q_4\right) & -q_1^2-q_2^2+q_3^2-q_4^2 \end{bmatrix}. \qquad \textbf{(1.5.1)}$$

Given the construction of the rotation matrix ***R***, the transformation from the GRF to the IRF can be performed, keeping in mind that the quaternions provided give the rotation from IRF to GRF, so that the transformation finally becomes:

$$\boldsymbol{V}_{IRF}=\begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{IRF}=\boldsymbol{R}^T\begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{GRF}\boldsymbol{R}=\boldsymbol{R}^T\boldsymbol{V}_{GRF}\boldsymbol{R}\,. \qquad \textbf{(1.5.2)}$$

The next step in the transformation process, is to transform the GOCE GGs from the IRF ($\boldsymbol{V}_{IRF}$) to the EFRF ($\boldsymbol{V}_{EFRF}$). In order to do that, it is necessary to use the provided rotation matrix (product **SST_PRM_2**) from the generic **SST_PSO_2** product (see**Table 8**). As already mentioned, the provided rotation matrix is given in UTC time, so the first process will be to correlate that time with GPS time. Therefore, the GPS time provided in the SST_PSO_2 HDR record for PRM (see **Table 7**) has to be extracted (0941155200.000000000) and added to the time column in the SST_PRM_2 product (first column) so that the new format of the SST_PRM_2 product will be as shown in Table 11.

The next step, is to make the quaternions interpolation on the GPS time that the GOCE GGs have been taken, which are now in V_{IRF} after applying Eq. (2.2.1). This will be performed as outlined in GO-MA-HPF-GS-0110 (2008), where we now suppose that we have known the quaternions from the SST_PRM_2 product in two epochs t_a and t_b, being q_a and q_b respectively, and we want to interpolate to an epoch t in between the two, so that $t_a < t < t_b$. First, given that there is sign ambiguity in the quaternions and assuming that the angle between the two rotation axes described by q_a and q_b is smaller than 90°, the sign of all components of one of the quaternions has in a first step to be flipped if the scalar product of the vector parts of the two quaternions is negative as:

Table 11: GOCE SST_PRM_2 DBL product after adding the GPS start time

```
#TRANSFORMATION:             GO_CONS_SST_PRM_2__20091101T235945_20091102T235944_0001.IDF
# Program that created the file: BERNESE/ROTMAT
# Date of creation:           2010-02-05 12:31:19
# Reference epoch:             2009-11-02 00:00:00 GPS
# First epoch:                2009-11-02 00:00:00 GPS
# Transformation direction:     Earth-fixed to inertial
# Pole file:                  G3_09306
# Nutation model:              IAU2000
# Nutation offsets:           not applied
# Subdaily model:             IERS2000
# End of header
      941155200.0         -0.0001637471514849        -0.0004621638507369        -0.3519297831131093
0.9360262749246993
      941155201.0         -0.0001637640590101        -0.0004621578532122        -0.3519639109355404
0.9360134427402280
      941155202.0         -0.0001637809663178        -0.0004621518550730        -0.3519980382900739
0.9360006093114475
      941155203.0         -0.0001637978734076        -0.0004621458563192        -0.3520321651766815
0.9359877746383684
      941155204.0         -0.0001638147802798        -0.0004621398569509        -0.3520662915953013
0.9359749387210141
……………………………………………………………………………………………………………………………………………………
```

$$q_b = -q_b \quad if \quad q_{a1}q_{b1} + q_{a2}q_{b2} + q_{a3}q_{b3} < 0\,. \tag{1.5.3}$$

Then, we can write the quaternion describing the differential rotation between the two epochs t_a and t_b, as:

$$q_{ab} = q_a^{*} q_b\,, \tag{1.5.4}$$

where, q_a^{*} denotes the conjugate or inverse of the quaternion such that:

$$q_a^* = q_{a4} - iq_{a1} - jq_{a2} - kq_{a3}, \tag{1.5.5}$$

with *I, j, k* being the hyper-imaginary numbers satisfying the condition $i^2=j^2=k^2=-1$. This means that in terms of the components of each of the quaternion rotations q_a and q_b the rotation between the two epochs described in Eq. (2.2.4) can be written as:

$$\begin{aligned}
q_{ab4} &= q_{a4}q_{b4} + q_{a1}q_{b1} + q_{a2}q_{b2} + q_{a3}q_{b3} \\
q_{ab1} &= q_{a4}q_{b1} - q_{a1}q_{b4} + q_{a3}q_{b2} - q_{a2}q_{b3} \\
q_{ab2} &= q_{a4}q_{b2} - q_{a2}q_{b4} + q_{a1}q_{b3} - q_{a3}q_{b1} \\
q_{ab3} &= q_{a4}q_{b3} - q_{a3}q_{b4} + q_{a2}q_{b1} - q_{a1}q_{b2}.
\end{aligned} \tag{1.5.6}$$

Note that if $q_{ab}=1$, then no interpolation is needed, since the epochs are the same, meaning that if a GOCE GG observation falls exactly on the timing that the RTM rotations are provided, the no interpolation is needed. Finally, the rotation angle corresponding to the rotation described by the elements of q_{ab} in Eq. (2.2.6), can be written as:

$$\Phi_{ab} = 2\arccos\left(q_{ab4}\right), \tag{1.5.7}$$

and can be linearly interpolated to the wanted epoch *t* according to:

$$\Phi_{at} = \Phi_{ab}\frac{t - t_a}{t_b - t_a}, \tag{1.5.8}$$

Now the goal is to determine the quaternions corresponding to this rotation angle Φ_{at}, so that we can then determine the rotation matrix. The quaternion corresponding to this interpolated rotation (rotation from epoch t_a to epoch t) can be written as:

$$q_{at4} = \cos\frac{\Phi_{at}}{2}, \tag{1.5.9}$$

$$q_{at1} = q_{ab1}\frac{\sin\frac{\Phi_{at}}{2}}{\sin\frac{\Phi_{ab}}{2}}, \tag{1.5.10}$$

$$q_{at2} = q_{ab2}\frac{\sin\frac{\Phi_{at}}{2}}{\sin\frac{\Phi_{ab}}{2}}, \tag{1.5.11}$$

and

$$q_{at3} = q_{ab3}\frac{\sin\frac{\Phi_{at}}{2}}{\sin\frac{\Phi_{ab}}{2}}. \tag{1.5.12}$$

Having described the differential rotation between the rotations q_a and q_t, which interpolates the quaternions q_a and q_b to epoch t, we can then define the quaternion q_t as:

$$q_t = q_a q_{at}\,, \tag{1.5.13}$$

and its components:

$$\begin{aligned}
q_{t4} &= q_{a4}q_{at4} - q_{a1}q_{at1} - q_{a2}q_{at2} - q_{a3}q_{at3} \\
q_{t1} &= q_{a4}q_{at1} + q_{a1}q_{at4} - q_{a3}q_{at2} + q_{a2}q_{at3} \\
q_{t2} &= q_{a4}q_{at2} + q_{a2}q_{at4} - q_{a1}q_{at3} + q_{a3}q_{at1} \\
q_{t3} &= q_{a4}q_{at3} + q_{a3}q_{at4} - q_{a2}q_{at1} + q_{a1}q_{at2}\,.
\end{aligned} \tag{1.5.14}$$

Having determined with Eq. (2.2.14) the components of the quaternion q_t, we can now define the necessary rotation matrix for the transformation from the IRF to the EFRF:

$$\boldsymbol{R}_{EFRF-IRF} = \begin{bmatrix} q_{t1}^2 - q_{t2}^2 - q_{t3}^2 + q_{t4}^2 & 2\left(q_{t1}q_{t2} + q_{t3}q_{t4}\right) & 2\left(q_{t1}q_{t3} - q_{t2}q_{t4}\right) \\ 2\left(q_{t1}q_{t2} - q_{t3}q_{t4}\right) & -q_{t1}^2 + q_{t2}^2 - q_{t3}^2 + q_{t4}^2 & 2\left(q_{t2}q_{t3} + q_{t1}q_{t4}\right) \\ 2\left(q_{t1}q_{t3} + q_{t2}q_{t4}\right) & 2\left(q_{t2}q_{t3} - q_{t1}q_{t4}\right) & -q_{t1}^2 - q_{t2}^2 + q_{t3}^2 - q_{t4}^2 \end{bmatrix}. \tag{1.5.15}$$

Given the construction of the rotation matrix $\boldsymbol{R}_{EFRF-IRF}$, the transformation from the IRF to the EFRF can be performed, keeping in mind that the quaternions provided give the rotation from EFRF to IRF, so that the transformation finally becomes:

$$\boldsymbol{V}_{EFRF} = \begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{EFRF} = \boldsymbol{R}^T_{EFRF-IRF} \begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{IRF} \boldsymbol{R}_{EFRF-IRF} = \boldsymbol{R}^T_{EFRF-IRF}\boldsymbol{V}_{IRF}\boldsymbol{R}_{EFRF-IRF}\,. \tag{1.5.16}$$

The next step in the transformation process, is to correlate the GOCE GGs from the EFRF ($\boldsymbol{V}_{EFRF}$), where we have them available with the GPS time tagging only, with the GOCE orbital position elements *X, Y, Z* as these are provided in the **SST_PKI_2** data product from the generic **SST_PSO_2** product (see **Table 9**). As already mentioned, the provided orbital element are given in UTC time, so the first process will be to correlate that time with GPS time. Therefore, the GPS time provided in the SST_PSO_2 HDR record for PKI (see **Table 7**) has to be extracted (0941155200.000000000) and added to the time row in the SST_PKI_2 product (sixth column) so that the new format of the SST_PKI_2 product will be as shown in **Table 12**.

Table 12: GOCE SST_PKI_2 DBL content

```
#cP2009 11  2  0  0  0.80680000   86343 ZERO  IGS05 KIN AIUB
## 1556  86400.80680000     1.00000000 55137 0.0000093379630
+   1   L15  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

```
++       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
%c L  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i   0   0   0   0    0    0    0    0      0
%i   0   0   0   0    0    0    0    0      0
/* GOCE Precise Science Orbit
/* Kinematic orbit, day 306, year 2009
/* IAPG/AIUB
/*
*  2009 11  2  0  0  941155200.80678020
PL15   -390.612059   6623.987679     73.104149 193219.797196
*  2009 11  2  0  0  0941155201.80678020
PL15   -389.240315   6624.166512     65.402457 193219.799413
……………………………………………………………………………………………………………………………………………
```

Having the GPS time available for both the GOCE GGs in the EFRF and the orbital elements of GOCE in the new SST_PKI_2 product, simple linear interpolation will be used. Denoting once again the two epochs t_a and t_b that we have the orbital elements available (X_a, Y_a, Z_a and X_b, Y_b, Z_b), we want to interpolate to the epoch t in between the two to derive the spacecraft position for that time (X_t, Y_t, Z_t), so that $t_a < t < t_b$. Therefore, the change in position of GOCE for each vector is given as:

$$\Delta X_{at} = \Delta X_{ab} \frac{t - t_a}{t_b - t_a}, \tag{1.5.17}$$

$$\Delta Y_{at} = \Delta Y_{ab} \frac{t - t_a}{t_b - t_a}, \tag{1.5.18}$$

$$\Delta Z_{at} = \Delta Z_{ab} \frac{t - t_a}{t_b - t_a}. \tag{1.5.19}$$

So, finally the orbital position for the GOCE GGs is derived as:

$$\boldsymbol{X}_{t\ EFRF} = \boldsymbol{X}_{a\ EFRF} + \boldsymbol{\Delta X}_{ab} \Delta t_{ab} \Rightarrow \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix}_{EFRF} = \begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix}_{EFRF} + \left(\frac{t - t_a}{t_b - t_a} \right) \begin{bmatrix} \Delta X_{ab} \\ \Delta Y_{ab} \\ \Delta Z_{ab} \end{bmatrix}_{EFRF}, \tag{1.5.20}$$

and more analytically:

$$X_t = X_a + \Delta X_{ab} \frac{t - t_a}{t_b - t_a}, \tag{1.5.21}$$

$$Y_t = Y_a + \Delta Y_{ab} \frac{t - t_a}{t_b - t_a}, \tag{1.5.22}$$

$$Z_t = Z_a + \Delta Z_{ab} \frac{t - t_a}{t_b - t_a} . \tag{1.5.23}$$

In this way, we have each GOCE GG referred to the EFRF and expressed in Cartesian coordinates and then remains the conversion from Cartesian to geodetic ones, as:

$$\lambda_t = arctan \frac{Y_t}{X_t} , \tag{1.5.24}$$

$$\varphi_t = arctan \left(\frac{Z_t + e^2 \bar{N} \sin \varphi_t}{\sqrt{X_t^2 + Y_t^2}} \right) , \tag{1.5.25}$$

$$h_t = \frac{Z_t}{\sin \varphi_t} - \left(1 - e^2\right) \bar{N} , \tag{1.5.26}$$

where, the parameters of the defining ellipsoid refer to GRS80 (Moritz, 2000), so that *e* denotes the first eccentricity, $\bar{N}$ (denoted with the over-bar to distinguish it from the geoid height *N*) the curvature of the prime vertical, *a* and *b* the semi-major and semi-minor axis of the reference ellipsoid, so that

$$\bar{N} = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}} , \tag{1.5.27}$$

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} . \tag{1.5.28}$$

The defining parameters for GRS80 are a=6378137.0 m, b=6356752.3141 m, 1/f=298.257222101, GM=398600.5x10^9 m^3/s^2 and ω=7.292115x10^{-5} rad/s. Finally, there is one last transformation from the geodetic coordinates in the EFRF to the LNOF. This is performed with the following transformation:

$$\boldsymbol{R}_{EFRF-LNOF} = \begin{bmatrix} -\sin \varphi_t \cos \lambda_t & -\sin \varphi_t \sin \lambda_t & \cos \varphi_t \\ \sin \lambda_t & -\cos \lambda_t & 0 \\ \cos \varphi_t \cos \lambda_t & \cos \varphi_t \sin \lambda_t & \sin \varphi_t \end{bmatrix} , \tag{1.5.29}$$

$$\boldsymbol{X}_{LNOF} = \boldsymbol{R}_{EFRF-LNOF} \boldsymbol{X}_{EFRF} \Rightarrow \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix}_{LNOF} = \begin{bmatrix} -\sin \varphi_t \cos \lambda_t & -\sin \varphi_t \sin \lambda_t & \cos \varphi_t \\ \sin \lambda_t & -\cos \lambda_t & 0 \\ \cos \varphi_t \cos \lambda_t & \cos \varphi_t \sin \lambda_t & \sin \varphi_t \end{bmatrix} \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix}_{EFRF} . \tag{1.5.30}$$

Given the transformation of the GOCE GGs position vector in the LNOF, the last thing remaining is the transformation of their observations from the EFRF to the LNOF one. This will be performed with the same rotation matrix given in Eq. (2.2.29) as:

$$\boldsymbol{V}_{LNOF}=\begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{LNOF}=\boldsymbol{R}_{EFRF-LNOF}\begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}_{EFRF}\boldsymbol{R}_{EFRF-LNOF}^{T}=\boldsymbol{R}_{EFRF-LNOF}\boldsymbol{V}_{EFRF}\boldsymbol{R}_{EFRF-LNOF}^{T}\,. \qquad \textbf{(1.5.31)}$$

A final note should be given at this stage. It should be noted that the LNOF as defined by GOCE standards is described as a North-West-Up reference system, meaning that $X_{t\,LNOF}$ points along the meridian, $Z_{t\,LNOF}$ points along the radial direction and $Y_{t\,LNOF}$ points along the great circle westwards. This has two implications: a) in order to point along the parallel, then we should multiply the derived $V_{yy\,LNOF}$ with cos(λ_t) and b) in order to transform the $Y_{t\,LNOF}$ to point eastward, then the rotation matrix should be:

$$\boldsymbol{R}_{EFRF-LNOF}=\begin{bmatrix} -sin\,\varphi_t\,cos\,\lambda_t & -sin\,\varphi_t\,sin\,\lambda_t & cos\,\varphi_t \\ -sin\lambda_t & +cos\,\lambda_t & 0 \\ cos\,\varphi_t\,cos\,\lambda_t & cos\,\varphi_t sin\lambda_t & sin\,\varphi_t \end{bmatrix}_{eastward}, \qquad \textbf{(1.5.32)}$$

One crucial point is that given that the V_{xy} and V_{yz} components are modeled by an order of magnitude worse than the other ones (see also **Table 6**) by converting the GOCE GGs to the LNOF we introduce their errors in the other components. Finally, it should be noticed that the transformation of the position vector to the LNOF is not needed for general combination and validation studies, so that the final dataset that was used within GeoGravGOCE was the location as λ, ϕ, h and $\boldsymbol{V}_{LNOF}$.

1.6 Data archiving in the GeoGravGOCE server

All data to be used within the GeoGravGOCE project have been uploaded to the GeoGravGOCE FTP server. The datasets have been placed in the followings path:

“GeoGravGOCE_Data_Server/Gravity/”

The free-air gravity anomalies are stored in the file named “Gravity.xlsx”. The structure of the data is provided in Table 13. The file contains the original free-air anomalies, the reduced to EGM08 field and the final residual field after the removal of the contribution of EGM08 and the RTM effect, as it was.

Table 13: Structure of the file holding the gravity anomalies dataset

Column Name	**ID**	**fi**	**lamda**	**DgFA**	**H**	**DgFA EGM08red**	**DgFA EGM08&RTMred**
Description	Unique Identification Number	Station latitude	Station longitude	Free-air anomaly value	Station ortho-metric height	Free-air anomaly value reduced by the contribution of EGM08	Free-air anomaly value reduced by the contribution of EGM08 and by the RTM effect

It should be stressed that both the available gravity data sets have been provided to the project team without explicit permission for their distribution. Therefore, although the data have been uploaded to the project server their distribution is prohibited.

“GeoGravGOCE_Data_Server/GGMs/”

The root/GGMs/ folder contains several subfolders with all GGMs, while each sub-folder has the following structure (the example here refers to GOCO06s).

Table 14: Structure of each GGM folder in the GeoGravGOCE FTP server (GOCO06S is reported here).

GeoGravGOCE_Data_Server/GGMs/GOCO06S/ (root folder)

GOCO06s *(spherical harmonic coefficients)*
GOCO06s_gravdeg *(GGM gravity anomaly degree and error degree variances by degree and cumulative)*
GOCO06s_gravrms *(GGM cumulative RMS gravity anomaly signal and error)*
GOCO06s_undeg *(GGM geoid degree and error degree variances by degree and cumulative)*
GOCO06s_unrms *(GGM cumulative RMS geoid signal and error)*

“GeoGravGOCE_Data_Server/DTBM/”

Two DTBMs are used in GeoGravGoce and each dataset is stored in a separate Microsoft Excel File. The detailed DTBM is stored in the file named “detailed_DTBM.xlsx” and the reference DTBM is stored in the file name “reference_DTBM.xlsx”. The structure of the data is provided in Table 15.

Table 15: Structure of the file holding the DTBM dataset

Column Name	ID	fi	lamda	h
Description	Unique Identification Number	Station latitude	Station Longitude	Station geometric height

“GeoGravGOCE_Data_Server/GOCE_L2_EGG_NOM_2(GRF)/”

GOCE gradiometric observations are provided as a Level2 product, resulting from the Level1b measurements of the gradiometer after applying various corrections (direct tides, solid earth tides, ocean tides, pole tides and non-tidal temporal corrections), quality checks and flags. The Level2 gradiometric observations are provided in the products EGG_NOM_2 and results from the calibrated and corrected GOCE gravity gradients in the products EGG_NOM_1b.

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