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GRACE-FO D-103919

Gravity Recovery and Climate Experiment Follow-On

GFZ Level-2 Processing Standards Document for Level-2 Product Release 06

(Rev. 1.0, June 3, 2019)

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DOCUMENT CHANGE RECORD

Issue	Date	Pages	Change Description
1.0	Jun 3, 2019	all	Initial version

TABLE OF CONTENTS

I Document Description

I. 1 Purpose of the Document

This document serves as a record of the processing standards, models & parameters adopted for the generation of the Level-2 gravity field data products by the GRACE-FO Science Data System component at the GFZ German Research Centre for Geosciences. This document is issued once for every release of Level-2 data products generated by GFZ. That release number is included in the title of this document and refers to the field *rr* in the generic Level-2 product name (see Section I.2, *AD[1]*)

PID-2_YYYYDOY-YYYYDOY_dddd_GFZOP_mmmm_rrvv

where

PID	is a 3-character product identification mnemonic
-2	denotes that the product is a Level-2 product
YYYYDOY-YYYYDOY	specifies the date range (in year and day-of-year format) of the data used in creating this product
dddd	specifies the gravity mission
GFZOP	is the institution specific string for GFZ
mmmm	is a 4-character mnemonic used to identify the characteristics of the gravity solution
rrvv	is a 2-digit (leading-zero-padded) release number and 2-digit (leading-zero-padded) version number

The corresponding GFZ Release 06 (RL06) data files are related to the following data sets denoted by the product identifier (*PID*) which are published via GFZ Data Services:

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GAA-Files (*PID = GAA*):

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I. 2 Applicable Documents

This document may be used in conjunction with:

AD[1]	GRACE-FO Level-2 Gravity Field Product User Handbook (JPL D-103922)
AD[2]	GRACE-FO CSR Level-2 Processing Standards Document For Level-2 Product Release 06 (GRACE-FO D-103920)
AD[3]	GRACE-FO JPL Level-2 Processing Standards Document For Level-2 Product Release 06 (JPL D-103921)
AD[4]	GRACE 327-750, Product Description Document for AOD1B Release 06 (Rev. 6.1)
AD[5]	GRACE-FO Level-1 Data Product User Handbook (JPL D-56935)
AD[6]	Description of Calibrated GRACE-FO Accelerometer Data Products (ACT) - Level-1 Product Version 04 (JPL D-103863)
AD[7]	Release Notes for GFZ GRACE-FO Level-2 Products – version RL06
AD[8]	GRACE-FO SDS Newsletters

I. 3 Citation of the Document

Please cite this document as follows, if you work with data related to Level-2 Product Release 06:

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I. 4 Previously Issued Versions of the Document

This document has not been previously issued since product release 06 is the initial release of GRACE-FO Level-2 products.

II Processing Background

II. 1 Two-Step Approach

GFZ Level-2 products are calculated with GFZ's EPOS (Earth Parameter and Orbit System) software suite using the "two-step method" as e.g. already applied for CHAMP data processing (*Reigber et al. (2002)*, *Reigber et al. (2003)*):

> Step 1: adjustment of the high-flying GPS spacecraft orbit and clock parameters (GPS constellation) from ground-based tracking data.
>
> Step 2: GRACE-FO orbit determination and computation of observation equations with fixed GPS constellations from step 1.

Orbital arcs during GRACE-FO orbit determination have a nominal length of 24 hours. In case of e.g. data gaps or insufficient data quality, the arc length can be shorter; however, the minimum arc length is defined to be 3 hours.

II. 2 Input data

For GRACE-FO RL06 Level-2 products Level-1B instrument data of release 04 (ACT1B, GNV1B, GPS1B, KBR1B and SCA1B) (see *AD[5]*) and non-tidal atmosphere and ocean corrections from AOD1B product release 06 have been used (see *AD[4]*).

GRACE-FO GPS code and phase observations have been used undifferenced and by means of the ionosphere-free (L3) linear combination. Azimuth- and elevation-dependent phase center variations for GPS code and phase observations have been calculated and applied for each individual Level-2 product. For the geometrical offset between the satellites' center of mass and the reference point of the main GPS antennas the values 260.2357/-1.283/-388.248 mm for GRACE-FO spacecraft 1 (GF1) and 260.0443/-1.079/-387.4555 mm for GF2 have been applied for the X/Y/Z components in the satellite reference frame. For the GPS antenna phase center offset the values 0/0/-98 mm for L1 frequency and 0/0/-104 mm for L2 frequency are used for the X/Y/Z components in the satellite reference frame for both GF1 and GF2.

II. 3 Solution Space and Methodology

RL06 Level-2 products are generated in two versions: (1) up to degree and order 60x60 and (2) up to degree and order 96x96. For months with short-period repeat orbits, it might be possible that only Level-2 products up to degree and order 60x60 are published. All RL06 Level-2 products are the outcome of an unconstrained linearized least-squares adjustment.

II. 4 Modifications w.r.t. the GFZ GRACE Release 06 Processing

The most important modifications w.r.t. the GFZ GRACE RL06 time series (Dahle et al. 2018) are as follows:

Changes in the force models:

- The time-variable gravity background field was changed from GFZ RL05a Level-2 gravity fields, filtered with DDK1 (Kusche 2007), to a climatology model based on GFZ GRACE RL06 Level-2 gravity fields (see Section III.2.1).

Changes in the observation model:

- The parameterization of the accelerometers has been changed from estimating only the diagonal elements of the scale factor matrix to estimating a fully-populated scale factor matrix (see Section III.3).

III Orbit dynamics models

III. 1 Equations of Motion

The equations of motion for both GRACE-FO satellites are identical in mathematical form. In the remainder of this chapter, the equations will be provided for a single Earth orbiting satellite, with the understanding that the same equations apply to both GRACE-FO satellites. Where appropriate, the parameters or conditions unique to each satellite will be specified.

In the inertial frame the 2nd derivative of the satellite position vector $\ddot{\vec{r}}$ is a function of the time-varying force field $\vec{F}(t,\vec{r},\dot{\vec{r}})$ and the satellite mass m

$$\ddot{\vec{r}} = \vec{F}(t,\vec{r},\dot{\vec{r}})/m = \vec{f}_g + \vec{f}_{ng} + \vec{f}_{emp}$$

The subscript “g” denotes gravitational accelerations; “ng” denotes the acceleration due to the non-gravitational or skin forces; and “emp” denotes certain empirically modeled forces designed to overcome deficiencies in the remaining force models.

III.1.1 Time Systems

The independent variable in the equations of motion is the TDT (Terrestrial Dynamical Time). The relationship of this abstract, uniform time scale to other time systems is well known. The table below shows the relationship between various time systems and the contexts in which they are used.

System	Relations	Notes	Standards
TAI	Fundamental time system	International Atomic Time	n/a
UTC	UTC = TAI - n1 (Time-tag for saving intermediate products)	n1 are the Leap Seconds	Tables from *IERS 2010*
UT1	Calculated by applying corrections to UTC – used for precise calculation of the spin orientation of the Earth	Tabular UT1 corrections	*IERS EOP14 C04*
		Diurnal tidal variations adapted from *Ray et al. (1994)* 71 constituent model.	Similar to *IERS 2010* Table 8.3 (p129).
		Libration Corrections – 11 largest corrections to IAU 2000.	*IERS 2010*
TDT	TDT = TAI + 32.184s	This is the independent variable for orbit integration.	n/a
GPS	GPS = TAI - 19s	The relationship between GPS and TAI is fixed at 19s	GPS time is the standard of GRACE-FO observations time tagging (Time-tags in sec since 12:00 Jan 01, 2000 GPS Time).

III. 2 Gravitational Forces

The gravitational accelerations are the sum of planetary perturbations (including the sun and the moon) and the geopotential perturbations. The vector of planetary perturbations is evaluated using the planetary ephemerides (see Section III.2.6). The geopotential itself is represented in a spherical harmonic series with time-variable coefficients, to a specified maximum degree and order. The geopotential at an exterior field point, at time t, is expressed as

$$U_s(r,\varphi,\lambda,t) = \frac{GM_e}{r}\overline{C}_{00} + \frac{GM_e}{r}\sum_{l=2}^{N_{max}}\left(\frac{a_e}{r}\right)^l \sum_{m=0}^{l} \overline{P}_{lm}(\sin\varphi)\left[\overline{C}_{lm}(t)\cos m\lambda + \overline{S}_{lm}(t)\sin m\lambda\right]$$

where r is the geocentric radius, and (φ,λ) are geographic latitude and longitude, respectively, of the field point.

The model used for propagation of the equations of motion of the satellites is called the Background Gravity Model. This concept, and its relation to GRACE-FO estimates, is described further in *AD[1]*. The details of the background gravity models are provided in this document.

III.2.1 Static & Time-variable Geopotential

To compute the static geopotential, the EIGEN-6C4 model (*Förste et al. (2014)*) is used (see table below).

Parameter	Value	Remarks
GM_e	3.986004415E+14 m^3/s^2	taken from EIGEN-6C4
a_e	6378136.46 m	taken from EIGEN-6C4
N_{max}	200	fully normalized coefficients (see Note 1) taken from EIGEN-6C4
Note 1: The normalization conventions are as defined in *IERS 2010*, Section 6, Eqs 6.1 – 6.3.		

In order to optimize the data screening the time-variable part of the geopotential is modeled by a DDK5 filtered (Kusche 2007) climatology (linear trend, annual and semi-annual signal) up to degree and order 50 estimated from monthly GRACE GFZ RL06 gravity field solutions. Note that this time-variable part of the geopotential background model is only used during data screening; during gravity field parameter estimation no time-variable background model is used.

III.2.2 Solid Earth Tides

In order to consider the contribution of solid Earth tides, corresponding accelerations are computed and added to the geopotential accelerations. This approach is equivalent to applying corrections to geopotential coefficients as specified in *IERS 2010*, Section 6.2.

Model	Description	Notes
Planetary Ephemerides	DE430	see Section III.2.6
Frequency Independent Terms	Corrections to C_{20}, C_{21}, S_{21}, C_{22}, S_{22}, C_{30}, C_{31}, S_{31}, C_{32}, S_{32}, C_{33}, S_{33}, C_{40}, C_{41}, S_{41}, C_{42}, S_{42}	*IERS 2010*
	External Potential Love Numbers	*IERS 2010*
	Anelasticity Contributions	*IERS 2010*
Frequency Dependent Terms	Tidal corrections to C_{20}, C_{21}, S_{21}, C_{22}, S_{22}	21 long-periodic, 48 diurnal and 2 semi-diurnal tides used
	Anelasticity Contributions	*IERS 2010*
Permanent Tide in C_{20}	4.1736E-9	Included in these contributions (is implicitly removed from the value of the mean C_{20})

III.2.3 Ocean Tides

In order to consider the contribution of ocean tides, corresponding accelerations are computed and added to the geopotential accelerations. This approach is equivalent to applying corrections to geopotential coefficients as specified in *IERS 2010*, Section 6.3.

Model	Description	Notes
Tidal Arguments & Amplitudes/Phases	*Doodson (1921)* *Schwiderski (1983)*	
Tidal Harmonics	Multi-satellite selection of harmonics for discrete tidal lines from FES2014 model (*Carrere et al. 2016*).	Containing 34 tidal components (8 long periodic, 6 diurnal, 12 semi-diurnal, and 8 with higher frequency or non-linear). Admittance theory used to interpolate the secondary waves. Max. deg./ord. = 100.

III.2.4 Atmosphere & Oceanic Variability

The non-tidal variability in the atmosphere and oceans is removed using the AOD1B RL06 product. This product is based on a combination of atmospheric fields provided by ECMWF and the ocean model MPIOM forced with the same atmospheric fields. Note that atmospheric tides and their oceanic response are removed from the AOD1B RL06 products. Details of this product and its generation are given in *AD[4].*

This component of the geopotential is ingested as 3-hourly time series up to degree and order 180. The value of the harmonics at intermediate epochs is obtained by linear interpolation between the bracketing data points.

III.2.5 Potential Variations caused by Rotational Deformation (Solid Earth Pole Tide)

In order to consider the contribution of rotation deformation forces, corresponding accelerations are computed and added to the geopotential accelerations. This approach is equivalent to applying additions to geopotential coefficients C_{21} and S_{21} from an -elastic Earth model as specified in *IERS 2010*, Section 6.4.

Model	Description	Notes
An-elastic Earth Model Contribution to C_{21} & S_{21}	Scaled difference between epoch pole position (x_p, y_p) and mean pole.	*IERS 2010*
Polar Motion	Tabular input	*IERS EOP 14 C04*
Mean Pole	Linear model	*IERS 2010*[(1)]
Constant Parameters	Love number K_2 = 0.3077 + 0.0036 * i	*IERS 2010*

[(1)]: See update at http://iers-conventions.obspm.fr/chapter7.php

III.2.6 N-Body Perturbations

Unlike the geopotential accelerations, the perturbations due to the Sun, Moon and 5 planets (Mercury, Venus, Mars, Jupiter, and Saturn) are directly computed as accelerations acting on the spacecraft. The direct effects of the objects on the satellite are evaluated using point-mass attraction formulas. The in-direct effects due to the acceleration of the Earth by the planets are also modeled as point-mass interactions. However, for the Moon, the indirect effects include the interaction between a point-mass perturbing object and an oblate Earth – the so-called Indirect J2 effect.

Model	Description
Third-Body Perturbation	Direct & Indirect terms of point-mass 3rd body perturbations
Indirect J2 Effect	Moon only
Planetary Ephemerides	DE430

III.2.7 General Relativistic Perturbations

The general relativistic contributions to the accelerations are computed as specified in *IERS 2010*, Section 10.3 including Lense-Thirring and de Sitter effects.

III.2.8 Atmospheric Tides

Contributions from atmospheric tides to the geopotential are computed equivalent to those from ocean tides. The corresponding accelerations are based on the model by *Biancale & Bode (2006)* containing amplitudes and phases for atmospheric tides S1 and S2 up to degree 8 and order 5.

III.2.9 Potential Variations caused by Rotational Deformation of Ocean Masses (Ocean Pole Tide)

The centrifugal effect of polar motion on the oceanic mass, which mainly influences geopotential coefficients C_{21} and S_{21}, is corrected using an updated model of *Desai (2002)* which is complete up to degree and order 360, see *IERS 2010*, Section 6.5. Spherical harmonic coefficients of this model up to degree and order 30 are added to the corresponding ocean tide coefficients.

III. 3 Non-Gravitational Forces

The nominal approach is to use the GRACE-FO linear acceleration data $\vec{b}_{acc}$ to model the non-gravitational forces acting on the satellite.

The model used is:

$$\vec{f}_{ng} = q \otimes \left[\vec{b} + {}_{3x3}S\,(\vec{b}_{acc} - \vec{b}_{mean})\right]$$

where the q-operator represents rotations from the inertial frame to the satellite-fixed frame using the GRACE-FO attitude quaternion product; $\vec{b}$ represents an empirical bias vector; $\vec{b}_{mean}$ a corresponding mean value; and the 3x3 matrix S contains the scale factors in along-track, radial and cross-track direction as diagonal elements and their respective correlations as off-diagonal elements.

For the generation of GRACE-FO RL06 Level-2 products 3 biases in along-track and radial direction and 9 biases in cross-track direction are estimated for each orbital arc. Biases are always estimated at the beginning and at the end of an arc and equally spaced in between. The minimum spacing between biases is 3 hours, i.e. the number of estimated biases can be less than written above when the arc length is shorter than the nominal arc length of 24 hours. Additionally, the fully-populated 3x3 scale factor matrix is estimated, either once per orbital arc or once per month. The latter decision is based on the quality of the monthly gravity field solution and can vary from month to month (see *AD[7]* for the corresponding choice for a particular GFZ RL06 Level-2 product).

Note that ACT1B data (see AD[6] for further details) are used. These data are provided with 1 Hz sampling; downsampling to 0.2 Hz by means of simple decimation is applied.

III. 4 Empirical Forces

For the generation of RL06 Level-2 products once-per-revolution periodic (cosine and sine amplitudes) empirical accelerations are estimated in along-track and cross-track direction for each revolution. An a priori sigma of 1E-8 m/s^2 is applied to these empirical parameters.

III. 5 Numerical Integration

The predictor-corrector Cowell formulation is implemented (7^{th} order, fixed step-size (5s in accordance with the GRACE-FO accelerometer data measurement frequency)) used for integration of

a) the satellite equation of motion (position and velocity) and

b) the variational equation of the satellite (dependency of position and velocity on dynamical parameters)

The integration is performed in the Conventional Inertial System (CIS).

IV Earth Orientation & Satellite Attitude

IV. 1 Earth Orientation

Earth Orientation here refers to the model for the orientation of the Earth-fixed reference relative to the quasi-inertial reference. The former are necessary for associating observations, models and observatories to the geographic locations; and the latter for dynamics, integration & ephemerides.

Frame	System	Realization
Inertial	ICRS	J2000.0 (IERS)
Earth-fixed	CTRS	ITRF2014 (IGS14 realization)

The rotation between the Inertial and Earth-fixed frames is implemented as

$$ {}_{3x3}M_{trs}^{crs} = QRW $$

which converts the column array of components of a vector in the terrestrial frame to a column array of its components in the inertial frame. Each component matrix (Q, R or W) is a 3x3 matrix, and is individually described in the following.

The implementation is according to the *IERS 2010* (Section 5).

In the following, R_1, R_2, R_3 refer to the elementary 3x3 rotation matrices about the principal directions X, Y and Z, respectively.

IV.1.1 Transformation matrix (Q) for the celestial motion of the celestial intermediate pole

That matrix is defined as

$$ Q = \begin{pmatrix} 1-ax^2 & -axy & x \\ -axy & 1-ay^2 & y \\ -x & -y & z \end{pmatrix} \cdot R_3(s) $$

(see *IERS 2010*, Section 5.4.4) with *x, y* being the coordinates of the celestial intermediate pole (CIP) and *s* the celestial intermediate origin (CIO) locator (*IERS 2010,* Sections 5.5.4 and 5.5.6). The quantity *a* stands for *1/(1+z)* with

$$ z = \sqrt{1-x^2-y^2} \, . $$

The coordinates of the CIP have the representation

$$ x = x(IAU\,2006/2000) + \delta x $$
$$ y = y(IAU\,2006/2000) + \delta y $$

where the items indexed with IAU2006/2000 are given by a dedicated series expansion and *δx*, *δy* are "celestial pole offsets" monitored and reported by the IERS (*IERS 2010*, Section 5.5.4).

Note that the matrix Q comprehends the former equinox-based transformations of frame bias, precession and nutation (*IERS 2010*, Section 5.9).

IV.1.2 Sidereal Rotation (R)

This rotation is implemented as

$$R = R_3(-ERA)$$

where the Earth Rotation Angle (ERA) is given by the expression

$$ERA = 2\pi(0.7790572732\,640 + 1.0027378119\,1135448 \cdot T_u$$

In the computation of ERA the universal

Quantity	Model	Notes
ERA	Linear polynomial of UT1	*IERS 2010*, Section 5
UT1	3rd order natural spline interpolation	*IERS EOP 14 C04*

IV.1.3 Polar Motion (W)

The Polar Motion component of rotation is implemented as

$$W = R_3(-s')R_1(y_p)R_2(x_p)$$

where s' is the position of the Terrestrial Ephemeris Origin (TEO) on the equator of the Celestial Intermediate Pole (*IERS 2010*, Section 5.5.2) and x_p and y_p are the sum of tidal and libration components of the polar coordinates as well as the daily EOP 14 C04 series published by IERS (*IERS 2010*, Section 5.5.1).

Quantity	Model	Notes
Tabular variations	3rd order spline interpolation	*IERS EOP 14 C04*

IV. 2 Satellite Attitude

The inertial orientation of the spacecraft is modeled using tabular input data quaternions from SCA1B products. The same data (with appropriate definitions) is used for rotating the accelerometer data to inertial frame prior to numerical integration; for making corrections to the ranging observations due to offset between the satellite center of mass & the antenna location; as well as for computing the non-gravitational forces (if necessary).

Note that SCA1B data are provided with 1 Hz sampling; downsampling to 0.2 Hz by means of simple decimation is applied.

V References

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