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GFZ GRACE Level-2 Processing Standards Document for Level-2 Product Release 0005

Scientific Technical Report STR12/02 - Data

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Deutsches GeoForschungsZentrum GFZ

GRACE 327-743
(GR-GFZ-STD-001)

Gravity Recovery and Climate Experiment

GFZ GRACE Level-2 Processing Standards Document

for Level-2 Product Release 0005

(Rev. 1.0, March 17, 2012)

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DOCUMENT CHANGE RECORD

Issue	Date	Pages	Change Description
1.0	Mar 17, 2012	all	Initial version

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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 Science Data System component at the GFZ German Research Centre for Geosciences. GFZ Level-2 products are calculated using the EPOS (Earth Parameter and Orbit System) software suite. This document is issued once for every release of Level-2 data products generated by GFZ. The release number refers to the field *RRRR* in the generic Level-2 product name (see Section I.2, *AD[1]* or *AD[2]*)

PID-2_YYYYDOY-YYYYDOY_DDDD_SSSSS_MMMM_RRRR

Thus, the GFZ release 0005 Level-2 product names are as follows:

PID-2_YYYYDOY-YYYYDOY_DDDD_EIGEN_G----_0005

or

PID-2_YYYYDOY-YYYYDOY_DDDD_EIGEN_GK2-_0005

where

EIGEN = European Improved Gravity model of the Earth by New techniques
G---- = only GRACE data used for this model
GK2- = only GRACE data used for this model, but the model is stabilized (see Section II.3)

The corresponding GFZ release 0005 data files are related to the following data sets denoted by the product identifier (*PID*) which are published via GFZ's Information System and Data Center (ISDC):

GSM-Files (*PID = GX-OG-_2-GSM*):

GRACE Science Data System (2002): *Static Field Geopotential Coefficients estimated from Satellite Data only*, Information System and Data Center, GFZ German Research Centre for Geosciences, GERMANY
DOI: 10.5880/ISDC.GRACE/GX-OG-_2-GSM

GAA-Files (*PID = GX-OG-_2-GAA*):

GRACE Science Data System (2002): *Non-tidal Atmosphere Geopotential Coefficients averaged over certain Time Period*, Information System and Data Center, GFZ German Research Centre for Geosciences, GERMANY
DOI:10.5880/ISDC.GRACE/GX-OG-_2-GAA

GAB-Files (*PID = GX-OG-_2-GAB*):

GRACE Science Data System (2002): *Non-tidal Ocean Geopotential Coefficients averaged over certain Time Period*, Information System and Data Center, GFZ German Research Centre for Geosciences, GERMANY
DOI: 10.5880/ISDC.GRACE/GX-OG-_2-GAB

GAC-Files (*PID = GX-OG-_2-GAC*):

GRACE Science Data System (2002): *Non-tidal Atmosphere and Ocean Geopot. Coeff. averaged over certain Time Period*, Information System and Data Center, GFZ German Research Centre for Geosciences, GERMANY
DOI: 10.5880/ISDC.GRACE/GX-OG-_2-GAC

GAD-Files (*PID = GX-OG-_2-GAD*):

GRACE Science Data System (2002): *Ocean Bottom Pressure Geopot. Coeff. averaged over certain Time Period*, Information System and Data Center, GFZ German Research Centre for Geosciences, GERMANY
DOI: 10.5880/ISDC.GRACE/GX-OG-_2-GAD

I. 2 Applicable Documents

This document may be used in conjunction with:

AD[1] Level-2 Gravity Field Product User Handbook (GRACE 327-734, CSR-GR-03-01)

AD[2] Product Specification Document (GRACE 327-720, CSR-GR-03-02)

AD[3] UTCSR Level-2 Processing Standards Document (GRACE 327-742, CSR-GR-03-03)

AD[4] JPL Level-2 Processing Standards Document (GRACE 327-744)

AD[5] GRACE Gravity Field Solution Data Formats (GRACE 327-732, GR-GFZ-FD-001)

AD[6] AOD1B Product Description Document (GRACE 327-750, GR-GFZ-AOD-0001)

AD[7] GRACE Level 1B Data Product User Handbook (JPL D-22027)

AD[8] Release Notes for GFZ GRACE Level-2 Products – version RL05

AD[9] GRACE 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 0005:

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I. 4 Previously Issued Versions of the Document

This document has been previously issued for the following Level-2 data product releases, in reverse chronological order:

Product Release	Date Document Issued
0004	Feb. 19, 2007
0003	Nov. 04, 2005
0002	Sep. 20, 2005
0001	Nov. 24, 2003

II PROCESSING BACKGROUND

II. 1 TWO-STEP APPROACH

For GRACE Level-2 gravity field product generation the "two-step method" has been applied as 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 from ground-based tracking data.
>
> Step 2: GRACE orbit determination and computation of observation equations with fixed GPS spacecraft positions and clocks from step 1.

While previous releases 0001 and 0002 have been calculated using 1.5 days arcs, the maximum arc length of release 0003 till release 0005 has been set to 1 day.

During the release 0005 adjustment of the GPS sender satellite positions and clocks (step 1) various improvements in the GPS data processing have been adopted leading to a homogeneously reprocessed GPS constellation. This resulted in an improved determination of the GRACE satellite orbits in step 2 which had – in combination with updated release 0005 GRACE processing standards described in this document - a clear impact on the quality of the gravity field models of release 0005.

II. 2 INPUT DATA

For this Level-2 product release GRACE Level 1B instrument data of release 02 (see *AD[7]*) and non-tidal atmosphere and ocean corrections from AOD1B product release 05 have been used (see *AD[6]*).

GRACE high-low GPS code and phase observations have been used un-differenced and only for elevations above 10 degrees of the local horizon of the navigation antennas leading to an almost equally balanced number of GPS observations for GRACE-A and GRACE-B. GFZ-derived azimuth-elevation dependent phase center corrections for GPS-SST observations have been applied. For the GPS phase center the values 0/0/-444 mm have been applied for the X/Y/Z components in the satellite reference frame.

II. 3 STATISTICAL CONSTRAINTS

Release 0005 monthly Level-2 products are generally generated up to degree and order 90 and without any statistical constraints. Only for selected months where limitations in the ground track coverage due to repeat or nearby repeat orbit pattern occur (e.g. in mid 2004), the solutions are stabilized (details can be found in the *AD[8]*). A mean field (to be published later) up to degree and order 180 covering the available time span of monthly release 0005 Level-2 products will also be unconstrained.

II. 4 MODIFICATIONS WRT RELEASE 0004

The most important modifications w.r.t. release 0004 are as follows:

Changes in the force models:

- The static background field was changed from EIGEN-GL04C to EIGEN-6C (see Section III.2.1)
- The secular rates for low degree harmonics as applied for release 0004 are no longer used. Instead, trend coefficients up to degree and order 50 included in the EIGEN-6C model have been applied with a temporal resolution of 1 day (see Section III.2.1)
- Additionally, annual and semi-annual coefficients from EIGEN-6C also up to degree and order 50 have been applied with a temporal resolution of 1 day (see Section III.2.1)
- As the time-variable part of the geopotential background model (trend, annual and semi-annual coefficients from EIGEN-6C) is restored (see Section III.2.1), each gravity field solution can be regarded as mean field over the solution's time span and no reference epochs have to be taken into account anymore (i.e. no secular rates have to be added by the user).
- The ocean tide model was changed from FES2004 to EOT11a (see Section III.2.3)
- The atmospheric and oceanic short-term mass variations are calculated from AOD1B RL05 products (see Section III.2.4).
- The model for planetary ephemerides was changed from DE403 to DE421 (see Section III.2.6).

Changes in the reference frame:

- Implementation of the CIO (Celestial Intermediate Origin) based transformation between celestial and terrestrial reference frame as described in the *IERS Conventions 2010* (named *IERS 2010* in the following) (see Section IV).
- Reprocessed GPS constellation based on IGS08 realization of ITRF 2008.

Changes in the observation model:

- GFZ-derived azimuth-elevation dependent phase center corrections for GRACE-A and –B GPS-SST observations have been applied instead of the ones provided by JPL.
- Accelerometer biases are estimated 1-hourly instead of only at the beginning and end of each orbital arc; accelerometer scale factors are not estimated anymore (see Section III.3).

III ORBIT DYNAMICS MODELS

III. 1 EQUATIONS OF MOTION

The equations of motion for both GRACE 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 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 Independent Variable (Time Systems)

The independent variable in the equations of motion is the TT (Terrestrial 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	TT = TAI + 32.184s	TT the independent variable for orbit integration.	n/a
UTC	TAI = UTC + 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 EOP 08 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*

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GPS	GPS = TT + 19s	The relationship between GPS and TT is fixed to 19s	GPS time is the standard of GRACE 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 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-6C model (*Förste et al. (2011)*) is used (see table below).

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

The time-variable part of the geopotential is represented by the trend, annual and semi-annual coefficients up to degree and order 50 which are part of EIGEN-6C. These coefficients are used to calculate daily corrections to the mean geopotential.

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Note that the time-variable part of the geopotential background model is restored by re-adding its mean over the time span of days used for processing of a specific solution, i.e. there is no difference in interpreting the signal content of release 0005 Level-2 products compared to release 0004!

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	DE 421	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 EOT11a model (*Savcenko & Bosch (2011)*).	Containing 18 waves (8 long periodic, 4 diurnal, 5 semi-diurnal, 1 non-linear). Admittance theory used to interpolate the secondary waves. Max deg/ord = 80.

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III.2.4 Atmosphere & Oceanic Variability

The non-tidal variability in the atmosphere and oceans is removed applying the AOD1B RL05 product. This product is based on a combination of the ECMWF operational atmospheric fields (0.5° spatial and 6h temporal resolution, as AOD1B RL04) and the baroclinic ocean model OMCT (with increased vertical and horizontal resolution and updated parametrization) driven with the same atmospheric fields. Note that the AOD1B product still includes the atmospheric tides. Details of this product and its generation are given in *AD[6]*.

This component of the geopotential is ingested as 6 hourly time series to degree and order 100. 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 (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 unelastic Earth model as specified in *IERS 2010*, Section 6.4.

Model	Description	Notes
Unelastic 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 08 C04*
Constant Parameters	Love number $K_2 = 0.3077 + 0.0036 * i$	*IERS 2010*

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	DE 421

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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 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 attitude quaternion product; $\vec{b}$ represents an empirical bias vector; $\vec{b}_{mean}$ a corresponding mean value and the diagonal of the 3x3 matrix S contains the scale factors in along-track, radial and cross-track direction, respectively (off-diagonal elements are 0).

In principle, both biases and scale factors are estimable parameters. However, as already mentioned in Section II.4, solely 1-hourly biases and no scale factors have been estimated during the generation of release 0005.

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III. 4 Empirical Forces

For this product release, no empirical accelerations are modeled or estimated.

III. 5 Numerical Integration

The predictor-corrector Cowell formulation is implemented (7^{th} order, fixed step-size (5s in accordance with the GRACE 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).

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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	ITRF2008 (IGS08 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

$$x = x(IAU2006/2000) + \delta x$$
$$y = y(IAU2006/2000) + \delta y$$

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

$$ERA = 2\pi(0.7790572732640 + 1.00273781191135448 \cdot T_u$$

In the computation of ERA the universal time T_u = UT1 is interpolated using a 3rd order natural spline from the tabulated EOP values of the IERS EOP 08 C04 series to the actual epochs. Tidal and libration corrections are added to UT1 *(IERS 2010*, Section 5.5.3).

Quantity	Model	Notes
ERA	Linear polynomial of UT1	*IERS 2010*, Section 5
UT1	3rd order natural spline interpolation	*IERS EOP 08 C04*

IV.1.3 Polar Motion (W)

The Polar Motion component of rotation is implemented as

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

Here 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 08 C04 series published by IERS (*IERS 2010*, Section 5.5.1).

Quantity	Model	Notes
Tabular variations	3rd order spline interpolation	*IERS EOP 08 C04*

IV. 2 SATELLITE ATTITUDE

The inertial orientation of the spacecraft is modeled using tabular input data quaternions. 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).

At epochs where the GRACE quaternion product is not available, linear interpolation between adjacent values is used.

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