

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

Gravity Recovery and Climate Experiment

GFZ Level-2 Processing Standards Document

For Level-2 Product Release 0003

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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 GeoForschungsZentrum Potsdam (GFZ). GFZ Level-2 products are calculated using EPOS (Earth Parameter and Orbit System) software. 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 *GRACE Product Specification Document* or *GRACE Level-2 User Handbook*)

PID-2_YYYYDOY-YYYYDOY_DDDD_SSSSS_MMMM_RRRR

Thus, the GFZ release 0003 Level-2 product names are as follows

PID-2_YYYYDOY-YYYYDOY_DDDD_EIGEN_G----_0003

where

EIGEN = European Improved Gravity model of the Earth by New techniques
G---- = only GRACE data used for this model

This document may be used in conjunction with:

1. GRACE Product Specification Document (327-720)
2. GRACE Gravity Field Solution Data Formats (327-732, GR-GFZ-FD-001)
3. GRACE Level-2 User Handbook (327-734)
4. GRACE UTCSR L-2 Processing Standards Document (327-742)
5. GRACE JPL L-2 Processing Standards Document (327-744)
6. GRACE AOD1B Product Description Doc (327-750, GR-GFZ-AOD-001)

I. 2 DOCUMENT CHANGE HISTORY

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

Product Release	Date Document Issued	Remarks
0002	Sep 20, 2005	
0001	Nov. 24, 2003	

The principal changes since the previous issue of this document are described in the remainder of this section, if necessary.

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 has been truncated to 1 day.

During the adjustment of the GPS sender satellites and clocks (step 1) an improved ambiguity fixing method has been applied for the determination of GPS phase ambiguities between GPS sender satellites and ground receivers resulting in significantly improved GPS sender ephemeris and clocks. This leads to improved determination of the GRACE satellite orbits in step 2 which has a clear impact on the quality of the gravity field models of release 003.

II. 2 INPUT DATA

For this level-2 product release GRACE level 1B instrument data of release 00 and 01 (since January 1, 2005) and non-tidal atmosphere and ocean corrections from AOD1B product release 03 have been used (see AOD1B Product Description Doc).

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.

II. 3 STATISTICAL CONSTRAINTS

Release 0003 monthly level-2 products ($n_{\max}=120$) are generally generated 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 2005), the solutions are constrained (Details can be found in the corresponding GFZ GRACE Level-2 release notes). The mean field ($n_{\max}=120$) is unconstrained.

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 \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
UT1	Calculated by applying corrections to UTC – used for precise calculation of the spin orientation of the Earth	Tabular UT1 corrections	<i>IERS C04</i>
		Diurnal tidal variations adapted from <i>Ray et al. (1994)</i> eight constituent model.	Similar to <i>IERS 96</i> Table 8.3 (p76).
		Nutation Corrections – 25 largest corrections to IAU 1980.	<i>IERS 96</i>

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).
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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 chapter N-Body Perturbations). 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

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

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 the *GRACE Level-2 User Handbook*. The details of the background gravity models are provided in this document.

III.2.1 Mean Geopotential & Secular Changes

Parameter	Value	Remarks
GM_e	3.986004415E+14	
a_e	6378136.46 m	
N_{\max}	150	EIGEN_CG03C coefficients (updated model of EIGEN_CG01C, Reigber et al., 2005)
$\dot{\bar{C}}_{20}$.11628E-10	
$\dot{\bar{C}}_{30}$.49000E-11	
$\dot{\bar{C}}_{40}$.47000E-11	

Note 1: The normalization conventions are as defined in IERS96, Chapter 6, Eqs 2-3.
Note 2: Note that the degree 1 terms are fixed to 0.0

III.2.2 Solid Earth Tides

Solid Earth tidal contribution to the geopotential are computed approximately as specified in Chapter 7, *IERS Conventions*. Corrections to specific spherical harmonic coefficients are computed and added to the mean field coefficients.

Model	Description	Notes
Planetary Ephemerides	DE-405	see N-Body Perturbations
Frequency Independent Terms	Contributions from Degree 2 to degree 4 Tides	IERS 2003
	External Potential Love Numbers	IERS 2003
	Anelasticity Contributions	IERS 2003
Frequency Dependent Terms	Tidal corrections to C(2,0), C(2,1), S(2,1), C(2,2), S(2,2)	21 long-periodic, 48 diurnal and 2 semi-diurnal tides used
	Anelasticity Contributions	IERS 2003
Permanent Tide in \bar{C}_{20}	4.173E-9	Included in these contributions (is implicitly removed from the value of the mean C20)

III.2.3 Ocean Tides

The ocean tidal contributions to the geopotential are computed as specified in Chapter 6, *IERS 2003 Conventions*, Eqs 13. Corrections to specific spherical harmonic coefficients of arbitrary (selectable) degree and order are computed and added to the mean field coefficients.

Model	Description	Notes
Tidal Arguments & Amplitudes/Phases	Doodson (1921) Schwiderski (1983)	
Tidal Harmonics	Multi-satellite selection of harmonics for discrete tidal lines from FES2004 model (Lefevre, 2005).	Containing 17 waves (8 long periodic, 4 diurnal, 5 semi-diurnal). Admittance theory used to interpolate the secondary waves. Max degree =80, max order = 80.

III.2.4 Atmosphere & Oceanic Variability

The non-tidal variability in the atmosphere and oceans is removed through using the AOD1B RL03 product. This product is a combination of the ECMWF operational atmospheric fields (0.5° spatial and 6h temporal resolution) and a baroclinic ocean model driven with this atmospheric fields. Note that the AOD1B product still includes the atmospheric tides, but, in contrast to release 0001 and 0002 products, both still generated with AOD1B RL01 products, a double bookkeeping of the S2 tide with the ocean tide model was avoided in release 0003, because the S2 tide was filtered from surface pressure data before forcing the baroclinic ocean model. Details of this product and its generation are given in the *AOD1B Product Description Document (GRACE 327-750, Rev. 2.0)*.

This component of the geopotential is ingested as 6 hourly time series to degree and order 50. 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)

The rotation deformation forces are computed as additions to spherical harmonic coefficients \bar{C}_{21} and \bar{S}_{21} , from an unelastic Earth model, as specified in Chapter 6, IERS 2003 Standards.

Model	Description	Notes
Unelastic Earth Model Contribution to C21 & S21	Scaled difference between epoch pole position (xp,yp) and mean pole.	IERS 2003
Polar Motion	Tabular input	<i>IERS C04</i>
Constant Parameters	Love number $K_2 = 0.3077 + 0.0036 * i$ Scale factor calculated in EPOS-OC	IERS 2003

III.2.6 N-Body Perturbations

Unlike the geopotential accelerations, the perturbations due to the Sun, Moon and 5 planets (Mercury, Venus, Mars, Jupiter, 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	Notes
Third-Body Perturbation	Direct & Indirect terms of point-mass 3 rd body perturbations	
Indirect J2 Effect	Moon only	
Planetary Ephemerides	DE-405	

III.2.7 General Relativistic Perturbations

The general relativistic contributions to the accelerations are computed as specified in Chapter 11, *IERS 96*.

III.2.8 Atmospheric Tides

Contributions from atmospheric tides to the geopotential are computed equivalent to ocean tides. Corrections to specific spherical harmonic coefficients evaluated up to degree 8 and order 5 are computed and added to the S_1 and S_2 mean field coefficients. Amplitudes and phases are taken from Bode and Biancale (2005)

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 \bar{C}_{21} and \bar{S}_{21} geopotential coefficients, is corrected using an updated model of Desai (2002) which is complete up to degree and order 100 (the adaption of the model into the IERS conventions is in preparation).

Corrections to the static spherical harmonic coefficients are computed up to degree and order 30 and added to the mean field 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:

$$\vec{f}_{ng} = \mathbf{q} \otimes [\vec{b}_{+3 \times 3} \mathbf{S} (\vec{b}_{acc} - \vec{b}_{mean})]$$

where the \mathbf{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; $\bar{\mathbf{b}}_{\text{mean}}$ 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).

The bias and scale factors are estimable parameters.

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 (7th order, fixed step-size (5 second 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)

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	ITRF-2000

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

$${}_{3 \times 3} M_{trs}^{crs} = PNRW$$

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 is itself a 3x3 matrix, and is now individually described.

Option 1 offered in the *IERS 96 Conventions* (Chapter 5) is implemented.

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 *Precession (P)*

The IAU 1976 Precession is modeled as

$$P = R_3(\zeta_A) R_2(-\theta_A) R_3(z_A)$$

where the component angles are evaluated using formulas in IERS conventions 1996. Reference epoch 2000.0 is used. The independent variable is TT since epoch J2000.0 (noon, 01-Jan-2000).

IV.1.2 *Nutation (N)*

The IAU 1980 Nutation model is used along with the associated corrections which are observed from VLBI and provided by IERS.

$$N = R_1(-\varepsilon_A)R_3(\Delta\psi)R_1(\varepsilon_A + \Delta\varepsilon_A)$$

Quantity	Model	Notes
Tabular variations	Linear interpolation	<i>IERS C04</i>

IV.1.3 Sidereal Rotation (*R*)

This rotation is implemented as

$$R = R_3(-GMST + Corr)$$

where the Greenwich Mean Sidereal Time (GMST) and the corrections are calculated as follows:

Quantity	Model	Notes
GMST	Polynomial	USNO Circular 163, Page A3
Equatorial components of precession & nutation	<i>(Aoki & Kinoshita, 1983)</i>	IERS 96
Tabular variations	Linear interpolation	<i>IERS C04</i>

IV.1.4 Polar Motion (*W*)

The Polar Motion component of rotation is implemented as

$$W = R_1(y_p)R_2(x_p)$$

Quantity	Model	Notes
Tabular variations	Linear interpolation	<i>IERS C04</i>

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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