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

Gravity Recovery and Climate Experiment

GFZ Level-2 Processing Standards Document

For Level-2 Product Release 0004

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DOCUMENT CHANGE RECORD

Issue	Date	Pages	Change Description
1.0	Feb 19, 2007	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 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 0004 Level-2 product names are as follows

PID-2_YYYYDOY-YYYYDOY_DDDD_EIGEN_G----_0004

or

PID-2_YYYYDOY-YYYYDOY_DDDD_EIGEN_GK2-_0004

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 constrained (see Chapter II.3)

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
0003	Nov. 04, 2005	
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 and release 0004 have 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 already in release 0003 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 had a clear impact on the quality of the gravity field models of release 0003. Additionally, for release 0004 the GRACE processing standards described in this document have been adopted resulting in homogeneously processed GPS sender and LEO satellites.

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 04 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. JPL-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 0004 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 2004), the solutions are constrained (details can be found in the corresponding GFZ GRACE Level-2 release 0004 notes). The mean field (n_{max}=120) will be unconstrained.

II. 4 MODIFICATIONS WRT RELEASE 0003

The most important modifications w.r.t. release 0003 are

Changes in the force models:

- The static background field was changed from EIGEN-CG01C to EIGEN-GL04C (see Section III.2.1)
- The secular rates for C_{21} and S_{21} were included (see Section III.2.1)
- The reference epoch for secular rates was changed from 1997.0 to 2000.0 (see Section III.2.1). This may cause modifications in the users´ software implementation!
- The K_2 tide of the FES2004 model was corrected, the M_4 tide additionally implemented (see Section III.2.3)
- The atmospheric and oceanic short-term mass variations are calculated from AOD1B RL04 products. A re-adding of GAB products, as recommended in TN04 in case of land applications, is no longer necessary (see Section III.2.4).
- The relativity was extended by Lense-Thirring and de Sitter effects (see Section III.2.7)
- A software bug in the implementation of the ocean pole tide model was corrected (see Section III.2.9).

Changes in the reference frame:

- Implementation of the IERS2003 nutation and precession model (see Section IV)
- The numerical integration of the orbits and variational equations is now performed in the Conventional Inertial System (CIS). Until release 0003 it was performed in the quasi-inertial True of Date System (TDS) (see Section III.5).

Changes in the observation model:

- JPL-derived azimuth-elevation dependent phase center corrections for GPS-SST observations have been applied.

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

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 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

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

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 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	*IERS2003*
a_e	6378136.46	*IERS2003*
$N_{\max}$	150	EIGEN_GL04C coefficients (Förste et al., 2007)
$\dot{\overline{C}}_{20}$	1.162755E-11	*IERS2003, Reference epoch 2000.0*
$\dot{\overline{C}}_{21}$	-.337000E-11	*IERS2003, Reference epoch 2000.0*
$\dot{\overline{S}}_{21}$	1.606000E-11	*IERS2003, Reference epoch 2000.0*
$\dot{\overline{C}}_{30}$	.49000E-11	*Reference epoch 2000.0*

$\dot{C}_{40}$	.47000E-11	*Reference epoch 2000.0*
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 Note 3: The reference epoch up to release 0003 was 1997.0!		

III.2.2 Solid Earth Tides

Solid Earth tidal contribution to the geopotential is 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 $\overline{C}_{20}$	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 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.

III.2.4 Atmosphere & Oceanic Variability

The non-tidal variability in the atmosphere and oceans is removed through using the AOD1B RL04 product. This product is a combination of the ECMWF operational atmospheric fields (0.5° spatial and 6h temporal resolution) and the baroclinic ocean model OMCT 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 and 0004, because the S2 tide was filtered from surface pressure data before forcing the baroclinic ocean model. Additionally, a mass conserving approach was again applied to calculate oceanic mass variations. Therefore, in contrast to GFZ release 0003 products (see TN04), the GAB products have NOT to be added back to the release 0004 GSM products in case of land applications! Details of this product and its generation are given in the *AOD1B Product Description Document (GRACE 327-750).*

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 $\overline{C}_{21}$ and $\overline{S}_{21}$, 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	*IERS C04*
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, 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	Notes
Third-Body Perturbation	Direct & Indirect terms of point-mass 3rd 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 the IERS2003 conventions including Lense-Thirring and de Sitter effects.

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 $\overline{C}_{21}$ and $\overline{S}_{21}$ 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:

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

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).

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 (7^{th} 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)

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	ITRF-2000

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

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

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 (B, P, N, R or W) is a 3x3 matrix, and is individually described in the following.

The implementation is according to the *IERS 2003 Conventions* (Chapter 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 Frame-Bias Matrix (B)

The frame bias matrix is defined as

$$ B = R_3(-d\alpha_0)R_2(-d\psi_0 \sin\varepsilon_0 - \delta X)R_1(d\varepsilon_0 + \delta y) $$

Here $d\alpha_0$, $d\psi_0$ and $d\varepsilon_0$ are the frame biases in right ascension, the longitude and the obliquity, respectively at the basic epoch J2000.0. The quantities δX, δY are daily tabulated celestial pole offsets determined from VLBI observations published by the IERS within EOPC04 series. All this has been implemented according the IAU2000 convention.

Quantity	Model	Notes
Tabular variations	3rd order Spline interpolation	*IERS C04*

IV.1.2 Precession (P)

The IAU 2000 Precession is modeled as

$$P = R_1(-\varepsilon_0)R_3(\psi_A)R_1(\omega_A)R_3(-\chi_A)$$

where the component angles are evaluated using formulas given in the IERS conventions 2003. Reference epoch 2000.0 is used. The independent variable is TT since epoch J2000.0 (noon, 01-Jan-2000).

IV.1.3 Nutation (N)

The IAU 2000 Nutation model is used. The associated corrections in nutation which are observed from VLBI and provided by IERS do no longer appear in the nutation matrix (N), but rather in the frame bias matrix (B) as δX, δY.

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

The quantities Δψ and Δε comprehend the lunisolar as well as the planetary nutation terms.

IV.1.4 Sidereal Rotation (R)

This rotation is implemented as

$$R = R_3(-GMST + q(t) + \Delta\psi \cdot \cos(\varepsilon_A))$$

where the Greenwich Mean Sidereal Time (GMST) is the sum

$$GMST = GST + p(t)$$

of the Greenwich Sidereal Time (GST) and a polynomial correction p(t). q(t) is a trigonometric polynomial of lunisolar and planetary terms. Δψ is the nutation in the longitude and ε_A is the obliquity of the ecliptic at the epoch t. In the computation of GST the universal time UT1 is interpolated using a 3rd order natural spline from the tabulated EOP values of the IERS C04 series to the actual epochs.

Quantity	Model	Notes
GST	Linear polynomial of UT1	IERS 2003, Chapter 5
p(t)	Polynomial	IERS 2003, Chapter 5
q(t)	Trigonometric polynomial of lunisolar/planetary terms	IERS 2003, Chapter 5

UT1	3rd order natural spline interpolation	IERS C04 series

IV.1.5 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 (CIP) and X_p and Y_p are the sum of tidal and nutational components of the polar coordinates as well as the daily EOPC04 series published by IERS.

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