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(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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Frank Flechtner
GeoForschungszentrum Potsdam
Department 1: Geodesy and Remote Sensing
Prepared by:

Frank Flechtner, GFZ
GRACE Deputy Science Operations Manager

Contact Information:
GeoForschungsZentrum Potsdam
Department 1: Geodesy and Remote Sensing
c/o DLR Oberpfaffenhofen
D-82234 Wessling, Germany
Email: flechtne@gfz-potsdam.de

Reviewed by:

Roland Schmidt, GFZ
Heribert Meixner, GFZ
Hans Neumayer, GFZ

Approved by:

Byron D. Tapley, UTCSR
GRACE Principal Investigator

Christoph Reigber, GFZ
GRACE Co-Principal Investigator
### Document Change Record

<table>
<thead>
<tr>
<th>Issue</th>
<th>Date</th>
<th>Pages</th>
<th>Change Description</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>Sep 20, 2005</td>
<td>all</td>
<td>Initial version</td>
</tr>
<tr>
<td>1.1</td>
<td>Nov 04, 2005</td>
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<td>Updated L2 file name convention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>Updated chapter II.3</td>
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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:

<table>
<thead>
<tr>
<th>Product Release</th>
<th>Date Document Issued</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0002</td>
<td>Sep 20, 2005</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>Nov. 24, 2003</td>
<td></td>
</tr>
</tbody>
</table>
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 $\ddot{\mathbf{r}}$ is a function of the time-varying force field $\ddot{\mathbf{r}} = \ddot{\mathbf{F}}(t, \mathbf{r}, \dot{\mathbf{r}})$ and the satellite mass $m$

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

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.

<table>
<thead>
<tr>
<th>System</th>
<th>Relations</th>
<th>Notes</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAI</td>
<td>$TT = TAI + 32.184s$</td>
<td>TT the independent variable for orbit integration.</td>
<td>n/a</td>
</tr>
<tr>
<td>UTC</td>
<td>$TAI = UTC + \Delta l$ (Time-tag for saving intermediate products)</td>
<td>$\Delta l$ are the Leap Seconds</td>
<td>Tables from IERS</td>
</tr>
<tr>
<td>UT1</td>
<td>Calculated by applying corrections to UTC – used for precise calculation of the spin orientation of the Earth</td>
<td>Tabular UT1 corrections</td>
<td>$IERS 96$ Table 8.3 (p76).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diurnal tidal variations adapted from Ray et al. (1994) eight constituent model.</td>
<td>Similar to $IERS 96$ Table 8.3 (p76).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nutation Corrections – 25 largest corrections to IAU 1980.</td>
<td>$IERS 96$</td>
</tr>
</tbody>
</table>
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

\[
U(r, \varphi, \lambda, t) = \frac{GM_\odot}{r} C_{00} + \frac{GM_\odot}{r} \sum_{i=2}^{N_{\text{max}}} \left( \frac{a_i}{r} \right)^i \sum_{m=0}^{\min(l, m)} \bar{P}_{lm}(\sin \varphi) [\bar{C}_{lm}(t) \cos m\lambda + \bar{S}_{lm}(t) \sin m\lambda]
\]

where \( r \) is the geocentric radius, and \((\varphi, \lambda)\) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( GM_\odot )</td>
<td>( 3.986004415 \times 10^{14} )</td>
<td></td>
</tr>
<tr>
<td>( a_e )</td>
<td>( 6378136.46 ) m</td>
<td></td>
</tr>
<tr>
<td>( N_{\text{max}} )</td>
<td>150</td>
<td>EIGEN_CG03C coefficients (updated model of EIGEN_CG01C, Reigber et al., 2005)</td>
</tr>
<tr>
<td>( \bar{C}_{20} )</td>
<td>( 1.1628 \times 10^{-12} )</td>
<td></td>
</tr>
<tr>
<td>( \bar{C}_{30} )</td>
<td>( 4.9000 \times 10^{-12} )</td>
<td></td>
</tr>
<tr>
<td>( \bar{C}_{40} )</td>
<td>( 4.7000 \times 10^{-12} )</td>
<td></td>
</tr>
</tbody>
</table>
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.

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

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.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Arguments &amp; Amplitudes/Phases</td>
<td>Doodson (1921) / Schwiderski (1983)</td>
<td></td>
</tr>
<tr>
<td>Tidal Harmonics</td>
<td>Multi-satellite selection of harmonics for discrete tidal lines from FES2004 model (Lefevre, 2005).</td>
<td>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.</td>
</tr>
</tbody>
</table>
### 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 $C_{21}$ and $S_{21}$, from an unelastic Earth model, as specified in Chapter 6, IERS 2003 Standards.

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

### 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.
### 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 $C_{21}$ and $S_{21}$ 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:

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

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; \( \mathbf{b}_{\text{mean}} \) 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.

<table>
<thead>
<tr>
<th>Frame</th>
<th>System</th>
<th>Realization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial</td>
<td>ICRS</td>
<td>J2000.0 (IERS)</td>
</tr>
<tr>
<td>Earth-fixed</td>
<td>CTRS</td>
<td>ITRF-2000</td>
</tr>
</tbody>
</table>

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

\[ 3 \times 3 M_{crs}^{trs} = PNRW \]

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

\[ P = R_3(z_3)R_2(-\theta_3)R_1(z_2) \]

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.
\[ N = R_1(\varepsilon_A)R_3(\Delta \psi)R_1(\varepsilon_A + \Delta \varepsilon_A) \]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabular variations</td>
<td>Linear interpolation</td>
<td>IERS C04</td>
</tr>
</tbody>
</table>

**IV.1.3 Sidereal Rotation (R)**

This rotation is implemented as

\[ R = R_3(-\text{GMST} + \text{Corr}) \]

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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMST</td>
<td>Polynomial</td>
<td>USNO Circular 163, Page A3</td>
</tr>
<tr>
<td>Equatorial components of precession &amp; nutation</td>
<td>(Aoki &amp; Kinoshita, 1983)</td>
<td>IERS 96</td>
</tr>
<tr>
<td>Tabular variations</td>
<td>Linear interpolation</td>
<td>IERS C04</td>
</tr>
</tbody>
</table>

**IV.1.4 Polar Motion (W)**

The Polar Motion component of rotation is implemented as

\[ W = R_1(\gamma_p)R_2(\chi_p) \]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabular variations</td>
<td>Linear interpolation</td>
<td>IERS C04</td>
</tr>
</tbody>
</table>

**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.
V REFERENCES


Bode A., Biancale, R., Mean and Seasonal Atmospheric Tide Models based on 3-hourly and 6-hourly ECMWF Surface Pressure Data, GFZ Potsdam Technical Note (in preparation), 2005


Doodson, A.T.: The harmonic development of the tide-generating potential; Proc. R. Soc. A., 100, pp 305-329,1921


Lefevre, F., FES2004 package for Jason and ENVISAT Geophysical Data Records, personnel communication, 2005


McCarthy, D.: IERS Conventions 2000, IERS Technical Note 32

Ray, R, Steinberg, D., Chao, B., Cartwright, D.: Diurnal and semidiurnal variations in the Earth's rotation rate induced by ocean tides; Science, 264, pp. 830-832, 1994


data: EIGEN-CG01C, accepted by J. of Geodesy.