# GRACE

Gravity Recovery and Climate Experiment

## JPL Level-2 Processing Standards Document

## For Level-2 Product Release 04

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# DOCUMENT CHANGE RECORD

| Issue | Date | Pages | Change Description |
|---|---|---|---|
| 01.0 | Nov 26, 2003 | All | Initial Version |
| 02.0 | Nov 4, 2005 | All | Revised to describe new models for product release v. 2, 4 Nov 2005 |
| 03.0 | Jan 27, 2006 | 1 | Only change to reflect RL02 standards + AODRL01 (PPHA) |
| 04.0 | Feb 20, 2007 | All | Revised to reflect RL04 changes |
| 04.1 | Feb 27, 2007 | 5,8 | Cleared the release versions for ACC1B, SCA1B, KBR1B, & GPS1B used for the RL04 solutions within the table in section I.3. Corrected typos for c30-dot and c40-dot within the table in section II.2.1. Added reference. |
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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 NASA The Jet Propulsion Laboratory of the California Institute of Technology (JPL). This document is issued once for every release of Level-2 data products generated by JPL. The release number refers to the field *RL* in the generic Level-2 product name (see *Product Specification Document* or *Level-2 User Handbook*)

*PID-2_YYYYDOY-YYYYDOY_dddd_JPLEM_0000_0004*

This document uses in its title the release number *RL* for the specific product release whose processing standards are described herein.

This document may be used in conjunction with:

1. GRACE Product Specification Document (327-720)
2. GRACE Level-2 User Handbook (327-734)
3. GRACE CSR L-2 Processing Standards Document (327-742)
4. GRACE GFZ L-2 Processing Standards Document (327-743)
5. GRACE AOD1B Product Description Doc (327-750, GR-GFZ-AOD-0001)

## I. 2 DOCUMENT CHANGE HISTORY

This document has been previously issued for the Level-2 data product releases as listed in the change log earlier in this document. The principal changes since the previous issue of this document are described in the remainder of this document.

## I. 3 OVERVIEW OF DATA PROCESSING

This section contains a brief overview of the data processing done to obtain the Level-2 products in this release.

The gravity field estimates were made using the conventional dynamic, linear least squares adjustment for the orbit and gravity field from an optimally weighted combination of GRACE satellite data. Some specifics follow in the next table.

| **Processing Institution** | **Jet Propulsion Laboratory** | |
|---|---|---|
| | | |
| | **Software Used** | |
| Orbit and Linear Solver Software | MIRAGE | Version 2005 |
| | | |
| | **GRACE Data Products Used** | |
| *Product ID & Release* | *Data Rate* | *Remarks* |
| ACC1B (RL=00 & 01†) | 5 second | Used in the integrator |
| SCA1B (RL=00 & 01†) | 5 second | For observation models & transforming body-fixed accelerations |
| KBR1B (RL=00 & 01†) | 5-second Range Rate only | |
| GPS1B (RL=00 & 01†) | 5-minute pseudo-range and phase | FLINN Precise Orbits used for GPS satellites (held fixed during analysis) |
| AOD1B (RL=04) | Used as part of background force models | |
| | **Other Notes on Methodology** | |
| Solution obtained as an optimally weighted combination of information from GPS data for each GRACE satellite and inter-satellite K-Band Range-Rate – using **one-day dynamic arcs** over the prescribed data span. | | |

† The RL00 Level-1B data were used between Jan 1, 2003 and Dec 31, 2004; the RL01 data were used for the remainder of the mission.

# II ORBIT DYNAMICS MODELS

## II. 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

$$\ddot{\vec{r}} = \vec{f}_g + \vec{f}_{ng} + \vec{f}_{emp}$$

where 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.

### *II.1.1 Independent Variable (Time Systems)*

The independent variable in the equations of motion is the TDT (Terrestrial Dynamic 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 | na |
| UTC | TAI = UTC + n1 (Time-tag for saving intermediate products) | n1 are the Leap Seconds | Tables from USNO |
| TDT | TDT = TAI + 32.184 s | This is the independent variable for integration. Distinction between TDB & TDT is ignored. | IAG 1976 recommendations |
| GPS | GPS = UTC + n2 (basis for the time-tagging of GRACE Observations) | n2 are Leap Seconds since Jan 6, 1980 | Time-tags in sec since 1200 Jan 01, 2000 GPS Time. |

### *II.1.2 Coordinate System*

The fundamental reference frame for the mathematical model is the non-rotating, freely-falling (inertial) reference frame with the origin defined as the center of mass of the Earth. The Inertial and Earth-fixed reference frames, and their relative orientations and associated standards are further described in the chapter on Earth Kinematics.

## II. 2 GRAVITATIONAL FORCES

The gravitational accelerations are the sum of direct planetary perturbations and the geopotential perturbations. The vector of direct planetary perturbations is evaluated using the planetary ephemerides. The geopotential itself is represented in a spherical harmonic series with time-variable coefficients, to a specified maximum degree and order, and accelerations are computed by evaluating the Earth-fixed gradient of the geopotential. The accelerations are then rotated (after summation with the non-gravitational accelerations) to inertial frame for the integration of equations of motion. In general,

$$\vec{f}_g = {}_{3x3}M_{ef}^{in}(P,N,R)\,\vec{f}_g^{\,ef}$$

The 3x3 rotation matrix M, which depends on Earth Precession, Nutation & Polar Motion is described in the chapter on Earth Kinematics.

Contributions to the spherical harmonic coefficients of the geopotential, and the associated implementation & standards are now compiled. The geopotential at an exterior field point, at time t, is expressed as

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

where r is the geocentric radius, and $(\varphi,\lambda)$ 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 *Level-2 User Handbook*. The details of the background gravity model are provided here.

Hereafter, the Document *IERS Conventions (2003)* is abbreviated *as IERS-2003*.

### *II.2.1 Mean Geopotential & Secular Changes*

| Parameter | Value | Remarks |
|---|---|---|
| $GM_e$ | 3.986004415E+14 $m^3/s^2$ | *IERS-2003 Standards* |
| $a_e$ | 6378136.3 m | |
| $N_{\max}$ | Complete to degree and order 180 | ***GIF22a*** is background static model. It uses coefficients of GGM02C (*Tapley et al. 2005*) from degree 121 to 200, and EGM96 (*Lemoine et al. 1998*) from degree 201 to 360 |
| $\dot{\bar{C}}_{20}$ | +0.11628E-10/y | *IERS-2003 Standards (Epoch of $\bar{C}_{20}$ is 2000.0)* |
| $\dot{\bar{C}}_{30}$ | +0.049E-10/y | *Epoch 2000.0* (*Cheng et al. 1997*) |
| $\dot{\bar{C}}_{40}$ | -0.047E-10/y | *Epoch 2000.0* (*Cheng et al. 1997*) |
| $\dot{\bar{C}}_{21}$ & $\dot{\bar{S}}_{21}$ | -0.337E-11/y and 1.606E-11/y | *IERS-2003 Standards (Epoch of $\bar{C}_{21}$ and $\bar{S}_{21}$ is 2000.0)* |
| Note 1: The normalization conventions are as defined in IERS-96, Chapter 6, Eqs 2-3. Note 2: Note that the degree 1 terms are identically zero when the origin of the coordinate system is the center of mass of the Earth | | |

### *II.2.2 Solid Earth Tides*

Solid Earth tidal contribution to the geopotential are computed approximately as specified in Chapter 6.1, *IERS Conventions(2003)*. Corrections to specific spherical harmonic coefficients are computed and added to the mean field coefficients.

| Model | Notes | |
|---|---|---|
| Planetary Ephmerides | DE-405 | |
| Frequency Independent Terms | Degree 2 & 3 – expression in Eq. (1), Ch.6, *IERS-2003*. | Parameter values from Table 6.1, *IERS-2003* |
| | Ellipticity contributions from Degree 2 tides to Degree 4 terms | Eq. 4, *IERS-2003* |
| Frequency Dependent Terms | Tidal corrections to all degree-2 | Table 6.3, *IERS-2003* |
| Permanent Tide in $\bar{C}_{20}$ | 4.173E-9 | Removed from total contributions as calculated above (implicitly included in value of mean $\bar{C}_{20}$) |

### *II.2.3 Ocean Tides*

The ocean tidal contributions to the geoptoential are computed as specified in JPL Interoffice Memorandum "Convolution Formulism for the Ocean Tide Potential" by S. Desai, 4 March 2005. Corrections to specific spherical harmonic coefficients of arbitrary (selectable) degree and order are computed and added to the mean field coefficients.

| Model | Description | Notes |
|---|---|---|
| Convolution Weights | Derived from FES2004 (monthly, fortnightly, diurnal, semidiurnal) and SCEQ (Semi-annual and Annual) | *Lefevre et al. 2005; Desai S.D. and D.-N. Yuan, 2006* |
| Expansion | Complete to degree 90 | |

### *II.2.4 Tabular Atmosphere & Oceanic Variability*

The non-tidal variability in the atmosphere and oceans is removed through using the AOD1B product. This product is a combination of the ECMWF operational atmospheric model and a barotropic ocean model driven with this atmospheric model. For JPL RL04, we use the AOD1B RL04, based upon ECMWF (as usual) and the baroclinic Dresden OMCT model with mass runoff constrained to zero. The details of this product and its generation are given in the *AOD1B Description Document (GRACE 327-750, v3, 2007).*

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.

In order to improve the accuracy of interpolation, the following procedure is adopted. An estimate of the atmospheric S2 tidal effects on $\overline{C}_{22}$ and $\overline{S}_{22}$ are removed from the AOD1B product. This estimate is simply the difference of the TEG4 multi-satellite estimate of this tidal harmonic and the altimetric determination of this harmonic from the CSR 4.0 tidal model. In this way, the combination of the atmospheric and oceanic S2 tidal effects on the (2,2) harmonics are modeled using the ocean tide model.

### *II.2.5 Solid Earth Pole Tide (Rotational Deformation)*

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

| Model | Description | Notes |
|---|---|---|
| Elastic Earth Model Contribution to C21 & S21 | Scaled difference between epoch pole position and mean pole. See Chapter III (Earth Kinematics) for values and linear variation model for the mean pole. | |
| Polar Motion | Tabular input | |
| Mean Polar Motion & Rates | Linear trend | *IERS-2003* |
| Constant Parameters | Scale factor = $-1.333\times10^{-9}$ / arcsec | $K_2 = 0.3077 + i0.0036$ |
| Anelasticity | Included, *IERS-2003* | |

### *II.2.6 Ocean Pole Tide*

The self-consistent equilibrium model of Desai is used (*Desai 2002*). A spherical harmonic expansion to degree 90 is used, with the same polar motion time series as for the Solid Earth Pole Tide or Earth kinematics (See Section II.2.5 or III.1.4). The contributions to the spherical harmonic coefficients are computed in the orbit software .

### *II.2.7 N-Body Perturbations*

Unlike the geopotential accelerations, the perturbations due to the Sun, Moon and all the planets 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 Sun & 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 | |

### *II.2.8 General Relativistic Perturbations*

The general relativistic contributions to the accelerations are computed as specified in Chapter 10 of the *IERS-2003 Conventions*.

## II. 3 NON-GRAVITATIONAL FORCES

The nominal approach is to use the GRACE accelerometer data to model the non-gravitational forces acting on the satellite.

The model used is:

$$\vec{f}_{ng} = q \otimes \left[ \vec{b} + {}_{3x3}\mathrm{E}\ \vec{f}_{acc} \right]$$

where the q/operator represents rotations to inertial frame using the GRACE Attitude Quaternion product; b represents an empirical bias vector; and the 3x3 matrix E contains the scale factors along the diagonal, and no cross-coupling terms in the off-diagonal, that is, the matrix we model is diagonal at present.

The bias vector & scale matrix operate on the GRACE Accelerometer observation product, and are estimatable parameters.

## II. 4 EMPIRICAL FORCES

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

## II. 5 NUMERICAL INTEGRATION

The DIVA variable step/variable order integrator of Krogh (1973) is implemented.

| Model | Description | Notes |
|---|---|---|
| Dependent Variables<br>1. Equations of motion (position/velocity for each satellite)<br>2. State Transition Matrix (position/velocity mapping terms only) | | |
| Formulation | Cowell Formulation | |
| Order | 7 | |
| Step-Size | Variable, nominally 5 second | Varied with 1.E-12 tolerance for state |
| | | |

# III EARTH & SATELLITE KINEMATICS

## III. 1 EARTH ORIENTATION

Earth Orientation here refers to the model for the orientation of the Earth-fixed reference relative to the 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-2003*) |
| Earth-fixed | CTRS | IGS2000 |

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

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

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.

### *III.1.1 Precession (P)*

Following *IERS-96*, the IAU 1976 Precession is modeled as

$$P = R_3(\zeta_A) R_1(-\theta_A) R_3(z_A)$$

where the component angles are evaluated using formulas in USNO Circular 163, Page A2. Reference epoch 2000.0 is used. The independent variable is TDT since epoch J2000.0 (noon, 01-Jan-2000).

### *III.1.2 Nutation*

Following *IERS-96*, the IAU 1980 Nutation model is used along with the associated corrections, such that

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

The calculation of the nutation angles & their corrections is now summarized.

| **Quantity** | **Model** | **Notes** |
|---|---|---|
| Obliquity of Ecliptic ($\varepsilon_A$) | Polynomial | USNO Circular 163, Page A3 |
| Nutations in Longitude or Right Ascension ($\Delta\psi$) & Obliquity ($\Delta\varepsilon$) | Interpolation of nutations in DE405 | IAU 1980 |
| Nutation Corrections | Planetary corrections: 25 largest terms | *(Souchay 1995)* |
| | Anelasticity not included | |

### *III.1.3 Sidereal Rotation (R)*

This rotation is implemented as

$$R = R_3(-GST)$$

where the Apparent Greenwich Sidereal Time (GST) is calculated as follows:

| **Quantity** | **Model** | **Notes** |
|---|---|---|
| Tabular variations | Cubic interpolation | *IERS C04* |
| | Diurnal tidal variations | Not modelled |
| | Nutation Corrections – 25 largest corrections to IAU 1980. | *IERS-96* |
| GMST | Polynomial | USNO Circular 163, Page A3 |
| Equatorial components of precession & nutation | *(Aoki & Kinoshita)* | *IERS-96* |
| NOTE: Sidereal rotation rate is directly used in a single step GMST calculation, instead of the two-step calculation presented in *IERS-96*. | | |

### *III.1.4 Wobble (W)*

The Polar Motion component of rotation is implemented as

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

| Quantity | Model | Notes |
|---|---|---|
| Tabular variations | Cubic interpolation | *IERS C04* |
| Ocean Tidal Variations (Diurnal/Semi-Diurnal) | Not Modelled | |
| Note 1: The rotation matrices are implemented in the small angle, skew-symmetric matrix formulation.<br>Note 2: Rotational deformation accelerations & kinematic station displacements are proportional to the difference between this time-series and a linear model for the pole. | | |

## III. 2 Station Coordinates

This section summarizes the models for the mean and time-variable parts of the station coordinates adopted for data processing. It is important to understand that the JPL L-2 production fixes the GPS ephemerides to the JPL "FLINN" solution, and thus the station coordinates do not appear explicitly in the L-2 solution, but only implicitly in the FLINN solution.

For the FLINN solution, the following standards are used:

| Quantity | Model | Notes |
|---|---|---|
| Mean Station Positions | ITRF-2000 | Refers to the position of a geodetic marker or antenna phase center at each site. |
| Station Velocities | Individual Station velocities in ITRF-2000 | |
| Ocean Tidal Loading (Diurnal/Semi-Diurnal band) | Scherneck model (*IERS-96*) | |
| Station Eccentricities | See individual observation models | |
| Luni-Solar Solid Earth Tidal displacement | Chapter 7, *IERS-96* (Luni-Solar ephemerides from DE-405) | |
| Rotational Deformation | Scaling of difference of Wobble values from a linear trend model. | See Wobble rotation or Mean Field |
| Tidal Geonceter (Diurnal/Semi-Diurnal) | Included within Ocean Tidal Loading model | |
| Atmospheric Loading | Not modeled | |
| Post-glacial Rebound | Not modeled | |
| Slow (seasonal) Geocenter Variations | Not modeled | |

## III. 3 SATELLITE KINEMATICS

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.

### *III.3.1 Rotation of Velocity Components*

The position rotations are specified in Section II.1. The velocity components are rotated using the matrix approximation

$$\vec{v}_{crs} = M_{crs}^{trs}\vec{v}_{trs} + \left(PN\dot{R}S\right)\vec{r}_{trs}$$

### *III.3.2 GRACE GPS Antenna Offset Model*

The GRACE GPS navigation receiver is place on the top surface (see Product specification document). For the Purposes of orbit and gravity ield determination, the antenna phase center location vector for the LC ionosphere-free pseudo-range and phase is

(-0.4, -0.4, -413.967) millimeters for GRACE-A and
(0.602, -0.754, -414.277) millimeters for GRACE-B

in the Science Reference Frame. This is consistent with the value provided in the VGN1B product (RL01).

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