GRACE Follow-On

Gravity Recovery and Climate Experiment Follow-On

JPL Level-2 Processing Standards Document

For Level-2 Product Release 06

JPL D-103921

Dah-Ning Yuan
Jet Propulsion Laboratory
California Institute of Technology

Prepared by:

Dah-Ning Yuan, JPL

Contact Information:
Jet Propulsion Laboratory
MS 301-121
4800 Oak Grove Drive
Pasadena, CA 91109
Email: dah-ning.yuan@jpl.nasa.gov

DOCUMENT CHANGE RECORD

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1.0	May 28, 2019	All	First Version 1.0

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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 Follow-On Science Data System component at NASA 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 for a specific branch whose processing standards are described herein. The release number refers to the field *rr* in the generic Level-2 product name (see *Product Specification Document* or *Level-2 Gravity Field Product User Handbook*)

PID-2_YYYYDOY-YYYYDOY_dddd_JPLEM_mmmm_rrvv

Where *PID* is 3-character product identification mnemonic, *YYYYDOY-YYYYDOY* specifies the date range (in year and day-of-year format) of the data used in creating this product, *dddd* specifies the gravity mission, *mmmm* is a 4-character mnemonic used to identify the characteristics of the gravity solution, *rrvv* specifies 2-digit release number and 2-digit version number.

This document may be used in conjunction with:

1. GRACE Follow-On Level-1 User Handbook (JPL D-56935)
2. GRACE Follow-On Level-2 Gravity Field Product User Handbook (JPL D-103922)
3. GRACE Follow-On CSR L-2 Processing Standards Document (JPL D-103920)
4. GRACE Follow-On GFZ L-2 Processing Standards Document (JPL D-103919)
5. GRACE AOD1B Product Description Document for AOD1B Release 06 (327-750)

I. 2 DOCUMENT CHANGE HISTORY

This document is the first version of the GRACE Follow-On Level-2 product releases as listed in the Document Change Record.

II ORBIT DYNAMICS MODELS

II. 1 EQUATIONS OF MOTION

The equations of motion for both GRACE Follow-On 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 Follow-On 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	
UTC	TAI = UTC + n1 (Time-tag for saving intermediate products)	n1 are the Leap Seconds	Tabular input
TDT	TDT = TAI + 32.184 s	This is the independent variable for integration. Distinction between TDB & TDT is ignored.	IAG 1976 recommendations
GPS	TAI = GPS + 19 s (basis for the time-tagging of GRACE Follow-On Observations)	19 is UTC Leap Seconds since Jan 6, 1980	Time-tags in seconds since 12:00 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 III.1 on Earth Orientation.

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,

$$\vec{\boldsymbol{f}}_{\boldsymbol{g}} = {}_{3x3}\boldsymbol{M}_{\boldsymbol{itrs}}^{\boldsymbol{gcrs}}\, \vec{\boldsymbol{f}}_{\boldsymbol{g}}^{\boldsymbol{ef}}$$

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 (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 Follow-On estimates, is described further in the *Level-2 Gravity Field Product User Handbook*. The details of the background gravity model are provided here.

Hereafter, the IERS Conventions (2010) is abbreviated as *IERS-2010.*

II.2.1 Mean Geopotential & Secular Changes

Parameter	Value	Remarks
GM_e	3.986004415E+14 m^3/s^2	*IERS-2010 Standards*
a_e	6378136.3 m	
$N_{\max}$	Complete to degree/order 360	***GGM05C*** is background model
Note 1: The normalization conventions are as defined in IERS-2010, Eqs 6.2-6.3. Note 2: The implementation of computation of spherical harmonics & its derivatives is as described in (*Lundberg & Schutz, 1988*). Note 3: Note that the degree 1 terms are identically zero when the origin of the coordinate system is the center of mass of the Earth Note 4: The mean field ***GGM05C*** is a mean gravity field model created from a combination of GRACE and GOCE gravity information and surface gravity anomalies from the DTU13 global anomaly field, as described in *Ries et al. (2016)*. The epoch of GGM05C is 2008.0, the approximate midpoint of the ten-year GRACE data span used. The model coefficients are available from GRACE data archives, ICGEM, and from ftp://ftp.csr.utexas.edu/pub/grace/GGM05/.		

II.2.2 Solid Earth Tides

Solid Earth tidal contribution to the geopotential are computed approximately as specified in Chapter 6.2, *IERS Conventions 2010*. Corrections to specific spherical harmonic coefficients are computed and added to the mean field coefficients.

Model	Notes	
Planetary Ephmerides	DE-421	
Frequency Independent Terms	Degree 2 & 3 – expression in Eq. 6.6, *IERS-2010*	Constants from Table 6.3 *IERS-2010* are used.
	Ellipticity contributions from Degree 2 tides to Degree 4 terms in Eq. 6.7, *IERS-2010*	Constants from Table 6.3 *IERS-2010* are used.
	Love Numbers for elastic Earth	Third degrees
	Love Numbers for anelastic Earth	Second degrees
Frequency Dependent Terms	Tidal corrections to second degrees in Eq. 6.8a and 6.8b, *IERS-2010*	Constants from Table 6.5a, 6.5b, and 6.5c, *IERS-2010* are used.
	Anelasticity Contributions	(2,0) and (2,1)
Permanent Tide in $\overline{C}_{20}$	4.173E-9	Removed from these contributions (is implicitly included in value of C20)

II.2.3 Ocean Tides

The ocean tidal contributions to the geopotential are computed using convolution formalism (*Desai and Yuan 2006*). 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), Cartwright & Tayler (1971)*	
Convolution Weights	Diurnal, semi-diurnal band from FES2014b (*Lyard, et al., 2016*) Mm and Mf: *Egbert & Ray 2003* Long-period: Self-consistent equilibrium model (*Ray & Cartwright 1994*)	Convolution interval = 2 days
Expansion	Complete to degree/order 180	

II.2.4 Air Tides

The S_2 and S_1 air tidal contributions to the geopotential are computed to degree and order 180 using the Ray/Ponte model (*Ray and Ponte, 2003*). The atmospheric tidal effects on the harmonics are modeled using the ocean tide model.

II.2.5 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 RL06 gravity field product, we use the AOD1B RL06, based upon ECMWF 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)*.

This component of the geopotential is ingested as 3 hourly time series to degree and order 180. The value of the harmonics at intermediate epochs is obtained by linear interpolation between the bracketing data points.

II.2.6 Solid Earth Pole Tide

The rotation deformation forces are computed as additions to spherical harmonic coefficients, $\overline{C}_{21}$ and $\overline{S}_{21}$, from anelastic Earth model, as specified in Chapter 6.4, IERS Conventions (2010).

Model	Description	Notes
Anelastic Earth Model Contribution to C21 & S21	Scaled difference between epoch pole position and mean pole. See Chapter III (Earth Kinematics) for values and cubic variation model for the mean pole.	
Polar Motion	Tabular input	
Mean Polar Motion & Rates	Linear trend	Ries *(2017)*
Constant Parameters	Scale factor = -1.333×10^{-9} / arcsec	$K_2 = 0.3077 + i0.0036$
Anelasticity	Included, *IERS-2010*	

II.2.7 Ocean Pole Tide

The self-consistent equilibrium model of Desai (*Desai, 2002*) is used to compute ocean pole tide contribution to spherical harmonic coefficients for an anelastic Earth, as specified in Chapter 6.5, IERS Conventions (2010),

Model	Description	Notes
Anelastic Earth Model Contribution to harmonics	Completed to degree /order 180 – expression in Eq. 6.23, *IERS-2010*	
Polar Motion	Tabular input	
Mean Polar Motion & Rates	Linear trend	Ries *(2017)*
Constant Parameters	Load Love number to degree 30	$\gamma = 0.6870 + i0.0036$
Anelasticity	Included, *IERS-2010*	

II.2.8 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 indirect effects due to the acceleration of the Earth by the planets are also modeled as point-mass interactions.

Model	Description	Notes
Third-Body Perturbation	Direct terms of point-mass 3rd body perturbations	
Indirect J2 Effect	Not modeled	
Planetary Ephemerides	DE-430	

II.2.9 General Relativistic Perturbations

The general relativistic contributions to the accelerations are computed as specified in Chapter 10 of the IERS2010 Standards. The Schwarzchild term, Lense-Thirring precession, and geodesic precession are included for the acceleration of near Earth satellite motion.

II. 3 Non-Gravitational Forces

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

The model used is:

$$\vec{f}_{ng} = \boldsymbol{q} \otimes \left[\vec{b} + {}_{3x3}\mathrm{E}\, \vec{f}_{acc} + \vec{r}(t - t_0) \right]$$

where the ***q*** operator represents rotations to inertial frame using the GRACE Follow-On Attitude Quaternion product; ***b*** represents an empirical bias vector; and the 3x3 matrix ***E*** contains the scale factors along the diagonal, and cross-coupling terms in the off-diagonal, and ***r*** represents an empirical rate vector.

The bias vector, rate vector & scale matrix operate on the GRACE Follow-On Accelerometer observation product are estimatable parameters. Bias and rates for the XZ-components are estimated per orbital arc while the Y-component are estimated every 3 hour. The scale matrix parameters are estimated in the monthly solution as the gravity 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 1. Equations of motion (position/velocity for each satellite) 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 Earth-fixed reference relative to the Inertial reference. The former is necessary for associating observations, models and observatories to the geographic locations; and the latter is used for dynamics, integration & ephemerides.

Frame	System	Realization
Inertial	GCRS	J2000.0 (*IERS-2010*)
Earth-fixed	ITRS	IGS14

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

$$_{3x3}\boldsymbol{M}_{itrs}^{gcrs} = \boldsymbol{Q}(t)\boldsymbol{R}(t)\boldsymbol{W}(t)$$

which converts a vector in the International Terrestrial Reference System (ITRS) to a vector in the Geocentric Celestial Reference System (GCRS). Each component matrix is itself a 3x3 matrix, and is now individually described. This Coordinate transformation consistent with the IAU 2000/2006 resolutions including (1) ***W(t)*** is the rotation arising from polar motion relating ITRS and Terrestrial Intermediate Reference System (TIRS) using the Celestial Intermediate Pole (CIP) as its z-axis and Terrestrial Intermediate Origin (TIO) as its x-axis; (2) ***R(t)*** is the rotation arising from the rotation of the Earth around the axis of the CIP relating TIRS and Celestial Intermediate Reference System (CIRS) using CIP as its z-axis and Celestial Intermediate Origin (CIO) as its x-axis; (3) ***Q(t)*** is the rotation arising from the motion of the CIP in the GCRS relating CIRS and GCRS. The CIO based procedures (CIO is the origin adopted on the CIP equator) are described in the following. 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 CIO based transformation for the celestial motion of the CIP (Q)

The *IERS-2010* recommendation complys with the IAU 2000/2006 resolution on adoption of the P03 precession theory (Capitaine et al. 2003) and IAU 2000A nutation theory (Mathews et al. 2002). This transformation relates the ITRS to the GCRS at the date ***t*** can be written as:

$$\boldsymbol{Q} = \boldsymbol{R}_3(-\boldsymbol{E})\boldsymbol{R}_2\left(-\boldsymbol{d}\right)\boldsymbol{R}_3\left(\boldsymbol{E}+\boldsymbol{s}\right)$$

where the time coordinate, t, is Terrestrial Time (TT) since epoch J2000.0 (noon, 01-Jan-2000), and E and d are the coordinates of the CIP in the GCRS, and are calculated as

$$X = \sin d \cos E$$
$$Y = \sin d \sin E$$

Where X and Y, are evaluated using Eq. 5.16 of the *IERS-2010*. The CIO locator, s, provides the position of the CIO on the equator of the CIP. The calculation of these angles & their corrections is summarized.

Quantity	Model	Notes
The coordinates of the CIP in the GCRS (X and Y)	Eq. 5.16, Table 5.2a and 5.2b in *IERS-2010*	IAU2006 Precession and IAU2000A Nutation
Celestial Intermediate Origin locator (s)	Table 5.2d in *IERS-2010*	
Correction for X and Y		Tabular input

III.1.2 CIO based transformation for Earth rotation (R)

This rotation is implemented as

$$R = R_3(-ERA)$$

where the Earth Rotation Angle (ERA) is calculated as follows:

Quantity	Model	Notes
UT1 variations	Cubic interpolation	Tabular input
	Zonal Tide Regularization	Table 8.1 in *IERS-2010*
	Ocean tidal variations (Diurnal & Semi-diurnal)	Table 8.3a and 8.3b in *IERS-2010*
	Libration Variations (Semi-Diurnal)	Table 5.1b in *IERS-2010*
Earth Rotation Angle	Eq. 5.15 in *IERS-2010*	

III.1.3 Transformation for polar motion (W)

The Polar Motion component of rotation is implemented as

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

Quantity	Model	Notes
Polar coordinates (x_p & y_p)	Cubic interpolation	Tabular input
Terrestrial Intermediate Origin locator (s')	Eq. 5.13 in *IERS-2010*	
Ocean Tidal Regularization		Table 8.4 in *IERS-2010*
Ocean Tidal Variations (Diurnal/Semi-Diurnal)		Table 8.2a and 8.2b in *IERS-2010*
Libration Variations (Diurnal)		Table 5.1a in *IERS-2010*

III.1.4 Rotation of velocity components

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

$$\vec{v}_{gcrs} = M_{itrs}^{gcrs}\vec{v}_{itrs} + \dot{M}_{itrs}^{gcrs}\vec{r}_{itrs}$$

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 (*Desai et al., 2011*).

For the FLINN solution, the following standards are used:

Quantity	Model	Notes
Mean Station Positions	IGS14	Refers to the position of a geodetic marker and reference point for antenna calibrations. IGS realization of ITRF2014
Station Velocities	Individual Station velocities in ITRF2014	
Station Eccentricities	See individual observation models and IGS14 antenna calibrations	
Ocean Tidal Loading	FES2004 with hardisp.f	Spline interpolation from 11 main tides to 342 constituents
Luni-Solar Solid Earth Tidal Displacement	*IERS-2010*	Luni-Solar ephemerides from DE-421

Rotational Deformation	*IERS-2010*	Cubic mean pole model
Ocean Pole Tide Loading	*IERS-2010*	*Desai, 2002*
Tidal Geocenter Correction	Included within ocean tidal loading model, *IERS-2010*	
S_1-S_2 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 Follow-On quaternion product is not available, linear interpolation between adjacent values is used.

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