Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) Level-1 Data Product User Handbook

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Revision History

Revision	Date	Author(s)	Description
	2019-05-21	HYW et. al.	Initial GRACE-FO RL04 data release.
	2019-06-20	HYW	Add Revision History. Add "ACCTEMPCAL" SOE sensor/event identifier to Table 7.
	2019-07-26	HYW	Updates for LRI RL04 data release: Update product descriptions for CLK1B (as pertains to LLK1B product), KBR1B (as pertains to LRI1B product), LRI1A, LSM1A, and LSM1B. Update LRI Time description in Section 3.2.2. Add LRI Optical Frame description to Section 3.2.3. Update LLK1B product description and usage notes in Section 3.3.1. Update LRI ranging information in Section 3.3.2. Add "LRIDATATION" SOE sensor/event identifier to Table 7.
	2019-09-11	HYW	Update LRI Time description in Section 3.2.2. Remove LRI Optical Frame description in Section 3.2.3. In LSM1B product description, change coordinate frame from LRI Optical Frame to Science Reference Frame. Fix description of LRI CNR values in KBR1B product description. Update CLK1B "qualflg" parameter description.

Contents

1 Introduction

The purpose of this document is to assist investigators of the GRACE-FO mission by providing a comprehensive description of the content and format of the GRACE-FO SDS Level-1A and 1B data products.

GRACE-FO Level-1A and 1B data products are produced by the GRACE-FO SDS. The Level-1B data products provide all necessary inputs to derive monthly time-variations in the Earth's gravity field; they are also used for GRACE-FO orbit determination and mean gravity field determination. Level-1B products are processed from Level-1A products, which contain telemetry data converted into engineering units.

There are a few ways to use this document:

1. **Product Lookup**: Look up specific information on the data content of a given Level-1 product type in Section 4.

2. **Introduction to Data Products**: For an overview of the data product types, conventions, and format, as well as how they are produced by the SDS, refer to Section 3.

3. **Mission Background and External References**: For background information on the GRACE-FO mission, satellites, and instruments, refer to Section 2.

This document borrows from the "GRACE Level 1B Data Product User Handbook" [1] and the "GRACE Product Specification Document" [2].

The most current version of this document will be maintained on the Physical Oceanography Distributed Active Archive Center (PO.DAAC) site: `https://podaac.jpl.nasa.gov`.

2 Overview of GRACE-FO Mission

The GRACE-FO mission is a joint US/German mission launched on May 22, 2018 that uses twin satellites to accurately map variations in the Earth's gravity field over its designed five-year lifetime. It is designed as a successor to the Gravity Recovery and Climate Experiment (GRACE) mission, which was launched on March 17, 2002, and with which it shares many similarities.

GRACE-FO is a joint partnership between National Aeronautics and Space Administration (NASA) in the United States and German Research Centre for Geosciences (GFZ) in Germany. The Jet Propulsion Laboratory (JPL) carries out project management and systems engineering activities. For more information on the mission and project personnel, see `https://gracefo.jpl.nasa.gov`.

2.1 Objective

The primary mission objective is to continue the high-resolution monthly global maps of Earth's gravity field and surface mass changes of the original GRACE mission (04/2002 - 06/2017) over a period of five years. The secondary objectives are twofold: firstly, GRACE-FO will demonstrate the effectiveness of a novel Laser Ranging Interferometer (LRI) in improving the Satellite-to-Satellite Tracking (SST) measurement performance, laying the groundwork for improved future space-gravimetry missions. The LRI will be the first-ever demonstration of laser interferometry in space between satellites for use on future GRACE-like geodetic missions. Secondly, GRACE-FO will measure the structure of Earth's atmosphere by performing at least 200 radio occultation measurements per day of GPS refraction signals, a cost-effective technique to measure vertical atmospheric temperature and humidity profiles by observing how much signals from GPS satellites are distorted as they travel through the atmosphere.

Conceptually very similar to the GRACE mission, GRACE-FO consists of two identical satellites flying in formation around Earth at an initial altitude of approximately 490 kilometers and a nominal separation distance of 220+/-50 kilometers. Instruments on board the satellites precisely measure changes in the distance between them due to orbital perturbations caused by geographical and temporal variations in Earth's gravity field. By combining these data with precise knowledge of the satellites' positions as determined by GPS observations, position and orientation of the satellites as measured by star trackers, and non-gravitational forces acting on each satellite as measured by high-precision accelerometers, the distribution of Earth's mass changes near the surface will be calculated every month and tracked over time.

GRACE-FO will expand GRACE's legacy of scientific achievements. These include tracking mass changes in Earth's polar ice sheets and mountain glaciers (which impacts global sea level); estimating total water storage on land (from groundwater changes in deep aquifers to changes in soil moisture and surface water); inferring changes in deep ocean currents, a driving force in climate; and even measuring changes within the solid Earth itself, such as postglacial rebound and the impact of major earthquakes.

2.2 Requirements

To ensure that science and mission goals are accomplished, the following requirements were established:

- The Earth's geopotential field shall be characterized by the coefficients of a spherical harmonic expansion.
- The spherical harmonic coefficients shall be estimated to degree and order 150 or higher for the long-term mean part, and to degree and order 70 or higher for the time-variable part.
- The temporal variability shall be characterized by mean values of the coefficients over approximately 30 days.
- Approximately 200 GPS atmospheric profile soundings per day shall be acquired, subject to data system limitations. These data will provide globally distributed profiles each day of the excess delay, or bending angle, of the GPS measurements due to the ionosphere and atmosphere.

2.3 Mission Phases

Launch and Early Operations Phase (LEOP) In addition to the German Space Operations Center (GSOC) ground stations at Weilheim and Neustrelitz, NASA tracking stations at McMurdo, Spitzbergen, and Poker Flat shall be available for telemetry and command uplink during the LEOP phase.

The LEOP phase nominally ends when the following conditions have been met:

1. Both satellites are in safe, stable orbits with no danger of collision with each other, the launch vehicle, or co-passenger satellites.
2. Both satellites have attained nominal attitude control including successful star-camera acquisition.
3. Nominal uplink and downlink communications are achieved with GSOC stations.
4. The nominal separation distance between the satellites (220 km $\pm$ 50 km) has been achieved and stabilized.

In-Orbit Checkout Phase Following LEOP, there will be a three-month In-Orbit Checkout Phase. The aim of this phase is to check out the individual satellite bus and payload instrument functions. GPS, K-Band Ranging System (KBR), LRI, SuperSTAR Accelerometer (ACC), and Star Camera Assembly (SCA) data are evaluated. Initial calibrations will be completed for the distance between the satellite center-of-mass and the accelerometer proof mass, the orientation of each SCA with respect to the K-Band boresight vector, and accelerometer bias and scale factors. Using these calibrations, preliminary gravity field solutions will be computed, and verified through a combination of internal consistency checks and comparison with in-situ and ocean bottom pressure data.

Science Phase Next, the mission will enter the Science Phase, in which science data is routinely gathered from the science payload. This phase will continue until the end of mission, with the exception of brief periods for orbit maintenance and recalibrations.

2.4 Orbit

2.4.1 Orbital Parameters

The twin GRACE-FO satellites fly a polar orbit with an initial altitude at launch of 491.5 km (May 22, 2018), decaying to 300 km near the End-of-Mission (EOM). Table 2 shows the orbit parameters, with the EOM column denoting the desired conditions after five years.

Orbit Parameter	Initial Value	Tolerance	EOM
Semi-major axis	6878 km (500 km height)	± 10 km	6678 km (300 km height)
Eccentricity	<0.005	N/A	<0.005
Inclination	89°	± 0.05°	89°

Table 2: GRACE-FO orbital parameters (the initial launch altitude achieved on May 22, 2018 was 491.5 km).

Over the mission lifetime, the two satellites will remain in coplanar orbits. Due to drag force differences, the along-track separation will be variable. Station-keeping maneuvers will be carried out every 30 to 60 days, as necessary, to keep the two satellites at their nominal separation of 220 km ± 50 km. To ensure the uniform exposure and aging of the K-Band antennae in the two satellites, once during the mission, the leading and trailing satellites will exchange positions.

The altitudes of the two satellites will decay in tandem, from near 500 km at the beginning of the mission to 300 km and lower at the end of mission. In order to ensure an overall mission lifetime of five years, the altitudes of the two satellites may be reboosted once, if deemed necessary.

2.4.2 Ground-Track Coverage

The GRACE-FO orbit period will change as the orbit decays from an initial altitude of about 500 km to the EOM altitude of 300 km. This will cause the spacing between the ground tracks on successive orbits to decrease slowly. When the time required for m integer orbital periods is approximately equal to n integer sidereal days and m and n are sufficiently small, the ground tracks will repeat.

Over any typical 30-day span (the nominal interval of the gravity field solution) of non-repeating orbit configurations, there will be no discernible systematic patterns in the ground-tracks, and a geographically dense data coverage is obtained. In the repeating configurations, on the other hand, there will be large and systematic gaps in the geographical layout of the ground-tracks. These tracks will fill the gaps only after a long duration (more than 30 days), or after the natural altitude decay carries the satellites through such configurations.

2.5 Satellite Description

The two GRACE-FO satellites (Figure 1) are identical, except for the S-band radio frequencies used for communication with the ground, and the K-band and laser frequencies used for the inter-satellite ranging. Both satellites are capable of flying either in the lead or trailing positions, forward or backward into the residual atmospheric wind. The spacecraft is designed as a prismatic body with side panels at a 50° angle. The panels are designed to support the stringent requirements for alignment and stability.

The satellites were launched together on a single Falcon 9 launch vehicle from Vandenberg Air Force Base, California on May 22, 2018.

2.5.1 Satellite Nomenclature

The twin GRACE-FO satellites are identical in every respect, except for the differences in the oscillator reference and the S-Band communication frequencies. Table 3 shows the satellite and instrument designations.

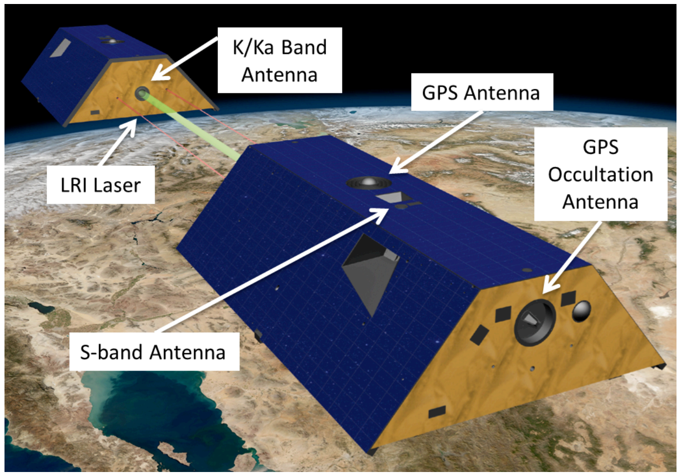

Figure 1: Twin GRACE-FO satellites. Image from "GRACE-FO Mission Plan" [3].

Description	Identifier	
Science Nomenclature	GRACE C	GRACE D
Operations Nomenclature (GSOC)	GraceFO 1 (GF1)	GraceFO 2 (GF2)
Satellite System Nomenclature (Astrium)	FM 1	FM 2
USO Frequency	4.832000 MHz	4.832099 MHz
Downlink Carrier Frequency	2211.000 MHz	2260.800 MHz
Uplink Carrier Frequency	2051.000 MHz	2073.500 MHz
Relative position after launch	Leading	Trailing
Star Camera Heads, or Camera Head Unit (CHU)	ID=1 or CHU1	ID=1 or CHU4
	ID=2 or CHU2	ID=2 or CHU5
	ID=3 or CHU3	ID=3 or CHU6
Accelerometer	FM1	FM2

Table 3: GRACE-FO satellite designations.

2.5.2 Exterior Dimensions

Figures 2 and 3 show the exterior dimensions of the GRACE-FO satellites.

2.5.3 Mass Properties

Table 4 shows the nominal launch values of mass, center of gravity, and moments of inertia of the two satellites. Mass values are updated during the mission, and provided in the MAS1A and MAS1B data products.

2.5.4 Surface Properties

Surface properties are summarized in Table 5. For each surface, the area, the components of its unit normal in SF, the material, and the emissivity and absorptivity/reflectivity coefficients are provided.

2.5.5 Sensors

The mission goals are carried out using the following science instruments:

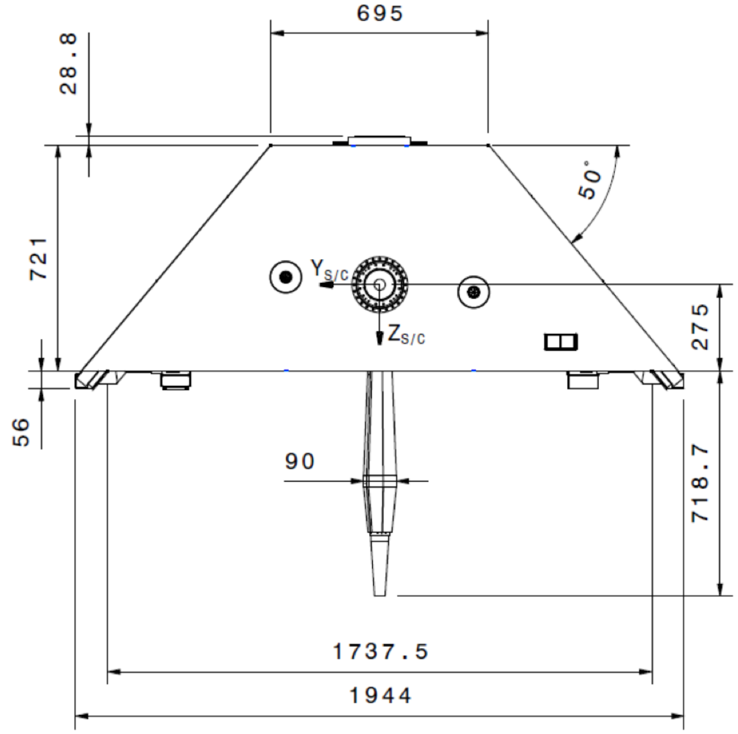

Figure 2: Front-view schematic of GRACE-FO satellite. All dimensions in mm. [4]

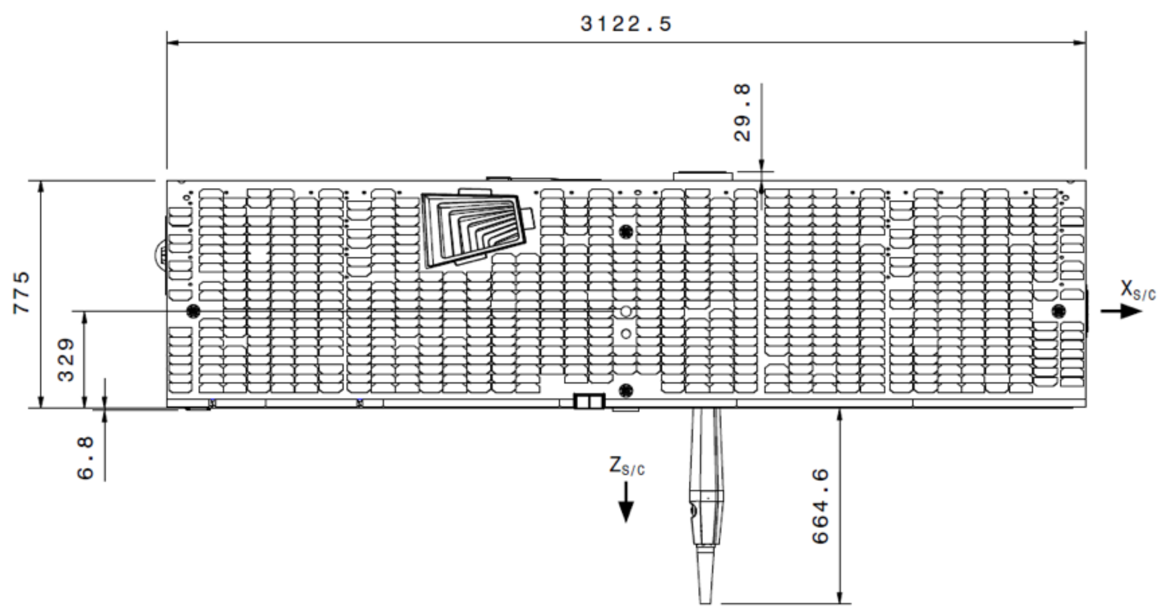

Figure 3: Side-view schematic of GRACE-FO satellite. All dimensions in mm. [4]

ACC Located at the center of mass of each satellite. Measures all non-gravitational forces acting on each satellite, including air drag, solar radiation pressure, and attitude control activator operation.

Mass Property		FM 1	FM 2
Mass at Launch [5]		601.214 kg	601.209 kg
Center of Gravity (CG) [5]	X	-0.249 mm	-0.285 mm
	Y	-0.403 mm	1.346 mm
	Z	1.266 mm	0.506 mm
Distance from CG to ACC Proof Mass [4]	ΔX	-0.08 mm	-0.06 mm
	ΔY	0.0 mm	-0.01 mm
	ΔZ	-0.15 mm	-0.04 mm
Moments of Inertia [5]	I_{xx}	110.491 kgm^2	109.635 kgm^2
	I_{yy}	580.673 kgm^2	579.759 kgm^2
	I_{zz}	649.690 kgm^2	648.795 kgm^2
	I_{xy}	-1.024 kgm^2	-0.497 kgm^2
	I_{xz}	0.347 kgm^2	0.359 kgm^2
	I_{yz}	0.036 kgm^2	0.057 kgm^2

Table 4: GRACE-FO nominal satellite mass properties in Satellite Frame (SF) at launch

Panel	Area (m2)	Unit Normal			Material	Emiss (IR)	Absorp (Vis)	Refl (Vis)		Refl (IR)	
		X	Y	Z				Geom	Diff	Geom	Diff
Front	0.9551567	+1.0	0.0	0.0	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Rear	0.9551567	-1.0	0.0	0.0	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Starboard (outer)	3.1554792	0.0	+0.766044	-0.642787	Si Glass Solar Array	0.81	0.65/0.72 (note 2)	0.05	0.30	0.03	0.16
Starboard (inner)	0.2282913	0.0	-0.766044	+0.642787	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Port (outer)	3.1554792	0.0	-0.766044	-0.642787	Si Glass Solar Array	0.81	0.65/0.72 (note 2)	0.05	0.30	0.03	0.16
Port (inner)	0.2282913	0.0	+0.766044	+0.642787	SiOx/Kapton	0.62	0.34	0.40	0.26	0.23	0.15
Nadir	6.0711120	0.0	0.0	+1.0	Teflon (note 1)	0.75	0.12	0.68	0.20	0.19	0.06
Zenith	2.1673620	0.0	0.0	-1.0	Si Glass Solar Array	0.81	0.65/0.72	0.05	0.30	0.03	0.16
Boom	0.0461901 (note 4)	–	–	–	SiOx/Kapton (note 3)	0.62	0.34	0.40	0.26	0.23	0.15

(1) Fluoro ethylene propylene

(2) 0.65 for operating solar array (i.e. power being drawn); 0.72 for non-operating array

(3) S-Band antenna on the boom is protected by a carbon radome (emiss = 0.85; absorp = 0.95), neglected here.

(4) Planar projection area of the cylindrical Boom, along any direction in the SF (X-Y) plane

Table 5: GRACE/GRACE-FO surface properties

GPS Receiver Assembly Provides navigation data and atmospheric occultation science measurements.

Inertial Measurement Unit (IMU) Measures angular velocity and provides angular changes in attitude.

KBR Precisely measures the changes in the separation between the two satellites using phase tracking of K and Ka-band signals sent between the two satellites.

LRI Precisely measures the changes in the separation between the two satellites using phase tracking of laser signals sent between the two satellites.

Laser Retro Reflector (LRR) The LRR on board each satellite provides the external calibration of the onboard microwave orbit determination system (GPS). Laser ranging data can be used to support the precise orbit determination in connection with GPS data for gravity field recovery.

SCA The three star cameras mounted close to the accelerometer on each satellite provide the precise attitude references for the satellites when making science measurements.

An overview of the instruments can be found in [6].

2.5.6 Antenna Locations

The recommended values for the locations of the antenna signal centers, in the Science Reference Frame (SRF), are provided in the following Level-1B products:

- GPS backup antenna: VGB1B
- GPS main antenna: VGN1B
- GPS occultation antenna: VGO1B
- KBR horn: VKB1B
- Satellite Laser Ranging (SLR) reflector: VSL1B

2.5.7 Thrusters

Each satellite has twelve 10-mN N_2 gas thrusters for attitude control, and two 50-mN N_2 gas thrusters for orbit control. Table 6 shows each thruster's number, ID, location relative to the origin of the SF, nominal force, intended direction of control ("Ctrl": roll, pitch, or yaw in SF), and firing direction ("Ptg": pointing in SF). The thruster locations in reference to the satellite body is also shown in Figure 4.

	No.	**ID**	**Location (mm)**			**Force (mN)**			**Ctrl**	**Ptg**
			X	**Y**	**Z**	**X**	**Y**	**Z**		
Branch 1	1	A11	-1470	-719	0	0	10	0	Y(-)	-Y
	2	A12	-1470	0	-444	0	0	10	P(+)	-Z
	3	A13	-1470	719	0	0	-10	0	Y(+)	+Y
	4	A14	-1470	0	275	0	0	-10	P(-)	+Z
	5	A15	0	-945	270	0	10	0	R(-)	-Y
	6	A16	0	-492	-270	0	10	0	R(+)	-Y
Branch 2	1	A21	1470	719	0	0	-10	0	Y(-)	+Y
	2	A22	1470	0	275	0	0	-10	P(+)	+Z
	3	A23	1470	-719	0	0	10	0	Y(+)	-Y
	4	A24	1470	0	-444	0	0	10	P(-)	-Z
	5	A25	0	492	-270	0	-10	0	R(-)	+Y
	6	A26	0	945	270	0	-10	0	R(+)	+Y
Orbit Control	1	O11	-1561	-250	0	49.4	7.9	0	dV	-X
	2	O22	-1561	250	0	49.4	-7.9	0	dV	-X

Table 6: GRACE-FO thruster properties [4]

3 SDS Data Products

3.1 SDS Overview

The SDS processes, verifies, archives, and distributes science and housekeeping telemetry data. It also receives, processes, and archives ancillary data (e.g., meteorological fields) necessary for data processing and verification.

The SDS is a distributed ground data system; system development, data processing, and archiving are shared among JPL, University of Texas, Center for Space Research (UTCSR), and GFZ. It is organized into three sequential "levels" of processing, shown in Figure 5.

These levels of processing produce the data products described below. Data products resulting from Levels-1A through 3 will be made available to the scientific community. Note that this document focuses on Level-1 data products; Levels-0, 2, and 3 are briefly described here for context.

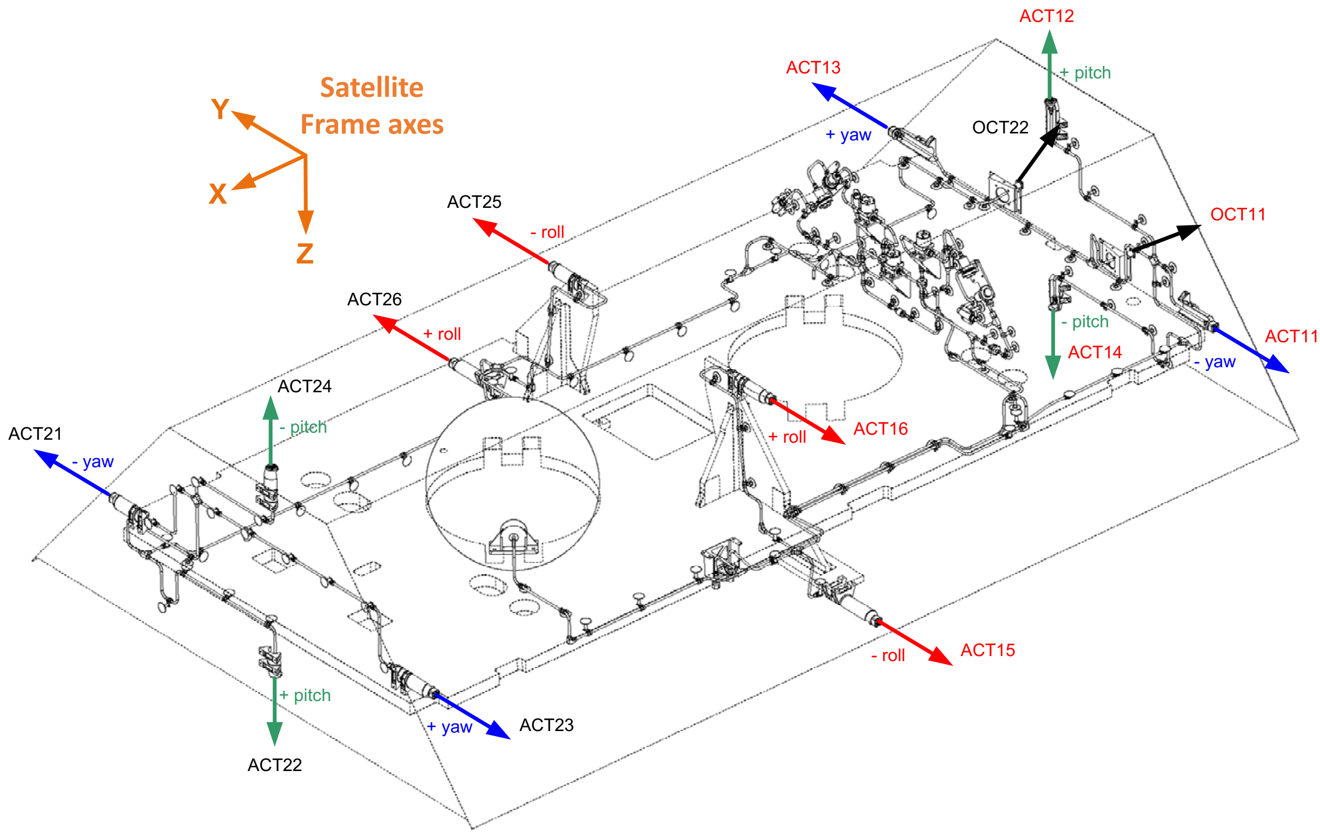

Figure 4: Locations of thrusters on satellite body.

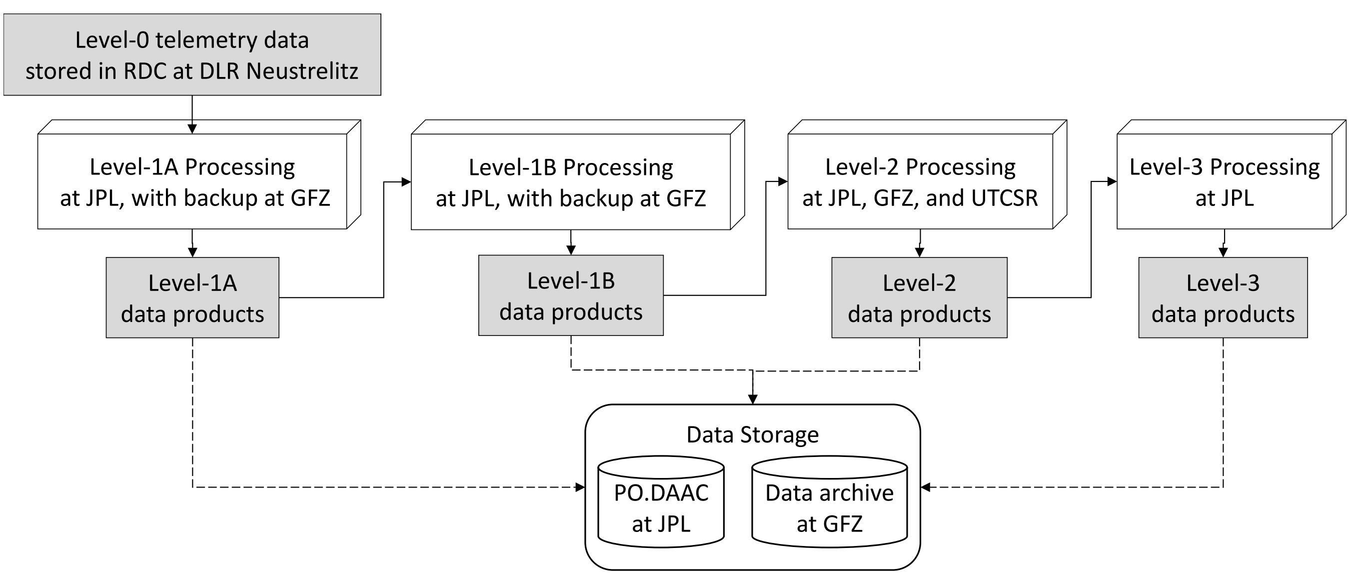

Figure 5: GRACE-FO SDS processing levels and flow.

Level-0 Data Level-0 data products are the result of telemetry data reception, collection, and decommutation by the GRACE-FO Raw Data Center (RDC) at Deutsches Zentrum Für Luft und Raumfahrt (DLR) in Neustrelitz.

The telemetry data from each downlink pass is separated into the Science Instrument and Spacecraft Housekeeping data streams, and placed in a rolling archive at the RDC. Therefore, for each downlink pass, two files (science and housekeeping) from each satellite are made available in the rolling archive. These files are defined to be the Level-0 data.

Level-1A Data Level-1A data is the result of "non-destructive" processing applied to Level-0 data. Sensor calibration factors are applied to convert the binary encoded measurements to engineering units. Where necessary, time tag integer second ambiguity is resolved and data is time tagged to the respective satellite receiver clock time. Editing and quality control flags are added, and the data is reformatted for further processing. This is considered "non-destructive" processing, meaning that the Level-1A data is reversible to Level-0, except for bad data packets. This level also includes the ancillary data products needed for processing to the next data level.

Level-1B Data Level-1B data is the result of (possibly irreversible) processing applied to Level-1A data. The data is re-tagged or resampled to GPS Time, filtered, downsampled to a lower rate, and/or converted to quantities used in Level-2 processing. Collectively, Level-1A and Level-1B processing is called Level-1 processing. This level also includes the ancillary data products generated during this processing, and the additional data needed for further processing.

Level-2 Data Level-2 data includes orbit solutions for the satellites and monthly average estimates of the Earth gravitational potential, in the form of 90x90 spherical harmonic geopotential coefficients or spherical cap mass concentrations. The gravity field model data will be available within 60 days of acquisition.

Level-3 Data Level-3 converts the monthly gravity anomalies from Level-2 into units of surface mass anomalies (typically liquid-water-equivalent-height) and maps the data to a geographical grid. Depending on the Level-2 input data type, different post-processing filters as well as geophysical data corrections are applied. The filters typically consist of some form of correlated error and/or spatial smoothing filter; the geophysical corrections involve, e.g., restoring oceanic load that was subtracted in the estimation process, and glacial isostatic effects. Level-3 grids are updated as new Level-2 data becomes available.

3.2 Data Conventions

The data content of the Level-1 data product files follow the following conventions with regards to units, time frames, and coordinate systems.

3.2.1 Units

All quantities reported are given in SI units. Any exceptions will be specifically noted in the data content description for a given data product.

- Time: seconds (s)
- Distance (range, displacement, GPS pseudorange and phase, and their errors and RMS; vector magnitudes): meters (m)
- Time derivatives of distance (velocity, acceleration, and their errors): meters per second, meters per second squared (m/s, m/s^2)
- Angles and their time derivatives: radians (rad), radians per second (rad/s), radians per second squared (rad/s^2)
- Phase (KBR and LRI phase measurements): cycles
- Frequency: hertz (Hz)

- Magnetic field strength: nanoteslas (nT)
- Current: amperes (A)
- Voltage: volts (V)
- Temperature: degrees Celsius (°C)
- Mass (satellite mass, fuel mass, and their errors): kilograms (kg)
- Pressure (tank and regulator pressure): bar (1 bar = 100000 Pa)

3.2.2 Time Frames

The time frames below are used by Level-1 data products. For information on how to convert among these time frames, see Section 3.3.1. For more information on timing, see the "GRACE Follow-On Systems Timing Description" [7].

Receiver Time The Ultra-Stable Oscillator (USO) on board each satellite serves as the frequency and time reference for that satellite. The USO reference frequency is used to generate an approximately 38-MHz signal on-board, which, in turn, is used to sample both the GPS and KBR phase measurements. The transitions of the GPS zenith (navigation) antenna sampler define the Receiver Time. It is understood in the remainder of this document that the Receiver Time refers to its specific realization on board each spacecraft.

Instrument Processing Unit (IPU), KBR, and GPS measurements (Level-1A data products) are time-tagged to within 50 picoseconds of Receiver Time. ACC and other (Level-1A) measurements are time-tagged to within 100 microseconds of Receiver Time. Although the on-board Receiver Time is reckoned in seconds from the epoch of January 6, 1980, the Receiver Time time-tags in Level-1 products will be given in seconds since the epoch of January 01, 2000, noon 12:00 hours.

LRI Time The LRI uses the USO frequency for its timekeeping, and hence runs at the same rate as Receiver Time. LRI Time is initialized at startup via a signal from the Onboard Computer (OBC); this initialization introduces a delay, or bias, of no more than 1.5 s between Receiver Time and LRI Time, which persists until the next time the LRI is rebooted [8].* This bias is often reported in telemetry datation reports, and is referred to as the datation bias. The datation bias, when known, is reported in the SOE file (see Section 3.5.2). Note that LRI uses the USO frequency upsampled eight-fold; therefore, a datation bias can be converted from clock ticks to seconds by dividing by 8 times the USO frequency.

*Note that the IPU periodically reboots to correct errors in Receiver Time due to drift in USO frequency. Because the LRI does not reboot when the IPU does, the offset of LRI Time from Receiver Time - i.e. the datation bias - is further increased by the value of this correction to Receiver Time at each IPU reboot.

OBC Time Measurements that are not IPU, KBR, or GPS are time-tagged in OBC Time. Unlike Receiver Time, this time system is not referenced to the frequency of the USO, but to a quartz oscillator on the OBC. However, these two time frames are synchronized on-board by one-second pulses generated by the IPU (which is referenced to the USO and maintains Receiver Time) and sent to the OBC, and the mapping between OBC and Receiver time-tags are available in telemetry measurements.

GPS Time For GRACE-FO, GPS time is defined as seconds past January 1, 2000, 12:00:00. This is different from other missions' definition of GPS time, which is seconds past January 6, 1980, 00:00:00. The GRACE-FO GPS time has the same rate as UTC time, but no leap seconds are applied:

GPS time = UTC time + leap seconds since epoch

where UTC time is expressed in seconds past January 1, 2000, 12:00:00.

For example:

GPS time = 90000000 sec (8-NOV-2002 04:00:00.0000 GPS)
UTC time = 89999987 sec (8-NOV-2002 03:59:47.0000 UTC)
leap seconds at 90000000 UTC = 13 sec

For a table of leap seconds past a given epoch see the International Earth Rotation Service (IERS) Earth Orientation Center at the U.S. Naval Observatory (http://maia.usno.navy.mil).

3.2.3 Coordinate Systems

The coordinate systems below are used by the data products. The satellite body-fixed frames are shown in Figure 6.

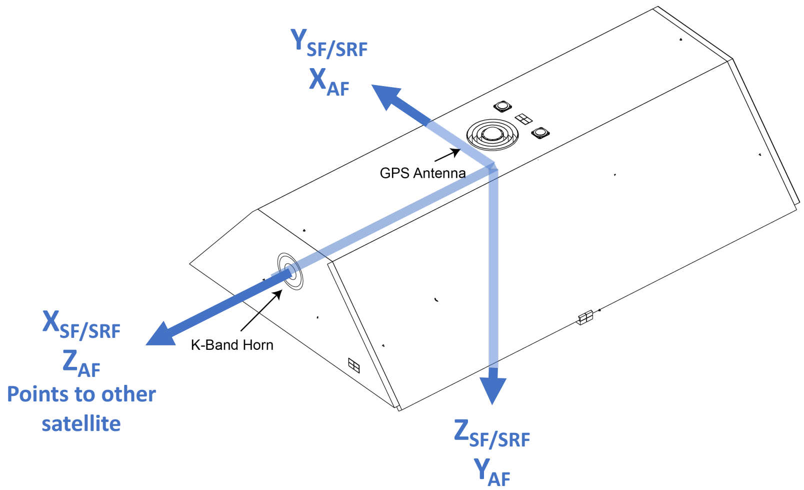

Figure 6: The satellite-body fixed frames SF, SRF, and ACC Frame (AF) in relation to the satellite body.

Satellite Frame "SF" This frame is fixed to the satellite body. It has the same origin as the AF, and its coordinate axes are as follows:

X_{SF} = from the origin to a target location of the phase center of the K/Ka Band horn (Roll Axis)
Y_{SF} = forms a right-handed triad with X_{SF} and Z_{SF} (Pitch Axis)
Z_{SF} = normal to X_{SF} and to the plane of the main equipment platform, and positive towards the satellite radiator (Yaw Axis)

During flight, the satellites have nadir-pointing Yaw axis orientation, with the Roll axes in the anti-flight and in-flight directions for the leading and trailing satellites, respectively.

Accelerometer Frame "AF" The origin of this frame is defined to be the center of mass of the ACC proof mass, which is within 0.1 mm of the satellite's center of mass. This frame is aligned by reference optical marks on the exterior surface, and its coordinate axes are directed as follows:

$X_A = +Y_{SF}$ (ACC Least Sensitive Axis)
$Y_A = +Z_{SF}$
$Z_A = +X_{SF}$

Science Reference Frame "SRF" This frame has the same origin and coordinate axes as the SF. Although the GRACE-FO ground calibrations and in-flight measurements utilize several of the coordinate systems, for consistency, all Level-1B products are provided in the SRF.

Star Camera Frame (SCF) Each satellite carries three SCAs, each of which has its own Star Camera Head unit and its own SCF. The origin of each SCF is at the intersection of the optical axis (boresight) with the mounting plane for the star camera head. The Star Camera Head nomenclature is given in Section 2.5.1. The quaternions that define the rotation between each of the three SCFs and the SRF can be found in the QSA1B data product. In general, the +Z axis of each SCF extends out along the boresight of the star camera.

Earth-Fixed Frame The Earth-Fixed Frame referenced in this document is the International Terrestrial Reference Frame (ITRF), whose realization will vary over the life of this document. As of this writing, it is ITRF2014 realized by the International Global Navigation Satellite Systems (GNSS) Service (IGS) [9]. During the life of this document, there maybe updates to this frame.

Inertial Frame The Inertial Frame is realized by a rotation of the Terrestrial Reference Frame, which is a function of time as specified in [10], with additional measurements to determine the Earth's rotation (UT1) and polar motion.

3.3 Data Product Types

This section presents the main types of Level-1 data products, with short discussions of the algorithms that produce each type. For greater detail on the Level-1 processing algorithms that are only briefly described here, see the "GRACE-FO Algorithm Specification/Theoretical Basis Document." This section was also based on the "GRACE Algorithm Theoretical Basis Document" [11].

3.3.1 Timing

All Level-1B data product time-tags are in GPS Time; no further time-tag corrections are needed to use Level-1B data. The time-tags of Level-1A data products that contain measurements are in OBC Time, with the following exceptions: GNV1A, GPS1A, KBR1A, IHK1A, and ILG1A products are time-tagged in Receiver Time, and LHK1A, LLG1A, LRI1A, and LSM1A products are time-tagged in LRI Time. A few Level-1A products that are not measurements but are the results of Level-1A processing, such as LLT1A, PCI1A, and PLT1A, have time-tags in GPS Time. For an explanation of the various time frames referenced here, see Section 3.2.2.

Figure 7 shows how Level-1 timing data products are used to convert time-tags among the time frames described in Section 3.2.2.

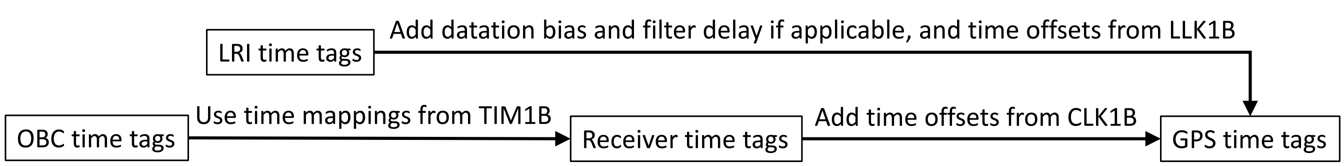

Figure 7: How timing data products are used to convert time-tags among the different GRACE-FO time frames.

Below are descriptions of the three timing data products:

CLK1B: Provides, for a given Receiver time-tag, the offset value (seconds) that needs to be added to convert it into GPS Time. This offset is a quadratic fit to the offset between Receiver and GPS Time that was estimated onboard the satellites (which can be found in the GNV1A data product), with added corrections estimated by the Precision Orbit Determination (POD) process described in Section 3.3.6.

TIM1B: Provides, for a given OBC time-tag, the corresponding Receiver time-tag. These mappings are measured on-board the satellites, where the OBC clock is synchronized to Receiver Time via per-second signals.

LLK1B: Provides, for a given LRI time-tag, the offset value (seconds) that needs to be added to convert it into GPS Time, after the datation bias (see Section 3.2.2) and a filter delay, if applicable, have been removed. These offsets are the sum of the Receiver-to-GPS Time offsets (provided in the CLK1B product) and a daily estimated offset. The daily estimated time offset is obtained via least-squares estimation that seeks to minimize the difference between LRI and KBR instantaneous, i.e., corrected, range. If there is more than one continuous LRI phase interval within an LRI1B product, a time offset is estiminated for each continuous interval. The LRI instanteous range used as input to this estimation has first been corrected for the Receiver-to-GPS Time CLK1B offsets, the datation bias, as well as an onboard phase measurement filter delay of 28802038 clock ticks = 28802038/(8*USO frequency) seconds in LRI Time, since LRI uses the USO frequency upsampled eight-fold [12]. This daily estimated offset seeks to capture any unknown bias between LRI and Receiver Time outside of the known datation bias and filter delays. Therefore, the LLK1B offsets should be applied to LRI time-tags after the datation bias and applicable filter delays have been removed from them - see below.

Using the time offset values from these products, any data record - which is essentially a time-tag paired with numerical value(s) - can be converted from one time frame to another via the following steps:

1. For LRI1A, LSM1A, and LHK1A: convert datation bias (from SOE file; see Section 3.5.2) from clock ticks to seconds by dividing by 8*nominal USO frequency (see Table 3), and subtract the datation bias from the time-tags. For LRI1A, also subtract an additional onboard filter delay of "28802038 clock ticks / (8*USO frequency)" seconds from the time-tags. For LHK1A records with the sensor names "i_[0, 1, 2, 3]" and "q_[0, 1, 2, 3]", also subtract an additional onboard filter delay of "3999960 clock ticks / (8*USO frequency)" from the time-tags [13].
2. Get the offset value for the data time-tag, via linear interpolation on the offset values in the timing product.
3. Add the offset value to the data time-tag - this converts the time-tag to its value in the destination time frame.
4. Via quadratic Lagrange interpolation, get the data value at the original time-tag's numerical value, before the offset was added.

In this way, data can be converted from one time frame to another without changing the numerical values of its time-tags.

3.3.2 Ranging

Each satellite carries a set of KBR and LRI instruments, with which microwave K band and laser signals are sent between the two satellites. The line-of-sight distance change between the two satellites, partially induced by the variations in Earth's gravity field, is derived from measured phase changes in these inter-satellite signals.

The signal phase change measurements, which are ~10 Hz, are provided in the KBR1A and LRI1A data products. The quality of these phase change measurements is checked, and data quality flags are set. Items checked include breaks in the phase measurements, time gaps, and "discontinuities" between K and Ka band measurements (if the difference between the K phase values and 0.75 of the Ka phase values exceeds 0.05 cycle at a given time-tag). The time frame of the measurements are converted from Receiver Time (for K-band measurements) or LRI Time (for laser measurements) to GPS Time; see Section 3.3.1 for how this time conversion is done.

Then, the biased range is formed from the phase measurements. This biased range is the true inter-satellite range plus an unknown bias; the bias is arbitrary for each piecewise continuous segment of signal phase change measurements and may change over day boundaries.

The KBR biased range, also known as Dual One Way Range (DOWR), is formed at each measurement time-tag as follows:

$$\Psi = c * (\psi_C + \psi_D)/(f_C + f_D)$$

where

Ψ = K or Ka biased range
c = speed of light
ψ_C = K or Ka phase measurement at satellite C
ψ_D = K or Ka phase measurement at satellite D
f_C = K or Ka frequency of satellite C
f_D = K or Ka frequency of satellite D

The K and Ka band frequencies come from the USO1B data product, which takes into account the drift in the USO clock frequency (which can be found in the CLK1B data product).

Furthermore, for K band, the ionosphere-free biased range combination is calculated as:

biased range = ($\mathrm{ion_{Ka}}$ * Ψ_{Ka}) - ($\mathrm{ion_K}$ * Ψ_K)

where

$\mathrm{ion_{Ka}}$ = 16/7
$\mathrm{ion_K}$ = 9/7
Ψ_K = biased K range
Ψ_{Ka} = biased Ka range

The interpretation of LRI phase measurements differ for each satellite depending on whether it is operating in the role of the "master" or "transponder" satellite. Whether satellite C or D is operating in the master or transponder role at a given time can be determined from the SOE file (see Section 3.5.2). When the master's laser signal arrives at the transponder, the transponder adds a frequency of 10 Mhz (as determined according to the onboard frequency of the transponder's USO) to the incoming signal, and sends it back to the master. Thus, the master's phase measurement contains the round-trip (master to transponder to master) range measurement plus a transponder-added ramp component. [14]

The LRI biased range, also known as Two-Way Range (TWR), is formed at each measurement time-tag as follows:

$\Psi = c * (-\psi_M(t) + R_T(t-\tau))/(2f)$

where

Ψ = laser biased range
c = speed of light
$\psi_M(t)$ = laser phase measurement at master satellite, whether it be C or D, at time t
$R_T(t-\tau)$ = transponder-added phase ramp value at time t-τ. In Level-1 processing, the actual transponder phase measurement $\psi_T(t-\tau)$ is used in this calculation.
τ = time it takes for light signal to travel from transponder and arrive at master at time t
f = laser frequency at "master" satellite. Nominal ground-measured values are 2.81616393e14 Hz for satellite C and 2.81615684e14 for satellite D [15].

Ionospheric correction is not done for laser ranging.

Then, gaps in the range data that are shorter than 21.0 s in size are filled in with cubic interpolation (lower orders of interpolation are used if there are fewer than 2 data points on either side of the gap to be filled). Finally, the range values are passed through a "CRN" filter that down-samples them to the desired output frequency and calculates their first two time derivatives, inter-satellite range rate and range acceleration (K-band and laser range values are filtered using different filter parameters). Each filtered range value will have its data quality flag set to indicate the amount of interpolated range values that were used in the filtering process for that value.

The following corrections for the biased range are also calculated from 10 Hz data and CRN-filtered down to the desired output frequency:

Light Time Correction: This is an additive correction to the range that accounts for the fact that both satellites are moving along their lines of sight while the K-band and laser signals are being transmitted between them (it takes less time for the signal originating from the leading satellite to be received by the trailing satellite, and more time for the signal originating from the trailing satellite to be received by the leading satellite). This "light time" correction is calculated using the products of orbit determination (the PLT1A product for the KBR case and the LLT1A product for the LRI case). Its first two time derivatives - to be used as additive corrections to range rate and range acceleration - are also calculated via the CRN filter.

Antenna Offset Correction (for K-Band Ranging only): K-band signals do not originate from the satellites' center-of-mass locations, but from the "phase centers" of the KBR horns (antennas). Therefore, there is an additive correction to the inter-satellite KBR range to make it more closely describe the range between the satellites' centers of mass. This correction is calculated as the projection of the antenna offset vector (the vector from each satellite's center of mass to the phase center of its KBR horn) on the line-of-sight between the two satellites (determined from satellite attitude information in the SCA1B data products and state information in the GNI1B data products). Its first two time derivatives - to be used as additive corrections to range rate and range acceleration - are also calculated via the CRN filter. These antenna offset corrections are also provided in the PCI1A data products.

LRI Scale Correction (for Laser Ranging only): The frequency of the laser signal is determined by a physical "cavity" on the LRI. The assumed nominal frequencies are the ground-measured values of 2.81616393e14 Hz for satellite C and 2.81615684e14 for satellite D [15]. Since the exact value of that frequency changes over the mission and cannot be measured onboard, the LRI phase difference measurements cannot be accurately translated to range differences (since range = speed of light * phase values / frequency). Therefore, a daily multiplicative scale correction to the range quantity and its time derivatives is estimated via least-squares estimation that seeks to minimize the difference between LRI and KBR instantaneous, i.e., corrected, range. In other words:

$\lambda = \lambda_0(1 + \epsilon)$

where

λ = corrected scaled wavelength of phase measurements
λ_0 = wavelength of phase measurements according to nominal ground-measured laser frequency
ϵ = correction estimated by comparing LRI and KBR instantaneous/corrected ranges. LRI range quantities and its time derivatives are multiplied by $1 + \epsilon$.

A scale correction is estimated for each continuous interval of LRI range values that also has an overlapping interval of KBR range values. This scale correction and the daily time offset described in Section 3.3.1 are estimated together.

LRI Phase Glitch Removal (for Laser Ranging only): LRI1A phase measurements contain "glitches", or small jumps in phase, that occur at thruster firings. For the most part, the phase glitches seen in the two satellites' measurements correspond to each other. Level-1 processing detects phase glitches by checking the sizes of the third finite differences of the phase measurements. Then, a filter glitch response model - a model of the response of the onboard phase measurement filter to a phase glitch - is fitted to the detected glitches. This fit is removed from the phase measurements, reducing the size of the glitch [16]. Note, however, that glitches are not completely removed, and remaining residuals can be seen in the TWR quantity and its time derivatives in the LRI1B product. These residuals can be larger when the size of the original phase jump is unusually large or if the glitch pattern does not match the filter glitch response model well. Note that these remaining residuals visible in the TWR quantities have been passed through a CRN filter, which alters their character. For further explanation and analysis of phase glitches, see [17].

The KBR1B and LRI1B data products contain the filtered biased ranges, the corrections described above, and the first two time derivatives of the light time and KBR antenna offset corrections. Although KBR and LRI ranging attempt to measure the same inter-satellite range quantity, systematic differences can be seen between the corrected KBR1B and LRI1B range quantities and their time derivatives. These differences may be affected by the process by which LRI phase measurements are corrected, in particular the accuracy of the estimation and application of the aforementioned scale correction and time offset, and possibly by characteristics intrinsic to the phase measurements themselves. Ongoing work is needed to understand such factors in comparing KBR and LRI range data.

3.3.3 Attitude

The GRACE-FO attitude is reconstructed through an optimal combination of SCA1A and IMU1A, when possible. A Kalman filter algorithm combines the given input sensor data into a higher fidelity attitude solution than can be achieved from SCA data alone.

There are 3 star camera head units onboard each GRACE-FO spacecraft, which provide measurement with approx. 2 Hz sampling rate. The cameras are subject to regular blinding by the sun and moon, but the arrangement of the three star cameras ensures that data from at least two cameras is present at most times in the mission.

The GRACE-FO IMU consists of 4 fiber optic gyroscopes in tetrahedral configuration. The IMU1A data represent filtered angle in individual gyro frames, given at 8 Hz sampling rate. The filtered angle is then transformed into angular rates about the SRF axes and input into the Kalman filter. Any configuration of three gyros allows computation of the spacecraft angular rates.

The satellite attitude estimates are formed from a tuned combination of the attitude instrument data incorporating data-based models of the instrument noise profiles. SCA noise is modeled as point-by-point white noise, field-of-view dependent noise and alignment error on each camera. More information about the SCA noise models can be found in [18]. IMU noise is modeled with bias random walk, once-per-revs and twice-per-revs model. The final attitude solution is then provided in SCA1B data product.

3.3.4 Accelerometer

The ACC1A data products contain the measured linear and angular acceleration components of the ACC proof mass of each satellite. Linear acceleration measurements are 10 Hz. Angular acceleration measurements are 1 Hz for the GRACE mission and 10 Hz for the GRACE-FO mission.

The quality flags of this Level-1A data are checked, and the time frame of the 10-Hz linear acceleration measurements are converted from OBC to GPS Time using the TIM1B and CLK1B data products. This is done by correcting the time-tags to GPS time, then resampling the phase values at time-tags that are multiples of 0.1 s via quadratic Lagrange interpolation. GRACE angular 1-Hz measurement values are not resampled in this way; their time-tags are simply changed to their nearest integer values in GPS time. For GRACE-FO, angular 1-Hz values are taken as averages over 1-second intervals of the 10-Hz measurements.

Data gaps that are 100 s or shorter are filled via cubic interpolation that uses up to 200 data points on other side of the gap. Gaps longer than 100 s are not filled. Finally, the linear acceleration values are compressed using a CRN filter (using different filter parameters than in range filtering) to a frequency of 1 Hz. The data at each time-tag will have its data quality flag set to indicate the amount of interpolated "filled" values that were used in the filtering process for that value. For the GRACE mission, these final values can be found in the ACC1B data products.

To enable more optimal gravity field recovery for the GRACE-FO mission, the calibrated accelerometer products ACT1A and ACT1B are provided. The ACT1A product is derived from ACC1A data using a variety of calibration procedures detailed in [19]. The ACT1A data product is then converted to ACT1B using the aforementioned procedure for converting ACC1A to ACC1B. Note that the angular acceleration values in the ACT1A and ACT1B are set to zero. Due to the necessity of these calibrations, ACC1A, but not ACC1B, products will be provided for the GRACE-FO mission.

3.3.5 GPS Tracking Flight Data

GPS1A data products contain three range measurements (CA, L1, and L2) at 10-s intervals and three phase measurements (CA, L1, and L2) at 1 Hz. The GPS1B data products contain final processed values: three range measurements (CA, L1, and L2) and three phase measurements (CA, L1, and L2), all at 10-s intervals. The Level-1 processing that occurs between these two products is described below.

The phase measurements are checked for L1-L2 and CA-L2 continuity. A data quality flag is set if phase discontinuity exceeds one L1 cycle. Cycle slips, i.e., phase discontinuities within an arc, are also identified. The time-tags of all data are corrected from Receiver to GPS Time using the CLK1B data product. Data is also edited for too-low Signal-to-noise ratio (SNR) values.

Ionospheric effects, calculated as below using the phase data, are then removed from range data:

negative-ion CA phase $= (2.546 + 1.546)\phi_{CA} - 2(1.546)\phi_2$
negative-ion L1 phase $= (2.546 + 1.546)\phi_1 - 2(1.546)\phi_2$
negative-ion L2 phase $= 2(2.546)\phi_1 - (2.546 + 1.546)\phi_2$

where ϕ_{CA} = CA carrier phase, ϕ_1 = L1 carrier phase, and ϕ_2 = L2 carrier phase.

The phase values are smoothed and compressed using a cubic fit. Then, ionospheric effects are calculated again using the smoothed and compressed phase values and added back to the range data. Finally, a bias is added to the phase values to make them close to their range counterparts.

3.3.6 Orbit

POD, a process similar to the one used for GRACE [20], uses GPS data (e.g., GNV1A) to determine the clock offset between Receiver Time, in which the KBR measurements are time-tagged, and GPS time. This process fixes the integer ambiguities of the carrier phase biases to a network of GPS ground receivers and adjusts a time series of stochastic accelerations to account for unmodeled forces. The USO driving the GRACE-FO GPS receiver is the same oscillator driving the KBR instrument; the clocks for GPS and KBR are the same up to a bias. The clock offsets, including relativistic effects, are recorded in the CLK1B product.

In the process of determining the relative clock offsets, the precise position and velocity are also determined. The time series of the satellites' position and velocity in Earth-fixed coordinates are output to the GNV1B product, and to the GNI1B product in inertial coordinates. In addition, the PLT1A and LLT1A products contain the inertial states as well as inter-satellite signal travel "light" times. These orbit solutions and light times are then used to compute the "light time" corrections to convert KBR and LRI biased range measurements and their time derivatives, which include time-of-flight and geodesic effects (with the Earth as a point mass determining the general relativistic geodesic distance), to Euclidean biased range values - see Section 3.3.2 for more information.

3.3.7 Housekeeping

Housekeeping data products contain instrument health and calibration data, which are collected onboard and can be used to make corrections to the main measurements. The Level-1A products contain time-tags in OBC time, while Level-1B products contain time-tags in GPS time.

- ACC: AHK1A, AHK1B
- High resolution temperature: HRT1A, HRT1B
- IPU: IHK1A, IHK1B
- IPU log messages: ILG1A
- LRI: LHK1A, LHK1B
- LRI log messages: LLG1A
- Magnetometer and magnetorquer: MAG1A, MAG1B
- Spacecraft Mass: MAS1A, MAS1B
- Thrusters: THR1A, THR1B
- Cold Gas Tank: TNK1A, TNK1B

3.3.8 Calibration

The following calibration data products contain satellite and instrument physical properties. Since this information does not get updated often, they are not produced on a daily basis. The list is as follows, organized by instrument:

KBR

- VKB1B: vector offset from ACC proof mass (origin of SF, SRF, and AF) to KBR horn phase center

SCA

- QCP1B rotation quaternions from the combined SCA "pilot" frame to the KBR pointing frame (in which X axis is along KBR boresight)
- QSA1B: rotation quaternions from SCFs into SRF

GPS

- VGB1B: vector offset from SRF origin to GPS backup navigation antenna
- VGN1B: vector offset from SRF origin to GPS main antenna
- VGO1B: vector offset from SRF origin to GPS occultation antenna

Other

- VCM1B: vector offset from ACC proof mass to satellite center of mass, from calibration maneuvers or tracking model
- VSL1B: vector offset from SRF origin to SLR corner cube reflector

3.4 Data Product Format

The Level-1 data products contain data that span one day in GPS Time, and are released in ASCII text format. Although the data content differs among the products (this is described in detail in Section 4), below are format characteristics that apply to all products.

3.4.1 File Naming Convention

The file naming convention for all data products is as follows:

PRDID_YYYY-MM-DD_S_VV.asc

where

PRDID = product identification label. For example, "ACC1A"
YYYY = year
MM = month
DD = day of month
S = satellite identifier. For example, "C," "D," or "Y" (combined data from satellites "C" and "D." "X" = combined data from satellites "A" and "B")
VV = SDS software version number

For example, the data product named "KBR1B_2019-01-01_Y_04.txt" contains Level-1B KBR data over the GPS date January 01, 2019 combined from both satellites, processed using SDS software version number 4. Note that version number "0" indicates that the data product is the result of daily "quicklook" processing, while a non-zero version number indicates that it is a "final" product. Quicklook products are produced on a daily basis using whatever telemetry comes in for that day; final products, released many days later, may contain late-arriving telemetry data that is missing in quicklook products.

3.4.2 File Structure and Content

Each data product file contains two parts: a header and a body.

Header Each file begins with an informational header in the YAML format. After the line "`#End of YAML header`" at the end of this header, time-tagged data records begin. Note that although accuracy is strived for in data product headers for informational purposes, it is generally not advised to design one's data processing to depend upon their contents. Below is a sample KBR1B header. Note that this is a draft header, and the final version may differ slightly in fields and values:


```
header:
  dimensions:
    num_records: 17281
  global_attributes:
    acknowledgement: GRACE-FO is a joint mission of the US National Aeronautics and Space
    Administration and the German Research Center for Geosciences.  Use the digital object
    identifier provided in the id attribute when citing this data.
    See https://podaac.jpl.nasa.gov/CitingPODAAC
    conventions: CF-1.6, ACDD-1.3, ISO 8601
    creator_email: gracefo@podaac.jpl.nasa.gov
    creator_institution: NASA/JPL
    creator_name: GRACE Follow-On Science Data System
    creator_type: group
    creator_url: http://gracefo.jpl.nasa.gov
    date_created: 2019-05-15T23:21:00Z
    date_issued: 2019-05-16T16:09:52Z
    history:
      - "INPUT FILE NAME               : KBR1A_C_0<-KBR1A_2019-01-01_C_04.dat"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_C_0<-2019-04-08 18:12:41 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_C_0<-9a1b2"
      - "INPUT FILE BUILDTIME TAG      : KBR1A_C_0<-1:03_PDT"
      - "INPUT FILE NAME               : KBR1A_D_0<-KBR1A_2019-01-01_D_04.dat"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_D_0<-2019-04-08 18:12:46 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_D_0<-9a1b2"
      - "INPUT FILE BUILDTIME TAG      : KBR1A_D_0<-1:03_PDT"
      - "INPUT FILE NAME               : KBR1A_C_1<-KBR1B_2019-01-01_C_04.dat"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_C_1<-2019-05-15 23:00:06 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_C_1<-8293"
      - "INPUT FILE NAME               : KBR1A_D_1<-KBR1B_2019-01-01_D_04.dat"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_D_1<-2019-05-15 23:00:10 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_D_1<-8293"
      - "INPUT FILE NAME               : KBR1A_C_2<-KBR1B_2019-01-01_C_04.dat.ord"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_C_2<-2019-05-15 23:02:32 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_C_2<-9a1b2"
      - "INPUT FILE NAME               : KBR1A_D_2<-KBR1B_2019-01-01_D_04.dat.ord"
      - "INPUT FILE CREATION TIME (UTC): KBR1A_D_2<-2019-05-15 23:02:36 by operator"
      - "INPUT FILE SOFTWARE VERSION   : KBR1A_D_2<-9a1b2"
      - "INPUT FILE NAME               : PCI1A_C<-PCI1A_2019-01-01_C_04.dat"
      - "INPUT FILE CREATION TIME (UTC): PCI1A_C<-2019-05-07 23:10:02 by operator"
```

```
    - "INPUT FILE NAME               : PCI1A_D<-PCI1A_2019-01-01_D_04.dat"
    - "INPUT FILE CREATION TIME (UTC): PCI1A_D<-2019-05-07 23:10:04 by operator"
    - "INPUT FILE NAME               : USO1B_C<-USO1B_2019-01-01_C_04.dat"
    - "INPUT FILE CREATION TIME (UTC): USO1B_C<-2019-04-18 21:42:19 by operator"
    - "INPUT FILE NAME               : USO1B_D<-USO1B_2019-01-01_D_04.dat"
    - "INPUT FILE CREATION TIME (UTC): USO1B_D<-2019-04-18 21:42:23 by operator"
  id: 10.5067/GFJPL-L1B04
  institution: NASA/JPL
  instrument: KBR
  instrument_vocabulary: NASA Global Change Master Directory instrument keywords
  keywords: GRACE-FO, KBR
  keywords_vocabulary: NASA Global Change Master Directory (GCMD) Science Keywords
  license: https://science.nasa.gov/earth-science/earth-science-data/data-information-policy
  naming_authority: org.doi.dx
  platform: GRACE C+D
  platform_vocabulary: NASA Global Change Master Directory platform keywords
  processing_level: 1B
  product_version: 04
  program: NASA Earth Systematic Missions Program
  project: NASA Gravity Recovery And Climate Experiment Follow-On (GRACE-FO)
  publisher_email: podaac@jpl.nasa.gov
  publisher_institution: NASA/JPL
  publisher_name: Physical Oceanography Distributed Active Archive Center
  publisher_type: group
  publisher_url: http://podaac.jpl.nasa.gov
  references: https://podaac.jpl.nasa.gov/gravity/gracefo-documentation
  source: Inter-satellite range, range rate and range acceleration from KBR between GRACE-FO satellites
  summary: Biased inter-satellite ranges and their first two time derivatives, range rate and range accel
  time_coverage_start: 2019-01-01T00:00:00.00Z
  time_coverage_stop: 2019-01-02T00:00:00.00Z
  title: GRACE-FO Level-1B K-Band Ranging Data
non-standard_attributes:
  epoch_time: 2000-01-01T12:00:00.00Z
  software_build_time: 2019-05-06T14:04:51-07:00
  software_version: 49573
  start_time_epoch_secs: 599572800
  stop_time_epoch_secs: 599659200
variables:
  - gps_time:
      comment: 1st column
      coverage_content_type: referenceInformation
      long_name: Continuous seconds past 01-Jan-2000 11:59:47 UTC
      units: second
  - biased_range:
      comment: 2nd column
      coverage_content_type: physicalMeasurement
      long_name: CRN-filtered biased inter-satellite range with ionospheric correction
      units: m
  - range_rate:
      comment: 3rd column
      coverage_content_type: modelResult
      long_name: First time derivative of biased_range
      units: m/s
  - range_accl:
```

```
    comment: 4th column
    coverage_content_type: modelResult
    long_name: Second time derivative of biased_range
    units: m/s2
- iono_corr:
    comment: 5th column
    coverage_content_type: modelResult
    long_name: biased ionospheric correction for biased_range, for Ka frequency
- lighttime_corr:
    comment: 6th column
    coverage_content_type: modelResult
    long_name: Light time correction for biased_range
    units: m
- lighttime_rate:
    comment: 7th column
    coverage_content_type: modelResult
    long_name: Light time correction for range_rate
    units: m/s
- lighttime_accl:
    comment: 8th column
    coverage_content_type: modelResult
    long_name: Light time correction for range_accl
    units: m/s2
- ant_centr_corr:
    comment: 9th column
    coverage_content_type: modelResult
    long_name: Antenna phase center offset correction for biased_range
    units: m
- ant_centr_rate:
    comment: 10th column
    coverage_content_type: modelResult
    long_name: Antenna phase center offset correction for range_rate
    units: m/s
- ant_centr_accl:
    comment: 11th column
    coverage_content_type: modelResult
    long_name: Antenna phase center offset correction for range_accl
    units: m/s2
- K_A_SNR:
    comment: 12th column
    coverage_content_type: physicalMeasurement
    long_name: SNR of K band for GRACE-FO C satellite
    units: 0.1 db-Hz
- Ka_A_SNR:
    comment: 13th column
    coverage_content_type: physicalMeasurement
    long_name: SNR of Ka band for GRACE-FO C satellite
    units: 0.1 db-Hz
- K_B_SNR:
    comment: 14th column
    coverage_content_type: physicalMeasurement
    long_name: SNR of K band for GRACE-FO D satellite
    units: 0.1 db-Hz
- Ka_B_SNR:
```

```
        comment: 15th column
        coverage_content_type: physicalMeasurement
        long_name: SNR of Ka band for GRACE-FO D satellite
        units: 0.1 db-Hz
    - qualflg:
        comment: 16th column
        coverage_content_type: qualityInformation
        flag_masks: 1b, 2b, 4b, 8b, 16b, 32b, 64b, 128b
        flag_meanings:
          - bit 0 = Phase break
          - bit 1 = unreliable PCI1A data for ant_centr_corr
          - bit 2 = interpolated PCI1A data for ant_centr_corr
          - bits 3-4 = Not defined
          - bit 5 = data corrected for time tag bias in either K or Ka phase
          - bit 6 = Interpolated data point (due to gap) exists > 5 s from center of CRN filter window
          - bit 7 = Interpolated data point (due to gap) exists <= 5 s from center of CRN filter window
        long_name: Quality flags, rightmost is bit 0
# End of YAML header
```


The section "`variables`" describes each column field in the data records, and will obviously differ for each type of data product.

Body After the header comes the data content of the file. Each line is one data record, and the parameters of each data record are arranged in whitespace-separated columns. Section 4 describes the data record parameters for the different types of data products. The data parameters follow the conventions described in Section 3.2.

3.4.3 Quality and Product Flags

All data records, regardless of product type, have a parameter called a data quality flag. A quality flag consists of 8 digits, to be read from right to left, each of which can be set to "0" or "1." For example, a quality flag with no flags set looks like "`00000000`," and a quality flag with flag positions 0 and 4 set looks like "`00010001`." Each of the eight flag positions, if set, denote information about the quality of the data record. Each data product type has different meanings assigned to each flag position; see Section 4 for the flag position meanings for a given data product type.

The data records of some product types also contain a parameter called a product flag. Unlike a quality flag, a product flag denotes what type of values the data record contains. For example, the following is a sample TNK1B data record:

```
137419201 889949 G C 1 00000000 00000011 208.1166381835938 1.690819978713989
```

According to the parameter description for this product type, the parameter "`00000011`" is a product flag, and the fact that flags 0 and 1 are set mean that the following two values, "`208.1166381835938`" and "`1.690819978713989`," are the tank pressure and the regulator pressure, respectively. If the product flag position for a certain kind of data value is not set, then that data value is not present in that data record. Note that the number of flag positions in a product flag can vary between products; see Section 4 for information on the product flag for a given data product type.

3.5 Related Files

3.5.1 Report Files

Every data product - aside from the non-daily products listed in Section 3.3.8 - comes with a report file, which contains statistics for that data product. A report file shares the same name as its data product, except with the extension ".rpt" instead of ".txt," and is a text file that contains one line of space-delimited values. The first 19 values in every report file are as follows, in the following order:

1. Name of data product file that this report file describes
2. Date in name of data product file, expressed as the time of midnight of that date, in seconds past January 1, 2000 12:00 UTC
3. Report file creation time, expressed in seconds past January 1, 2000 12:00 UTC
4. Time-tag of first data record
5. Time-tag of last data record
6. Number of data records
7. Average time interval between time-tags of successive data records. This includes the gap between the intended start epoch of the data product and the first data record time-tag, and the interval between the last data record time-tag and the intended end epoch of the data product, if these start/end gaps are > 1 s. (Note that the intended start/end epochs are of the product used within JPL SDS Level-1 processing, and not the midnight epochs to which the data product is trimmed before public release.)
8. Standard deviation of time intervals between time-tags of successive data records
9. Minimum time interval between time-tags of successive data records
10. Maximum time interval between time-tags of successive data records
11. Number of quality flag bits (this is usually "8")

12-19. Total number of quality flags set among all data records, from quality flag 0 (right-most flag) through quality flag 7 (left-most flag), respectively. See Section 3.4.3 for more information.

For some data products, its report file will contain additional values listed after these common values. See the description for a specific data product in Section 4 for these additional report file values.

3.5.2 SOE File

The SOE file records satellite events and changes in the state of satellite sensors - this information may be used in Level-1B processing. Each line, or record, in the file contains space-delimited values in the order below. Note that if the first value in a line is "x," then that record is considered to be deleted.

1. Time-tag in GPS Time. The satellite event or sensor state value(s) in this record applies from this time-tag, to the time-tag of the next record with the same satellite and sensor/event identifier.
2. Satellite identifier
3. Sensor/event identifier. See Table 7 for list of possible identifiers.
4. "N," or number of numerical values to follow in this record. See Table 7 for the number of values for a given sensor/event identifier.

5 to 4+N. Numerical values for this event or sensor state. See Table 7 for the description of the numerical values for a given sensor/event identifier.

5+N. Text comment, such as time, date, and user who added this record

Table 7 lists the possible sensor/event identifiers and the numbers of values for each, along with the descriptions of the values.

Sensor or Event	No. of Values	Description of Values
ACC	1	'1' = main Interface Control Unit (ICU) active, '2' = redundant ICU active
ACCTEMPCAL	1	Duration of ACC temperature calibration
AOCS	1	'0' = AOCS NO_MODE, '1' = AOCS CMCMP (course pointing mode), '2' = AOCS CIMCMP (course pointing mode), '3' = AOCS AHM (attitude hold mode), '4' = AOCS BAHM (back up attitude hold mode), '5' = AOCS SM (science mode), '6' = AOCS BSM (back up science mode)
ICUVP	1	'0' = NOMINAL Vp value, '1' = OFF NOMINAL Vp value
IPU	1	'1' = main IPU active derived from IPU log message, '2' = redundant IPU active derived from IPU log message. Extra values may be ignored.
IPUR	3	Value 1: '1' = main IPU active, '2' = redundant IPU active, '-1' = IPU active not known from IPU log message Value 2: Time of IPU nudge from IPU log message (GPS seconds) Value 3: '1' = IPU flash OK, '2' = IPU flash corrupted, '-1' = IPU flash state not known from IPU log message Extra values may be ignored.
K_MI	3	Offset to be added to time-tag of K band phase measurements = constant bias term + rate of bias * (time-tag - offset of time-tag) Value 1: constant bias term Value 2: rate of bias Value 3: offset of time-tag
KAMI	3	Offset to be added to time-tag of Ka band phase measurements = constant bias term + rate of bias * (time-tag - offset of time-tag) Value 1: constant bias term Value 2: rate of bias Value 3: offset of time-tag
KBR	1	'1' = main KBR, '2' = redundant KBR
KTOFF	1	Time-tag offset to be applied to K and Ka band phase measurements
LRI	1	'0' = This satellite is in "master" role in laser ranging, '1' = This satellite is in "transponder" role in laser ranging
LRIDATATION	1	Number of clock cycles, at the frequency of 8 times the onboard USO frequency, by which LRI Time is offset from Receiver Time
MANV	4	Orbit Control Thruster maneuvers Value 1: Thruster on-time Value 2: Thruster force (N) along $+X_{SF}$ ("along-track") direction Value 3: Thruster force (N) along $+Y_{SF}$ ("cross-track") direction Value 4: Thruster force (N) along $+Z_{SF}$ ("radial") direction. This should be 0.
MTEA	3	X, Y, and Z-axis distances traveled by Trim Mass Assembly 1 since launch (mm)
MTEB	3	X, Y, and Z-axis distances traveled by Trim Mass Assembly 2 since launch (mm)
QSA	5	Value 1: Star camera head ID number Values 2-5: $\cos(\theta/2)$, i, j, and k-components of the rotation quaternion from the SCA to SRF Frame.
USO	1	'1' = main USO for satellite C, '3' = redundant USO on satellite C, '2' = main USO for satellite D, '4' = redundant USO on satellite D
VCM	3	X, Y, and Z-coordinates of center of mass in SRF
VGB	6	X, Y, and Z-coordinates of the L1 and L2 phase centers, respectively, for the GPS backup antenna in SRF
VGN	6	X, Y, and Z-coordinates of the L1 and L2 phase centers, respectively, for the GPS navigation antenna in SRF

VGO	6	X, Y, and Z-coordinates of the L1 and L2 phase centers, respectively, for the GPS occultation antenna in SRF
VKB	3	X, Y, and Z-coordinates of the KBR phase center in SRF
VSL	3	X, Y, and Z-coordinates of the SLR corner cube reflector in SRF

Table 7: SOE satellite/event identifiers, and the number and description of values for each.

3.5.3 GPS RINEX Files

The GPS data in the GPS1A and GPS1B data products will also be provided in the RINEX format. Currently, the RINEX Version 2 format is used, but Version 3 may eventually be adopted for data from the GRACE-FO Science Phase.

3.6 Data Product Distribution

GRACE-FO data, of which the Level-1 data products described in this document are only a subset, are archived and distributed through two agencies:

JPL PO.DAAC The PO.DAAC is one element of the Earth Observing System Data and Information System (EOSDIS), developed by NASA. The goal of the PO.DAAC is to serve the needs of the oceanographic, geophysical, and interdisciplinary science communities that require physical information about the oceans. Its archive of data products can be accessed at `https://podaac.jpl.nasa.gov`.

GFZ Information System and Data Center (ISDC) The ISDC is an access point for all manner of geoscientific data, its corresponding metadata, scientific documentation, and software tools. It is run and maintained by GFZ and can be accessed at `https://isdc.gfz-potsdam.de`.

4 Level-1 Data Products

This section describes the data content of the individual Level-1A and Level-1B product types, in Sections 4.1 and 4.2 respectively. See Section 3.2 for data units, time frames, and coordinate systems; Section 3.4 describes the format of the data products.

Below is an example of the information provided in this section for each data product type. A brief description is given, followed by a table defining the parameters, or columns, in the product's data content. Parameters may list different meanings for GRACE versus GRACE-FO data, in case of future GRACE product releases beyond the last released version of 03. Usage notes may be provided after the table. Note that the names of parameters will be referenced in **bold**. Finally, if the report file for this data product contains values in addition to the nineteen described in Section 3.5.1, those values will be listed and described:

KBR1B

Brief description of this data product type goes here.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
param_1	*Description of* **param_1**
param_2	*Description of* **param_2**

Usage Notes *Usage notes may go here, explaining how to interpret the parameters (such as* **param_1** *and* **param_2***), edit the data, etc.*

Additional Report File Values

20. *Description of additional report file value*
21. *...*

Detailed information on the instruments and sensors from which many data products' measurements originate are not provided in this document, but are available in various other detailed unit or system-level documentation.

The complete list of product types described in this section are as follows:

Level-1A

ACC1A	ACC measurements
ACT1A	Corrected ACC measurements
AHK1A	ACC housekeeping data
GNV1A	GPS navigation measurements
GPS1A	GPS measurements
HRT1A	High Resolution Temperature measurements
IHK1A	IPU housekeeping data
ILG1A	IPU log messages
IMU1A	IMU measurements
KBR1A	KBR phase measurements
LHK1A	LRI housekeeping data
LLG1A	LRI log messages
LLT1A	LRI states and light times
LRI1A	LRI phase measurements
LSM1A	LRI steering mirror measurements
MAG1A	Magnetometer and magnetorquer measurements
MAS1A	Spacecraft and fuel mass
PCI1A	Antenna offset corrections to KBR range
PLT1A	Satellite states and signal travel times from POD
SCA1A	SCA measurements
THR1A	Thruster activation data
TNK1A	Gas tank sensor data

Level-1B

ACC1B	Linear and angular accelerations (GRACE only)
ACT1B	Corrected linear and angular accelerations
AHK1B	ACC housekeeping data
CLK1B	Clock offsets for conversion from Receiver to GPS Time
GNI1B	Trajectory states in Inertial Frame
GNV1B	Trajectory states in Earth-Fixed Frame
GPS1B	GPS flight data
HRT1B	High Resolution Temperature data
IHK1B	IPU housekeeping data
IMU1B	IMU data
KBR1B	KBR ranging data
LHK1B	LRI housekeeping data
LLK1B	Clock offsets for conversion from LRI to GPS Time
LRI1B	LRI ranging data
LSM1B	LRI steering mirror data
MAG1B	Magnetometer and magnetorquer data
MAS1B	Spacecraft and fuel mass
QCP1B	Rotation from SCA “pilot” frame to KBR pointing frame
QSA1B	Rotation from SCFs into SRF
SCA1B	Processed SCA data
THR1B	Thruster activation data
TIM1B	Clock mapping from OBC to Receiver Time
TNK1B	Gas tank sensor data
USO1B	USO and K-Band frequency data
VCM1B	Vector offset for satellite center of mass
VGB1B	Vector offset for GPS backup navigation antenna
VGN1B	Vector offset for GPS main antenna
VGO1B	Vector offset for GPS occultation antenna
VKB1B	Vector offset for KBR antenna
VSL1B	Vector offset for SLR corner cube reflector

Note that the ancillary Level-1B product AOD1B is not described in this document. AOD1B is the Atmosphere and Ocean De-aliasing Level-1B product, which contains spherical harmonic coefficients describing non-tidal temporal variations in the Earth's gravity field caused by global mass variability in atmosphere and ocean at 3-hour sample rate. It is generated by GFZ, and is described in “Product Description Document for AOD1B Release 06” [21].

4.1 Level-1A

4.1.1 ACC1A

10-Hz linear acceleration and angular acceleration measurements of the ACC proof mass in AF. This format is also used by the ACT1A, AHK1A, and AHK1B data products. Parameters whose meanings differ for the “AHK1X” product types will be noted.

Note that the parameter **rcvtime_intg** is in GPS Time for the AHK1B product.

Parameter	Definition
rcvtime_intg	Integer seconds past 12:00:00 noon of January 1, 2000 in OBC Time
rcvtime_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. ‘R’ = Receiver, OBC, or LRI Time, ‘G’ = GPS Time
GRACEFO_id	Satellite identifier

qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: '0' = Receiver Time, '1' = Spacecraft elapsed time 1: '0' = Timing pulse sync, '1' = No timing pulse sync 2: Not defined if GRACE-FO. ICU board ('0' = nominal, '1' = redundant) if GRACE. 3: Not defined if GRACE-FO. Invalid ACC (GDEL) timing if GRACE. 4: ACC Mode. '0' = Normal range mode, '1' = Large range mode 5: IPU nav/timing packet received 6: No OBC-to-Receiver Time mapping 7: No clock correction available
prod_flag	Product flag. Meanings of individual integers, from position 0 at right to final position at left, are as follows: 0: lin_accl_x or TFEEU_IF 1: lin_accl_y or TFEEU_REF 2: lin_accl_z or TFEEU_X 3: ang_accl_x or TFEEU_YZ 4: ang_accl_y or analog_GND 5: ang_accl_z or +3.3V 6: bias_vol or Vp 7: Vd or MES_Vd 8: x1_out or MES_DET_X1 9: x2_out or MES_DET_X2 10: x3_out or MES_DET_X3 11: y1_out or MES_DET_Y1 12: y2_out or MES_DET_Y2 13: z1_out or MES_DET_Z1 14: tesu or TSU_Y+ 15: taicu or TICUN 16: tisu or TSU_Y- 17: v15picu or TSU_Z+ 18: v15micu or TSU_Z- 19: vr5picu or +5V 20: tcicu or TICUR 21: v15psu or +15V 22: v15msu or -15V 23: v48psu or +48V 24: v48msu or -48V 25: Status if GRACE. Not defined if GRACE-FO 26: ICU block number 27: 10Hz clock count or PPS Source 28: MHz clock count or Sync Quality Index 29: Status flag if AHK1X and GRACE-FO 30-31: Not defined
lin_accl_x	Linear acceleration along x-axis. TFEEU_IF if AHK1X.
lin_accl_y	Linear acceleration along y-axis. TFEEU_REF if AHK1X.
lin_accl_z	Linear acceleration along z-axis. TFEEU_X if AHK1X.
ang_accl_x	Angular acceleration about x-axis. TFEEU_YZ if AHK1X. 0 if ACT1B.
ang_accl_y	Angular acceleration about y-axis. analog_GND if AHK1X. 0 if ACT1B.
ang_accl_z	Angular acceleration about z-axis). +3.3V if AHK1X. 0 if ACT1B.
bias_vol	Proof-mass bias voltage (averaged). Vp if AHK1X.
vd	Amplitude of the AC voltage that operates the position sensors (Vrms). MES_Vd if AHK1X.
x1_out	Displacement of capacitive sensor X1. MES_DET_X1 if AHK1X.

x2_out	Displacement of capacitive sensor X2. MES_DET_X2 if AHK1X.
x3_out	Displacement of capacitive sensor X3. MES_DET_X3 if AHK1X.
y1_out	Displacement of capacitive sensor Y1. MES_DET_Y1 if AHK1X.
y2_out	Displacement of capacitive sensor Y2. MES_DET_Y2 if AHK1X.
z1_out	Displacement of capacitive sensor Z. MES_DET_Z1 if AHK1X.
tesu	Temperature of SU electronics. TSU_Y+ if AHK1X.
taicu	Temperature of ICU power supply board. TICUN if AHK1X.
tisu	Temperature of internal core. TSU_Y- if AHK1X.
v15picu	ICU (electronic box) reference voltage +15 V. TSU_Z+ if AHK1X.
v15micu	ICU reference voltage -15 V. TSU_Z- if AHK1X.
vr5picu	ICU reference voltage +5 V. +5V if AHK1X.
tcicu	Temperature of ICU A/D converter board. TICUR if AHK1X.
v15psu	SU (sensor unit) voltage +15 V. +15V if AHK1X.
v15msu	SU voltage -15 V. -15V if AHK1X.
v48psu	SU voltage +48 V. +48V if AHK1X.
v48msu	SU voltage -48 V. -48V if AHK1X.
status	60-second status bytes. Not defined if GRACE-FO.
icu_blk_nr	ICU block number. Assigned with the millisecond of the day of the timestamp for GRACE-FO.
Tenhz_count	10Hz clock count. PPS source if AHK1X. '0' = IN_SYNC_WITH_GPS, '1' = OUT_OF_SYNC, '2' = SYNC_IN_PROGRESS_BAD_PPS, '3' = SYNC_IN_PROGRESS_GOOD_PPS, '4' = SYNC_TO_GROUND_UTC_IN_PROGRESS, '5' = IN_SYNC_WITH_GROUND_UTC
Mhz_count	Mhz clock count. Sync Quality Index if AHK1X. '0' = PPS_RECEIVED_TIME_PACKET_RECEIVED, '1' = PPS_NOT_RECEIVED_TIME_PACKET_RECEIVED, '2' = PPS_RECEIVED_TIME_PACKET_NOT_RECEIVED, '3' = PPS_NOT_RECEIVED_TIME_PACKET_NOT_RECEIVED

statusflag	Status flag. Meanings of individual integers, from position 0 at right to position 31 at left, are as follows: 0: Test registers. '0' = Test ADC registers function is enabled, '1' = Test ADC registers function is disabled 1: Status, Vp. '0' = Vp 10V, '1' = Vp 40V 2: Status, Vd. '0' = Vd 5Vrms, '1' = Vp 1.25Vrms 3: Flag, SCI ACC X. '0' = ADC is synchronised, '1' = Time-out is detected 4: Flag, SCI ACC Y 5: Flag, SCI ACC Z 6: Flag, SCI ACC Phi 7: Flag, SCI ACC Theta 8: Flag, SCI ACC Psi 9: Flag, SCI VP 10: Flag, SCI MUX1 11: Flag, SCI MUX2 12: Flag, SCI MUX3 13: Flag, test registers. Shows when the ADC registers check has proceeded. '0' = ADC registers are NOT tested, '1' = ADC registers are tested 14: Flag, validity of registers. '0' = All the ADC registers are identical to the initial value, '1' = At least one of the ADC registers is corrupt 15: GWT. '0' = The stops are connected, '1' = The stops are NOT connected 16: Event Report Generation. '0' = Event Report Generation function is disabled, '1' = Event Report Generation function is enabled 17: PPS Channel. '0' = PPS_A, '1' = PPS_B 18: Uart Channel. '0' = Uart_A, '1' = Uart_B 19-31: Not defined

Additional Report File Values (Only for GRACE products beyond release version 03, which will include a time-tag fix. These fields will be "0" for GRACE-FO products.)

20. Number of records read from file
21. Number of records used for time-tag fix
22. Number of fixed time-tag records written
23. Number of records nulled
24. Number of non-incorporated records
25. Number of angular acceleration records added to fill
26. Consistency check sum. '0' = nominal, problem if not '0'

4.1.2 ACT1A

Corrected 10-Hz linear acceleration measurements of the ACC proof mass in AF. Aside from the report file described below, this data product uses the same format as the ACC1A data product.

Additional Report File Values (Fields 20 - 26 will be "0" for GRACE-FO products.)

20. Number of records read from file
21. Number of records used for time-tag fix
22. Number of fixed time-tag records written

23. Number of records nulled
24. Number of non-incorporated records
25. Number of angular acceleration records added to fill
26. Consistency check sum. '0' = nominal, problem if not '0'
27. Number of outliers surpassing threshold
28. Maximum time-span removed due to outliers

4.1.3 AHK1A

ACC housekeeping data. This data product uses the same format as the ACC1A data product.

4.1.4 GNV1A

0.5-Hz GPS-derived onboard navigation measurements. Note that there will be **n_prns** sets of the parameters **prn_id**, **el_prn**, **az_prn**, i.e., a set for each GPS satellite in the observations.

Parameter	Definition
rcv_time	Seconds past 12:00:00 noon of January 1, 2000 in Receiver Time
n_prns	Number of PRNs used in the solution
GRACEFO_id	Satellite identifier
chisq	Confidence factor of the solution (chi-squared)
cov_mult	Covariance precision multiplier for solution
voltage	Clock steering voltage in counts
xpos	Position, x value (WGS-84)
ypos	Position, y value (WGS-84)
zpos	Position, z value (WGS-84)
xpos_err	Formal error of xpos
ypos_err	Formal error of ypos
zpos_err	Formal error of zpos
xvel	Velocity along x-axis (WGS-84)
yvel	Velocity along y-axis (WGS-84)
zvel	Velocity along z-axis (WGS-84)
xvel_err	Formal error of xvel
yvel_err	Formal error of yvel
zvel_err	Formal error of zvel
time_offset	Time offset between GPS Time and Receiver Time
time_offset_err	Formal error of time_offset
time_drift	Drift in, or 1st time derivative of, time_offset (s/s)
err_drift	Formal error of time_drift (s/s)
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-7: Not Defined
prn_id	Identifications of PRNs. There will be n_prns sets of prn_id/el_prn/az_prn values.
el_prn	Elevations of PRNs. There will be n_prns sets of prn_id/el_prn/az_prn values.
az_prn	Azimuths of PRNs. There will be n_prns sets of prn_id/el_prn/az_prn values.

4.1.5 GPS1A

GPS phase and range measurements. Phase measurements are provided at 1 Hz, and range measurements are provided at 0.1 Hz. This data product uses the same format as the GPS1B data product.

4.1.6 HRT1A

High Resolution Temperature measurements. This data product uses the same format as the HRT1B data product.

4.1.7 IHK1A

IPU housekeeping data. This data product uses the same format as the IHK1B data product.

4.1.8 ILG1A

IPU log messages. This format is also used by the LLG1A data product.

Note that the parameter **rcv_time** is in LRI Time for the LLG1A product.

Parameter	Definition
rcv_time	Seconds past 12:00:00 noon of January 1, 2000 in Receiver Time
pkt_count	Count number ('1', '2', '3', etc.) of packet with this rcv_time. '-1'= timetag is reversed and switched with previous timetag.
GRACEFO_id	Satellite identifier
logpacket	Log packet string

4.1.9 IMU1A

8-Hz IMU measurements. This data product uses the same format as the IMU1B data product.

4.1.10 KBR1A

10-Hz KBR phase measurements. This data product uses the same format as the GPS1B data product.

4.1.11 LHK1A

LRI housekeeping data. This data product uses the same format as the IHK1B data product.

4.1.12 LLG1A

LRI log messages. This data product uses the same format as the ILG1A data product.

4.1.13 LLT1A

1-Hz satellite states (positions and velocities) and inter-satellite signal travel times ("light" times) for the LRI case, derived from POD. Although the data records for this product use the same format as data records in the PLT1A data product, the interpretation of the data records differ from those in a PLT1A file. See the documentation for PLT1A for these differences.

4.1.14 LRI1A

LRI phase measurements.

Parameter	Definition
rcvtime_intg	Integer seconds past 12:00:00 noon of January 1, 2000 in LRI Time
rcvtime_frac	Fractional portion of time tag, in nanoseconds
GRACEFO_id	Satellite identifier
prod_flag	Product flag. Meanings of individual integers, from position 0 at right to final position at left, are as follows: 0: piston_phase 1: phase0_int 2: phase0_frac 3: phase1_int 4: phase1_frac 5: phase2_int 6: phase2_frac 7: phase3_int 8: phase3_frac 9: fftSnr 10: noise8_9 11: noise11_12 12-15: Not Defined
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Start of new continuous interval after un-fillable phase break 1: Start of new continuous interval after fillable phase gap 2-7: Not defined
piston_phase	Average of 4 photodiode quadrants' phase values. Phase cycles = $0.1/2^{24} * (2^{32} *$ upper 32 bits of photodiode quadrant's count value + lower 32 bits of quadrant's count value)
phase0_int	Upper 32 bits from quadrant0 of photodiode (counts)
phase0_frac	Lower 32 bits from quadrant0 of photodiode (counts)
phase1_int	Upper 32 bits from quadrant1 of photodiode (counts)
phase1_frac	Lower 32 bits from quadrant1 of photodiode (counts)
phase2_int	Upper 32 bits from quadrant2 of photodiode (counts)
phase2_frac	Lower 32 bits from quadrant2 of photodiode (counts)
phase3_int	Upper 32 bits from quadrant3 of photodiode (counts)
phase3_frac	Lower 32 bits from quadrant3 of photodiode (counts)
fftSnr	Scaled signal amplitude from the FFT core; the signal level without any reference to the noise level
noise8_9	Noise from transponder heterodyne peak being in the 8-9 MHz band
noise11_12	Noise from transponder heterodyne peak being in the 11-12 MHz band

4.1.15 LSM1A

LRI steering mirror measurements in LRI FPGA Frame, which define the laser pointing to the other satellite.

Parameter	Definition
time_intg	Seconds past 12:00:00 noon of January 1, 2000 in LRI Time
time_frac	Fractional portion of time tag, in nanoseconds
time_ref	Time reference frame. 'S' = After the Science FPGA loads
GRACEFO_id	Satellite identifier
internalSensor0	Sensed position of steering mirror at yaw analog position sensor (counts)

internalSensor1	Sensed position of steering mirror at pitch analog position sensor (counts)
commanded0	Commanded offset position register of yaw position sensor
commanded1	Commanded offset position register of pitch position sensor
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-7: Not defined

4.1.16 MAG1A

Magnetometer measurements and magnetic torque rod activation data in SF (which is essentially taken to be SRF). This data product uses the same format as the MAG1B data product.

4.1.17 MAS1A

Satellite and tank gas masses over time based on thruster usage and tank observations. This data product uses the same format as the MAS1B data product.

4.1.18 PCI1A

0.2-Hz antenna phase center offset corrections to KBR inter-satellite range.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
ant_centr_corr	Antenna phase center offset correction to inter-satellite range
ant_centr_rate	First time derivative of ant_centr_corr
ant_centr_accl	Second time derivative of ant_centr_corr
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Based on attitude information from 1 star camera only 1: Value filled in via interpolation 2: Unreliable data 3-7: Not defined

Additional Report File Values

20. Compression RMS of phase center-to-CG range corrections (m)

4.1.19 PLT1A

1-Hz states (position and velocity) in Inertial Frame and inter-satellite signal travel times from POD. This format is also used by the LLT1A data product. The differences between the two data products are as follows:

PLT1A: In KBR ranging, signals are sent from one satellite to the other. This results in two data records for each timetag, in the following order:

1. Data record containing travel time **tau** of signal transmitted from satellite D at time **gps_time - tau** and received at satellite C at time **gps_time**, and state of satellite C's center of mass at time **gps_time**
2. Data record containing travel time **tau** of signal transmitted from satellite C at time **gps_time - tau** and received at satellite D at time **gps_time**, and state of satellite D's center of mass at time **gps_time**

LLT1A: In LRI ranging, the signal is sent from the "master" satellite to the other "transponder" satellite, with signal travel time **$\mathbf{tau_1}$**. The signal is then transponded back, with a frequency addition, by the "transponder" satellite back to the "master" with signal travel time **$\mathbf{tau_2}$**. Either satellite can be commanded to act as "master" or "transponder" at any given time. The two data records for each timetag are as follows:

1. Data record containing signal travel time from satellite D to satellite C, and state of satellite C's center of mass at time **gps_time**. If satellite C is in the "master" role (indicated by the data record's "qualflg" parameter), the signal travel time is **$\mathbf{tau_2}$**: the travel time of the signal that was received at C at time **gps_time** and sent by D at time **gps_time - $\mathbf{tau_2}$**. If satellite C is in the "transponder" role, the signal travel time is **$\mathbf{tau_1}$**: the travel time of the signal that was received at C at time **gps_time - $\mathbf{tau_2}$** and sent by D at time **gps_time - $\mathbf{tau_2}$ - $\mathbf{tau_1}$**.
2. Data record containing signal travel time from satellite C to satellite D, and state of satellite D's center of mass at time **gps_time**. If satellite D is in the "master" role (indicated by the data record's "qualflg" parameter), the signal travel time is **$\mathbf{tau_2}$**: the travel time of the signal that was received at D at time **gps_time** and sent by C at time **gps_time - $\mathbf{tau_2}$**. If satellite D is in the "transponder" role, the signal travel time is **$\mathbf{tau_1}$**: the travel time of the signal that was received at D at time **gps_time - $\mathbf{tau_2}$** and sent by C at time **gps_time - $\mathbf{tau_2}$ - $\mathbf{tau_1}$**.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
rcv_id	Identifier of satellite receiving the signal to which light travel time tau refers
trx_id	Identifier of satellite transmitting the signal to which light travel time tau refers
tau	Travel time of signal between satellites with identifiers rcv_id and trx_id. The signal is defined to be received at the receiving satellite at gps_time. By convention, this parameter is a negative number.
xpos	Position along X axis of satellite with identifier rcv_id
ypos	Position along Y axis of satellite with identifier rcv_id
zpos	Position along Z axis of satellite with identifier rcv_id
xvel	Velocity along X axis of satellite with identifier rcv_id
yvel	Velocity along Y axis of satellite with identifier rcv_id
zvel	Velocity along Z axis of satellite with identifier rcv_id
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: If LLT1A, '0' = Satellite with rcv_id is in master role, '1' = Satellite with rcv_id is in transponder role. Not defined if PLT1A 1-7: Not defined

4.1.20 SCA1A

SCA attitude measurements in the form of quaternions expressed in each of the three SCFs.

Parameter	Definition
rcvtime_intg	Integer seconds past 12:00:00 noon of January 1, 2000 in OBC Time
rcvtime_frac	Fractional portion of time tag, in microseconds
GRACEFO_id	Satellite identifier
sca_id	Star camera identification number. '1' = Star camera number 1, '2' = Star camera number 2, '3' = Star camera number 3.
sca_desig	Star camera designation. If GRACE: 'P' = Primary star camera, 'S' = Secondary star camera. If GRACE-FO: meaning not applicable, so value will always be 'P'.
quatangle	Cos($\theta/2$) component of rotation quaternion
quaticoeff	i-component of rotation quaternion
quatjcoeff	j-component of rotation quaternion
quatkcoeff	k-component of rotation quaternion

nlocks	Number of locks of star camera
nstars	Number of stars
sca_confid	SCA confidence. Contains 3 columns or values. Value 1 = SCA 'Residual' field, values 2 and 3 = Not defined. The residual is an accuracy estimate of the attitude solution; the smaller it is, the more accurate the attitude. A residual of '1' corresponds to approximately 0.8 arcsec 1-sigma NEA (noise equivalent angle) in pointing across the SCA lateral axes. The accuracy estimate for the rotation about the boresight is a factor of 10 higher. The AOCS (attitude and orbit control system) software discards the attitude quaternion if the residual is larger than '6', i.e. for values '7' through '255'.
sca_mode	SCA flags 0: Data validity flag. '0' = Invalid, '1' = Valid 1: Precision 2: Add 1/4 of star camera integration period to rcv_time 3: Non-stellar object (i.e. false stars) 4-5: Not defined 6: Orbit Correction. '1' = Used, '0' = Not used 7: Sequence
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Data validity flag. '0' = Valid, '1' = Invalid 1: Precision 2: Add 1/4 of star camera integration period to rcv_time 3: Non-stellar object (i.e. false stars) 4: SCAs not all in 1-Hz mode 5: Not defined 6: Orbit correction. '1' = Used, '0' = Not used 7: Sequence

4.1.21 THR1A

Thruster activation data. This data product uses the same format as the THR1B data product.

4.1.22 TNK1A

Cold gas tank sensor temperatures and pressures. This data product uses the same format as the TNK1B data product.

4.2 Level-1B

The ancillary Level-1B product AOD1B is not described in this section (see note in Section 4 about this data type).

4.2.1 ACC1B

1-Hz linear and angular accelerations of the ACC proof mass in SRF. This format is also used by the ACT1B data product. Note that the ACC1B product is not provided for the GRACE-FO mission; the ACT1B is to be used instead.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time

GRACEFO_id	Satellite identifier
lin_accl_x	Linear acceleration along X-axis
lin_accl_y	Linear acceleration along Y-axis
lin_accl_z	Linear acceleration along Z-axis
ang_accl_x	Angular acceleration about X-axis. 0 if ACT1B.
ang_accl_y	Angular acceleration about Y-axis. 0 if ACT1B.
ang_accl_z	Angular acceleration about Z-axis. 0 if ACT1B.
acl_x_res	Residual of lin_accl_x from non-CRN-filtered value
acl_y_res	Residual of lin_accl_y from non-CRN-filtered value
acl_z_res	Residual of lin_accl_z from non-CRN-filtered value
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Vp (proof mass voltage) out of nominal range 1: Not defined 2: At least one of acl_x_res, acl_y_res, and acl_z_res is $>$ 10 microns/s^2 3: Extrapolated CLK1B clock offset value used for data point $>$ 5 s from center of CRN filter window 4: Extrapolated CLK1B clock offset value used for data point $<=$ 5 s from center of CRN filter window 5: Interpolated data point (due to gap) exists $>$ 15 s from center of CRN filter window 6: Interpolated data point (due to gap) exists $>$ 5 s but $<$ 15 s from center of CRN filter window 7: Interpolated data point (due to gap) exists $<$ 5 s from center of CRN filter window

Additional Report File Values

20. Number of data gaps not filled
21. Compression RMS of **lin_acc_x** (m/s^2)
22. Compression RMS of **lin_acc_y** (m/s^2)
23. Compression RMS of **lin_acc_z** (m/s^2)
24. Compression RMS of **ang_acc_x** (rad/s^2)
25. Compression RMS of **ang_acc_y** (rad/s^2)
26. Compression RMS of **ang_acc_z** (rad/s^2)
27. Relative bias in x-direction (m/s^2)
28. Relative bias in y-direction (m/s^2)
29. Relative bias in z-direction (m/s^2)
30. Relative scale in x-direction
31. Relative scale in y-direction
32. Relative scale in z-direction
33. Relative res in x-direction (m/s^2)
34. Relative res in y-direction (m/s^2)
35. Relative res in z-direction (m/s^2)

4.2.2 ACT1B

Corrected 1-Hz linear accelerations of the ACC proof mass in SRF. This data product uses the same format as the ACC1B data product.

4.2.3 AHK1B

ACC housekeeping data. This data product uses the same format as the ACC1A data product. This product is the same as AHK1A, except that its time tags are converted to GPS Time.

4.2.4 CLK1B

Clock offset values to convert time tags to GPS Time. This format is also used by the LLK1B data product. If the product is CLK1B, then the **eps_time** offset value, if added to its corresponding Receiver time tag, will convert that time-tag to GPS Time. If product is LLK1B, then the **eps_time** offset value, if added to its corresponding LRI time-tag, will convert that time-tag to GPS Time; note that this offset value does not account for known onboard LRI datation or filter delay biases described in Section 3.2.2. Note that the parameter **rcv_time** is in LRI Time for the LLK1B product.

Parameter	Definition
rcv_time	Seconds past 12:00:00 noon of January 1, 2000 in Receiver Time
GRACEFO_id	Satellite identifier
clock_id	Clock ID
eps_time	Clock offset. GPS Time = rcv_time + eps_time
eps_err	Formal error of eps_time
eps_drift	Clock drift, or 1st time derivative of eps_time (s/s)
drift_err	Formal error of eps_drift (s/s)
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Linear extrapolation of eps_time not valid AFTER rcv_time 1: Linear extrapolation of eps_time not valid BEFORE rcv_time 2: Smoothed data lies before center of smoothing for start midnight 3: Smoothed data lies after center of smoothing for start midnight 4: Smoothed data lies before center of smoothing for end midnight 5: Smoothed data lies after center of smoothing for end midnight 6: Linear extrapolation not valid AFTER rcv_time for KBR and GPS 7: Linear extrapolation not valid BEFORE rcv_time for KBR and GPS

Usage Notes Clock offset values can be linearly interpolated between the given time tags. When there is a duplicate pair of records that contain the same time-tag and values, one of them will have a quality flag bit set to indicate that clock offset values cannot be extrapolated before or after that time-tag. For instance, a product will start with two duplicate records; the first of the two records will have **qualflg** bit 1 set to indicate that the clock offset value cannot be extrapolated before that time-tag. The product will also end with two duplicate records; the second of the two records will have **qualfg** bit 0 set to indicate that the clock offset value cannot be extrapolated after that time-tag. This can occur due to gaps in usable data or IPU resets onboard the satellites as well.

Additional Report File Values for CLK1B These statistics are on the differences between the clock offset solution values of two consecutive days, for the 4-hour overlap periods centered on the start and end midnights of the date in question.

20. Bias of linear fit to clock differences at start midnight (ns)

21. Standard deviation of bias of linear fit to clock differences at start midnight (ns)
22. Slope of linear fit to clock differences at start midnight (ns/s)
23. Standard deviation of slope of linear fit to clock differences at start midnight (ns/s)
24. RMS of clock differences at start midnight (ns)
25. RMS, relative to linear fit, of clock differences at start midnight (ns)
26. Number of clock differences in overlap at start midnight
27. Bias of linear fit to clock differences at end midnight (ns)
28. Standard deviation of bias of linear fit to clock differences at end midnight (ns)
29. Slope of linear fit to clock differences at end midnight (ns/s)
30. Standard deviation of slope of linear fit to clock differences at end midnight (ns/s)
31. RMS of clock differences at end midnight (ns)
32. RMS, relative to linear fit, of clock differences at end midnight (ns)
33. Number of clock differences in overlap at end midnight
34. Number of clock offset data points edited out due to large or negative **eps_err**

Additional Report File Values for LLK1B

20. Estimated daily bias between LRI Time and GPS Time, in addition to known LRI datation and/or onboard filter delay biases (s)
21. Estimation sigma of time bias (s)
22. If there is a 2nd continuous LRI1B data segment, estimated LRI Time bias for this segment (s)
23. If there is a 2nd continuous LRI1B data segment, estimation sigma of time bias for this segment (s)

4.2.5 GNI1B

1-Hz trajectory states from POD in Inertial Frame. This data product uses the same format as the GNV1B data product.

4.2.6 GNV1B

1-Hz trajectory states from POD in Earth-Fixed Frame. This format is also used by the GNI1B data product - in that case, the states will be in Inertial Frame.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
coord_ref	Coordinate reference frame. ‘E’ = Earth-Centered, Earth-Fixed, ‘I’ = Earth-Centered Inertial
xpos	Position, X value
ypos	Position, Y value
zpos	Position, Z value
xpos_err	Formal error of xpos
ypos_err	Formal error of ypos
zpos_err	Formal error of zpos

xvel	Velocity along x-axis
yvel	Velocity along y-axis
zvel	Velocity along z-axis
xvel_err	Formal error of xvel
yvel_err	Formal error of yvel
zvel_err	Formal error of zvel
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-1: Not defined 2: Overlap data missing before start midnight 3: Overlap data missing after start midnight 4: Overlap data missing before end midnight 5: Overlap data missing after end midnight 6: Not defined 7: Formal errors are not available

Additional Report File Values

20. Number of overlap points at start midnight
21. Position overlap RMS in radial direction at start midnight
22. Position overlap RMS in normal (cross-track) direction at start midnight
23. Position overlap RMS in transverse (along-track) direction at start midnight
24. Velocity overlap RMS in radial direction at start midnight
25. Velocity overlap RMS in normal (cross-track) direction at start midnight
26. Velocity overlap RMS in transverse (along-track) direction at start midnight
27. Number of overlap points at end midnight
28. Position overlap RMS in radial direction at end midnight
29. Position overlap RMS in normal (cross-track) direction at end midnight
30. Position overlap RMS in transverse (along-track) direction at end midnight
31. Velocity overlap RMS in radial direction at end midnight
32. Velocity overlap RMS in normal (cross-track) direction at end midnight
33. Velocity overlap RMS in transverse (along-track) direction at end midnight

4.2.7 GPS1B

0.1-Hz processed GPS phase and range data processed from inflight measurements. This format is also used by the GPS1A and KBR1A data products, and parameters whose meanings differ for these product types will be noted.

Note that the parameter **rcvtime_intg** is in Receiver Time for the GPS1A and KBR1A products.

Parameter	Definition
rcvtime_intg	Integer seconds past 12:00:00 noon of January 1, 2000 in GPS Time
rcvtime_frac	Fractional portion of time tag, in microseconds
GRACEFO_id	Satellite identifier
prn_id	GPS satellite PRN number if GPS1A or GPS1B. Equals '50' or '51' if KBR1A.

ant_id	GPS or KBR antenna ID. '0' = GPS navigation antenna, '2' = GPS occultation antenna, '4' = GPS backup navigation antenna, '9' or '11' = KBR antenna, '-11' = Missed interrupt detected in Ka band phase
prod_flag	Product flag. Meanings of individual integers, from position 0 at right to final position at left, are as follows: 0: C/A pseudorange 1: L1 pseudorange 2: L2 pseudorange 3: C/A carrier phase 4: L1 carrier phase 5: L2 carrier phase 6: SNR of C/A channel 7: SNR of L1 channel 8: SNR of L2 channel 9: C/A receiver channel 10: L1 receiver channel 11: L2 receiver channel 12: K band carrier phase. Raw L2 carrier phase if GPS1A or GPS1B 13: Ka band carrier phase 14: SNR of K band 15: SNR of Ka band
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Phase break occurred in L1, C/A, or K band phase 1: Phase break occurred in L2 or Ka band phase 2: Cycle slip detected in L1, C/A, or K band phase 3: Cycle slip detected in L2 or Ka band phase 4: Insane K or Ka polynomial coefficient if KBR1A, SNR of L1 is < 5 if GPS1A or GPS1B 5: K or Ka band phase is missing if KBR1A, SNR of L2 is < 5 if GPS1A or GPS1B 6: SNR of K band < 450 7: SNR of Ka band is < 450
CA_range	C/A pseudorange
L1_range	L1 pseudorange
L2_range	L2 pseudorange
CA_phase	C/A carrier phase (m)
L1_phase	L1 carrier phase (m)
L2_phase	L2 ion-smoothed carrier phase (m)
CA_SNR	SNR of C/A channel (units + integration time) (V/V)
L1_SNR	SNR of L1 channel (V/V)
L2_SNR	SNR of L2 channel (V/V)
CA_chan	C/A receiver channel
L1_chan	L1 receiver channel
L2_chan	L2 receiver channel
K_phase	K band carrier phase (cycles). Raw L2 carrier phase (m) if GPS1A or GPS1B
Ka_phase	Ka band carrier phase (cycles)
K_SNR	SNR K band channel (V/V)
Ka_SNR	SNR Ka band channel (V/V)

Additional Report File Values The following additional values are present in GPS1B report files, but not in GPS1A or KBR1A report files.

20. Compression RMS of CA phase (m)

21. Number of CA phase points
22. Compression RMS of L1 phase (m)
23. Number of L1 phase points
24. Compression RMS of L2 phase (m)
25. Number of L2 phase points
26. Number of phase breaks in output data
27. Number of discarded data points due to low **L1_SNR**
28. Number of discarded data points due to low **L2_SNR**
29. Number of discarded data points due to **L1_SNR** < 0.4***CA_SNR**$^2/1000$
30. Total number of discarded data points
31. Number of raw input data points

4.2.8 HRT1B

High Resolution Temperature data. This format is also used by the HRT1A data product.

Note that the parameter **time_intg** is in GPS Time for HRT1B and OBC Time for HRT1A.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
GRACEFO_id	Satellite identifier
TEMP_MEP_neg_y	I/F Support Structure to MEP -y temperature
TEMP_MEP_pos_y	I/F Support Structure to MEP +y temperature
TEMP_MEPm	I/F Support Structure to MEP mid temperature
TEMP_ICU	ICU Temperature Reference Point
TEMP_ICU_red	ICU Temperature Reference Point, redundant
TEMP_ACC_neg_z	ACC thermal Cage -z temperature
TEMP_ACC_pos_z	ACC thermal Cage +z temperature
TEMP_CFRP_pos_x	CFRP Frame at +x I/F to Baseplate temperature
TEMP_CFRP_pos_x_red	CFRP Frame at +x I/F to Baseplate redundant temperature
TEMP_CFRP_neg_x	CFRP Frame at -x I/F to Baseplate temperature
TEMP_CFRP_neg_x_red	CFRP Frame at -x I/F to Baseplate redundant temperature
TEMP_CFRP_neg_y	CFRP Frame at -y I/F to Baseplate temperature
TEMP_CFRP_neg_y_red	CFRP Frame at -y I/F to Baseplate redundant temperature
TEMP_ACCSen	Harness to ACC Sensor temperature
TEMP_ICU_spec	ICU special temperature
TEMP_MWA_neg_y	MWA -y Temp. Ref. Point, 2 out 3
TEMP_MWA_neg_yoff	MWA -y Temp. Ref. Point, 2 out 3 nominally off
TEMP_MWA_pos_y	MWA +y Temp. Ref. Point, 2 out 3
TEMP_MWA_pos_yoff	MWA +y Temp. Ref. Point, 2 out 3 nominally off
TEMP_Horn_pos_x	Horn Aperture +x temperature
TEMP_Horn_pos_x_red	Horn Aperture +x redundant temperature
TEMP_HornPl	Horn / platform I/F temperature
TEMP_HornPl_red	Horn / platform I/F Redundant temperature
TEMP_HMWA_neg_y	Harnass to MWA electronics -y temperature
TEMP_HMWA_pos_y	Harnass to MWA electronics +y temperature

TEMP_RFSamp	RF-Sampling Unit temperature
TEMP_USO_neg_y	USO Temp. Ref. Point, -y
TEMP_USO_neg_y_red	USO Temp. Ref. Point, -y, redundant
TEMP_USO_pos_y	USO Temp. Ref. Point, +y
TEMP_USO_pos_y_red	USO Temp. Ref. Point, +y, redundant
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: '0' = Receiver Time, '1' = Spacecraft elapsed time 1: '0' = Pulse sync, '1' = No pulse sync 2-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available

4.2.9 IHK1B

IPU housekeeping data. This format is also used by the IHK1A, LHK1A, and the LHK1B data products.

Note that the parameter **time_intg** is in Receiver Time for IHK1A, LRI Time for LHK1A, and GPS Time for IHK1B and LHK1B.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds for IHK1A and IHK1B, and nanoseconds for LHK1A and LHK1B
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time. For GRACE-FO LHK1A and LHK1B only: 'B' = Before the Science FPGA loads in Receiver Time, 'S' = After the Science FPGA loads in Receiver Time, 'G' = GPS Time (after the Science FPGA loads).
GRACEFO_id	Satellite identifier
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available
sensortype	Observation type. 'V' = Voltage, 'T' = Temperature, 'A' = Current
sensorvalue	Value of observation
sensorname	Sensor name

4.2.10 IMU1B

8-Hz IMU data. This format is also used by the IMU1A data product.

Note that the parameter **time_intg** is in GPS Time for IMU1B and OBC Time for IMU1A.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
GRACEFO_id	Satellite identifier
gyro_id	Gyro ID number
FiltAng	Filtered angle referenced to gyro axis (deg); see usage notes below. Measurement is passed through a predetermined but selectable 2nd-order low-pass filter.

qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available

Reference Axes for Measured Gyro Angle Values The **FiltAng** parameter angle values are in reference to the gyro axes in Table 23, as measured in the IMU frame (also known as the "optical cube" frame). These gyro axes can be transformed to the SF via the measured IMU-to-SF transformation matrices in Table 24.

Components of Gyro Axis in IMU Frame		Gyro 1	Gyro 2	Gyro 3	Gyro 4
Satellite 1	X	0.942826211	-0.472597539	-0.470092696	0.000592072
	Y	0.001810853	0.815825089	-0.817231401	-0.000382796
	Z	0.33327985	0.333288147	0.333385204	-0.999999751
Satellite 2	X	0.942687237	-0.471344745	-0.471100307	0.000753399
	Y	0.000111944	0.816437037	-0.816914065	0.000461058
	Z	0.33367763	0.333563632	0.332740005	-0.99999961

Table 23: Directions of IMU gyro axes in IMU frame, from Tables 4-1 and 4-2 in [22]

	Transformation Matrix		
Satellite 1	-0.501252164183920	0.865301254687325	-0.000080854668175
	0.865300283426991	0.501251737450002	0.001454374272271
	0.001299000425484	0.000659044684221	-0.999998939128437
Satellite 2	-0.501005885615109	0.865443870184570	0.000100692470726
	0.865443802410115	0.501005791604386	0.000470795904316
	0.000356999918493	0.000323015193725	-0.999999884106115

Table 24: Transformation matrices from IMU frame to SF, from Table 4-6 in [22]

4.2.11 KBR1B

Biased inter-satellite ranges and their first two time derivatives, range rate and range acceleration. The frequency of the data records is 0.2 Hz for a KBR1B product. This format is also used by the LRI1B data product, and parameters whose meanings differ for this product type will be noted.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
biased_range	CRN-filtered biased inter-satellite range. If KBR1B, contains ionospheric correction. See usage notes below table.
range_rate	First time derivative of biased_range
range_accl	Second time derivative of biased_range
iono_corr	If KBR1B: biased ionospheric correction for biased_range, for Ka frequency. If LRI1B: estimated scale correction epsilon for biased_range, range_rate, and range_accl due to unknown onboard LRI frequency (scale correction = 1 + epsilon)
lighttime_corr	Light time correction for biased_range
lighttime_rate	Light time correction for range_rate
lighttime_accl	Light time correction for range_accl
ant_centr_corr	If KBR1B: antenna phase center offset correction for biased_range. If LRI1B: not defined
ant_centr_rate	If KBR1B: antenna phase center offset correction for range_rate. If LRI1B: not defined
ant_centr_accl	If KBR1B: antenna phase center offset correction for range_accl. If LRI1B: not defined

K_A_SNR	If KBR1B: SNR of K band for GRACE-FO C (or GRACE A) satellite (units of 0.1 db-Hz). If LRI1B: CNR of laser ranging for GRACE-FO C (or GRACE A) satellite (db-Hz)
Ka_A_SNR	If KBR1B: SNR of Ka band for GRACE-FO C (or GRACE A) satellite (units of 0.1 db-Hz). If LRI1B: not defined
K_B_SNR	If KBR1B: SNR of K band for GRACE-FO D (or GRACE B) satellite (units of 0.1 db-Hz). If LRI1B: CNR of laser ranging for GRACE-FO D (or GRACE B) satellite (db-Hz)
Ka_B_SNR	If KBR1B: SNR of Ka band for GRACE-FO D (or GRACE B) satellite (units of 0.1 db-Hz). If LRI1B: not defined
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Phase break 1: If KBR1B: unreliable PCI1A data for ant_centr_corr. If LRI1B: not defined 2: If KBR1B: interpolated PCI1A data for ant_centr_corr. If LRI1B: not defined 3-4: Not defined 5: If KBR1B: data corrected for time tag bias in either K or Ka phase. If LRI1B: not defined 6: Interpolated data point (due to gap) exists > 5 s from center of CRN filter window 7: Interpolated data point (due to gap) exists <= 5 s from center of CRN filter window

Correcting Biased Range Before using the **biased_range**, **range_rate**, and **range_accl** values, the light time and antenna offset corrections must be added as follows:

Corrected biased range = **biased_range** + **lighttime_corr** (+ **ant_centr_corr** if KBR1B)

Corrected range rate = **range_rate** + **lighttime_rate** (+ **ant_centr_rate** if KBR1B)

Corrected range acceleration = **range_accl** + **lighttime_accl** (+ **ant_centr_accl** if KBR1B)

As provided, KBR1B **biased_range** values have already been corrected for ionospheric effects (i.e., **iono_corr**). LRI1B **biased_range**, as well as **range_rate** and **range_accl**, values have already been scaled for the uncertainty in LRI frequency by a factor of $1 + \epsilon$, where ϵ is the value in the **iono_corr** parameter field.

Data Editing The following are recommended editing guidelines for selecting good data records:

First, check the **qualflg** flag in position 0 to identify phase breaks. The remaining quality flags are provided as additional informative flags, and do not usually indicate further data editing recommendations.

In addition, it is also recommended to filter out the data whose SNR values (**K_A_SNR**, **Ka_A_SNR**, **K_B_SNR**, and **Ka_B_SNR**) are > 450.0 (units of 0.1 db-Hz).

The following formula converts SNR to a 1-second error in cycles of phase:

sigma in phase = $1/(2\pi y)$ cycles

in which

y = 1-second SNR voltage = $10^{\mathrm{SNR}/(10*20)}$

Getting Change in Total Electron Content (TEC) from Biased Ionosphere Correction for KBR1B The **iono_corr** values contain an arbitrary bias, and hence only indicate the change in the ionosphere as a function of time. To calculate the change in ionospheric TEC, use the following formula:

Δ TEC $= \delta R * f^2/40.3$

in which

Δ TEC is in units of TECU (10^{16} electrons/m^2)
δR = change in ionospheric correction (i.e., $\mathbf{iono\_corr}_{\mathrm{n}}$ - $\mathbf{iono\_corr}_{\mathrm{n\text{-}1}}$)
f = Ka band frequency

Additional Report File Values for KBR1B

20. Compression RMS of **biased_range** (m)
21. Compression RMS of **iono_corr**
22. Total arc length of valid **biased_range** data (h)
23. Number of residuals of corrected biased range against inter-satellite range from POD
24. Standard deviation of residuals of corrected biased range against inter-satellite range from POD (cm)
25. Minimum residual of corrected biased range against inter-satellite range from POD (cm)
26. Maximum residual of corrected biased range against inter-satellite range from POD (cm)
27. Number of continuous data arcs
28. Number of clock double-difference data points. A clock double-difference is calculated as follows: first, for each satellite, the difference between CLK1B offset values is calculated for each time-tag in an overlapping 4-hour interval centered on the start midnight of the date in question (the CLK1B values used are solutions from the two consecutive days that form the overlap). Then, the double-difference is the difference between the aforementioned clock offset overlap differences for the two satellites.
29. Mean of clock double-differences (ps)
30. Standard deviation of clock double-differences (ps)
31. Minimum of clock double-differences (ps)
32. Maximum of clock double-differences (ps)
33. RMS of clock double-differences (ps)

Additional Report File Values for LRI1B

20. Compression RMS of **biased_range** (m)
21. Not defined
22. Total arc length of valid **biased_range** data (h)
23. Number of residuals of corrected biased range against KBR1B corrected biased range
24. Standard deviation of residuals of corrected biased range against KBR1B corrected biased range (cm)
25. Minimum residual of corrected biased range against KBR1B corrected biased range (cm)
26. Maximum residual of corrected biased range against KBR1B corrected biased range (cm)
27. Number of continuous data arcs
28. Not defined
29. Estimated scale correction for biased range, range rate, and range acceleration, due to uncertainty in onboard LRI cavity frequency (range, range rate, and range acceleration multiplied by 1 + scale)
30. Estimation sigma of scale correction
31. If there is a 2nd continuous LRI1B data segment, estimated scale correction for this segment
32. If there is a 2nd continuous LRI1B data segment, estimation sigma of scale correction for this segment
33. Not defined

4.2.12 LHK1B

LRI housekeeping data. This data product uses the same format as the IHK1B data product. This product is the same as LHK1A, except that its time tags are converted to GPS Time.

4.2.13 LLK1B

Clock offset values to convert LRI time tags to GPS Time. This data product uses the same format as the CLK1B data product.

4.2.14 LRI1B

0.5-Hz biased inter-satellite ranges and their first two time derivatives, range rate and range acceleration, from LRI ranging. This data product uses the same format as the KBR1B data product.

4.2.15 LSM1B

10-Hz LRI steering mirror data, which define the laser pointing to the other satellite, in SRF with time-tags in GPS Time.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in nanoseconds
GRACEFO_id	Satellite identifier
lof_yaw	Yaw pointing angle (microrad)
lof_pitch	Pitch pointing angle (microrad)
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-6: Not defined 7: No clock correction available

4.2.16 MAG1B

Magnetometer measurements and magnetic torque rod activation data. This format is also used by the MAG1A data product.

Note that the parameter **time_intg** is in GPS Time for MAG1B and OBC Time for MAG1A.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
GRACEFO_id	Satellite identifier
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
MfvX_RAW	X-axis component of measured earth magnetic field (microT) in SF if MAG1A, in SRF if MAG1B
MfvY_RAW	Y-axis component of measured earth magnetic field (microT) in SF if MAG1A, in SRF if MAG1B
MfvZ_RAW	Z-axis component of measured earth magnetic field (microT) in SF if MAG1A, in SRF if MAG1B
torque1A	Magnetorquer 1 A, or positive X, current (mA)
torque2A	Magnetorquer 2 A, or positive Y, current (mA)

torque3A	Magnetorquer 3 A, or positive Z, current (mA)
torque1B	Magnetorquer 1 B, or negative X, current (mA)
torque2B	Magnetorquer 2 B, or negative Y, current (mA)
torque3B	Magnetorquer 3 B, or negative Z, current (mA)
MF_BCalX	Mag field calibration factor for X
MF_BCalY	Mag field calibration factor for Y
MF_BCalZ	Mag field calibration factor for Z
torque_cal	Mag torquer calibration factor
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: If MAG1A, '0' = OBC Time, '1' = Spacecraft elapsed time. Flag is carried from MAG1A into MAG1B, although all MAG1B time tags are in GPS Time 1: '0' = Pulse sync, '1' = No pulse sync 2: '0' = FGMA for GRACE-FO, '1' = FGMB for GRACE-FO. Not defined for GRACE. 3-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available

4.2.17 MAS1B

Satellite and tank gas masses over time based on thruster usage and tank observations. This format is also used by the MAS1A data product.

Note that the parameter **time_intg** is in GPS Time for MAS1B and OBC Time for MAS1A.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
GRACEFO_id	Satellite identifier
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available
prod_flag	Product flag. Meanings of individual integers, from position 0 at right to final position at left, are as follows: 0: mass_thr 1: mass_thr_err 2: mass_tnk 3: mass_tnk_err 4: gas_mass_thr1 5: gas_mass_thr2 6: gas_mass_tnk1 7: gas_mass_tnk2
mass_thr	Spacecraft mass based on thruster usage. Not available.
mass_thr_err	Error in mass_thr (from 'error bit 0'). Not available.
mass_tnk	Spacecraft mass from tank observations. Not available.
mass_tnk_err	Error in mass_tnk (from 'error bit 2'). Not available.
gas_mass_thr1	Mass of gas in tank 1 based on thruster usage. Not available.
gas_mass_thr2	Mass of gas in tank 2 based on thruster usage. Not available.
gas_mass_tnk1	Mass of gas in tank 1 based on tank and thruster observations
gas_mass_tnk2	Mass of gas in tank 2 based on tank and thruster observations

4.2.18 QCP1B

Rotation from the combined SCA "pilot" frame to the KBR pointing frame (in which X axis is along KBR boresight). This data product uses the same format as the QSA1B data product.

4.2.19 QSA1B

Rotation from SCFs into SRF. This format is also used by the QCP1B data product.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
sca_id	If QCP1B, 0. If QSA1B, SCA ID.
quatangle	Cos($\theta/2$) component of rotation quaternion
quaticoeff	i-component of rotation quaternion
quatjcoeff	j-component of rotation quaternion
quatkcoeff	k-component of rotation quaternion
qual_rss	Not defined.
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0-7: Not defined

4.2.20 SCA1B

1-Hz processed SCA data, in the form of rotation quaternions from Inertial Frame to SRF.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
sca_id	If SCA1B, type(s) of data used. For GRACE: '1' = SCA 1, '2' = SCA 2, '4' = SCAs 1+2, '5' = SCA 1 and ACC, '6' = SCA 2 and ACC, '7' = SCAs 1+2 and ACC, '8' = ACC. For GRACE-FO: '1' = SCA 1, '2' = SCA 2, '3' = SCAs 1+2, '4' = SCA 3, '5' = SCAs 1+3, '6' = SCAs 2+3, '7' = SCAs 1+2+3, '16' = IMU, '17' = SCA 1 and IMU, '18' = SCA 2 and IMU, '19' = SCAs 1+2 and IMU, '20' = SCA 3 and IMU, '21' = SCAs 1+3 and IMU, '22' = SCAs 2+3 and IMU, '23' = SCAs 1+2+3 and IMU.
quatangle	Cos($\theta/2$) component of rotation quaternion
quaticoeff	i-component of rotation quaternion
quatjcoeff	j-component of rotation quaternion
quatkcoeff	k-component of rotation quaternion
qual_rss	RSS of formal error of quaternions
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Interpolated value 1: Interpolated value using relative attitude data (IMU if GRACE-FO, ACC if GRACE) 2: Not defined 3: Data from 1 star camera only 4-7: Not defined

Additional Report File Values

20. Percent of SCA 1 observations used
21. Percent of SCA 2 observations used

22. Percent of SCA 3 observations used
23. Percent of IMU observations used
24. Percent of ACC observations used
25. RMS of postfit residuals of SCA 1 x-axis (microrad)
26. RMS of postfit residuals of SCA 1 y-axis (microrad)
27. RMS of postfit residuals of SCA 1 z-axis (microrad)
28. RMS of postfit residuals of SCA 2 x-axis (microrad)
29. RMS of postfit residuals of SCA 2 y-axis (microrad)
30. RMS of postfit residuals of SCA 2 z-axis (microrad)
31. RMS of postfit residuals of SCA 3 x-axis (microrad)
32. RMS of postfit residuals of SCA 3 y-axis (microrad)
33. RMS of postfit residuals of SCA 3 z-axis (microrad)
34. RMS of postfit residuals of IMU x-axis (microrad/s)
35. RMS of postfit residuals of IMU y-axis (microrad/s)
36. RMS of postfit residuals of IMU z-axis (microrad/s)
37. RMS of postfit residuals of ACC x-axis (microrad/s^2)
38. RMS of postfit residuals of ACC y-axis (microrad/s^2)
39. RMS of postfit residuals of ACC z-axis (microrad/s^2)

4.2.21 THR1B

Thruster activation data. This format is also used by the THR1A data product.

Note that the parameter **time_intg** is in GPS Time for THR1B and OBC Time for THR1A. Also, all thruster on-times and firing duration values, in parameters **on_time** and **accum_dur**, are in units of milliseconds.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
GRACEFO_id	Satellite identifier
thrust_count	Number of commanded work cycles for which each thruster has been activated. Integer values beyond 4294967295 will wrap back to 0. This parameter contains 14 values in separate columns, one for each thruster. From leftmost column to the rightmost: columns 0-5 = attitude control thrusters on branch 1, and columns 6-11 = attitude control thruster on branch 2. Columns 12-13 = orbit control thrusters on branches 1 and 2 respectively if GRACE and not defined if GRACE-FO.
on_time	Commanded thruster on-times for this time tag, in milliseconds. This parameter contains 14 values in separate columns, one for each thruster. From leftmost column to the rightmost: columns 0-5 = attitude control thrusters on branch 1, columns 6-11 = attitude control thruster on branch 2, columns 12-13 = orbit control thrusters on branches 1 and 2, respectively.

accum_dur	Accumulated commanded thruster firing duration times, in milliseconds. Integer values beyond 4294967295 will wrap back to 0. This parameter contains 14 values in separate columns, to be read from leftmost column to the rightmost. If GRACE: columns 0-5 = attitude control thrusters on branch 1, columns 6-11 = attitude control thruster on branch 2, columns 12-13 = orbit control thrusters on branches 1 and 2, respectively. For GRACE-FO: column 0 = sum for all 12 attitude control thrusters on the two branches, column 12 = sum for the two orbit control thrusters on the two branches.
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: On-time not calculated 1: Multiple unaccounted thrusts prior to current record 2: '1' = Branch 1 is active 3: '1' = Branch 2 is active 4-5: Not defined 6: No OBC-to-Receiver Time mapping 7: No clock correction available

Usage Notes Note that the **thrust_count** and **accum_dur** sums may sometimes lag behind the actual sum indicated by the **on_time** values. This is because thrust count and accumulated duration data may sometimes be output less frequently in telemetry than on-time data, which is output at each thruster firing.

4.2.22 TIM1B

Mappings from OBC to Receiver Time every 8 s.

Parameter	Definition
obctime	Integer seconds past 12:00:00 noon of January 1, 2000 in OBC Time
GRACEFO_id	Satellite identifier
TS_suppid	OBC time tag supplementary ID. '0' = SCET (spacecraft elapsed time), '1' = Receiver Time, '2' = SCET + pulse sync, '3' = Receiver Time + pulse sync, '7' = Receiver Time + pulse sync + IPU time packet received
rcvtime_intg	Integer seconds past 12:00:00 noon of January 1, 2000 in Receiver Time
rcvtime_frac	Fractional portion of time tag, in microseconds if GRACE and nanoseconds if GRACE-FO
first_icu_blknr	First ICU block number for time tag. '-1' = no ACC data available
final_icu_blknr	Final ICU block number for time tag. '-1' indicates no ACC data available
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Delta between OBC time tags is not 1 second 1: Multiple ICU blocks 2: In sync with GPS 3: Receiver Time mapping not defined 4: Missed antenna state packet 5: gdel flag set in one or more ICU data blocks 6: Unable to compute Receiver Time mapping 7: Not defined

4.2.23 TNK1B

Cold gas tank sensor temperatures and pressures. This format is also used by the TNK1A data product.

Note that the parameter **time_intg** is in GPS Time for TNK1B and OBC Time for TNK1A.

Parameter	Definition
time_intg	Integer seconds past 12:00:00 noon of January 1, 2000
time_frac	Fractional portion of time tag, in microseconds
time_ref	Time reference frame. 'R' = Receiver, OBC, or LRI Time, 'G' = GPS Time
GRACEFO_id	Satellite identifier
tank_id	Cold gas tank id. Tank 1 is on -X axis, tank 2 is on +X axis
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: '0' = OBC Time, '1' = Spacecraft elapsed time. Flag is carried from TNK1A into TNK1B, although all TNK1B time tags are in GPS Time 1: '0' = Pulse sync, '1' = No pulse sync 2-5: Not defined 6: No OBC-to-Receiver Time mapping 7 = No clock correction available
prod_flag	Product flag. Meanings of individual integers, from position 0 at right to final position at left, are as follows: 0: tank_pres 1: reg_pres 2: skin_temp 3: skin_temp_r 4: adap_temp 5: boss_fixed if GRACE-FO. Not defined if GRACE 6: boss_sliding if GRACE-FO. Not defined if GRACE 7: Not defined
tank_pres	For GRACE, cold tank internal pressure. For GRACE-FO, the actual pressure in the high CGPS pressure part (tank pressure)
reg_pres	For GRACE, pressure at the reference point on the pressure regulator housing. For GRACE-FO, the actual pressure in the low CGPS pressure part (tank pressure)
skin_temp	For GRACE, skin temperature of cold tank. For GRACE-FO, zenith direction skin temperature
skin_temp_r	Skin temperature of cold tank (redundant)
adap_temp	For GRACE, tank adaptor temperature. For GRACE-FO, nadir direction skin temperature
boss_fixed	For GRACE-FO, boss thermistors on the +X Tank: fixed end = +X/-Y orientation
boss_sliding	For GRACEFO, boss thermistors on the +X Tank: sliding end = -X/+Y orientation

4.2.24 USO1B

USO and K-Band frequency data derived from POD.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
uso_id	USO ID
uso_freq	USO frequency
K_freq	K band frequency
Ka_freq	Ka band frequency
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Linear extrapolation of values not valid AFTER gps_time 1: Linear extrapolation of values not valid BEFORE gps_time 2-7: Not defined

4.2.25 VCM1B

Vector location, in SRF, for satellite center of mass. This solution is obtained from calibration maneuver data or tracking model. This format is also used by the VGB1B, VGN1B, VGO1B, VKB1B, and VSL1B data products.

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
GRACEFO_id	Satellite identifier
mag	Magnitude of vector
cosx	Direction cosine of vector with SRF X-axis
cosy	Direction cosine of vector with SRF Y-axis
cosz	Direction cosine of vector with SRF Z-axis
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: L1 phase center offset vector, if GPS antenna 1: L2 phase center offset vector, if GPS antenna 2-7: Not defined

4.2.26 VGB1B

Vector position, in SRF, for GPS backup navigation antenna phase center. This data product uses the same format as the VCM1B data product.

4.2.27 VGN1B

Vector position, in SRF, for GPS main antenna phase center. This data product uses the same format as the VCM1B data product.

4.2.28 VGO1B

Vector position, in SRF, for GPS occultation antenna phase center. This data product uses the same format as the VCM1B data product.

4.2.29 VKB1B

Vector position, in SRF, for KBR antenna phase center. This data product uses the same format as the VCM1B data product.

4.2.30 VSL1B

Vector position, in SRF, for SLR corner cube reflector. This data product uses the same format as the VCM1B data product.

5 Acronyms

ACC SuperSTAR Accelerometer

AF ACC Frame

CG Center of Gravity

CHU	Camera Head Unit
CNR	Carrier-to-noise ratio
DLR	Deutsches Zentrum Für Luft und Raumfahrt
DOWR	Dual One Way Range
ECI	Earth-Centered Inertial
EOM	End-of-Mission
EOSDIS	Earth Observing System Data and Information System
GFZ	German Research Centre for Geosciences
GNSS	Global Navigation Satellite Systems
GPS	Global Position System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GSOC	German Space Operations Center
ICRS	International Celestial Reference System
IERS	International Earth Rotation Service
ICU	Interface Control Unit
IGS	International GNSS Service
IMU	Inertial Measurement Unit
IPU	Instrument Processing Unit
ISDC	Information System and Data Center
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
KBR	K-Band Ranging System
LEOP	Launch and Early Operations Phase
LRI	Laser Ranging Interferometer
LRR	Laser Retro Reflector
NASA	National Aeronautics and Space Administration
OBC	Onboard Computer
PO.DAAC	Physical Oceanography Distributed Active Archive Center
POD	Precision Orbit Determination
RINEX	Receiver Independent Exchange Format
RDC	Raw Data Center
SCA	Star Camera Assembly
SCF	Star Camera Frame
SDS	Science Data System
SF	Satellite Frame

SLR	Satellite Laser Ranging
SRF	Science Reference Frame
SNR	Signal-to-noise ratio
SOE	Sequence of Events
SST	Satellite-to-Satellite Tracking
TEC	Total Electron Content
TWR	Two-Way Range
USO	Ultra-Stable Oscillator
UTCSR	University of Texas, Center for Space Research

References

[1] Kelley Case, Gerhard Kruizinga, and Sien-Chong Wu. GRACE Level 1B Data Product User Handbook. Technical Report JPL D-22027, NASA Jet Propulsion Laboratory / California Institute of Technology, March 2010.

[2] Srinivas Bettadpur. Gravity Recovery and Climate Experiment Product Specification Document. Technical Report GRACE 327-720 (CSR-GR-03-02), Center for Space Research, The University of Texas at Austin, May 2012.

[3] Karen Dragon. GRACE Follow-On Mission Plan. Technical Report JPL D-71781, NASA Jet Propulsion Laboratory / California Institute of Technology, April 2015.

[4] Denis Fischer. GRACE-FO Science Data Systems Questions for Airbus. Personal communication, December 2017.

[5] Thomas Usbeck. GRACE-FO Spacecraft Mass. Personal communication, July 2018.

[6] Richard P. Kornfeld, Bradford W. Arnold, Michael A. Gross, Neil T. Dahya, William M. Klipstein, Peter F. Gath, and Srinivas Bettadpur. GRACE-FO: The Gravity Recovery and Climate Experiment Follow-On Mission. *Journal of Spacecraft and Rockets*, 56(3):931–951, 2019. doi: 10.2514/1.A34326.

[7] André Girerd, Eric Gustafson, and Gerhard Kruizinga. GRACE Follow-On Systems Timing Description. Technical Report JPL D-81406, NASA Jet Propulsion Laboratory / California Institute of Technology, June 2014.

[8] Serge Dubovitsky. Definition of Time Specification Relevant to LRI Operations. Technical report, NASA Jet Propulsion Laboratory / California Institute of Technology, October 2016.

[9] Zuheir Altamimi, Paul Rebischung, Laurent Métivier, and Xavier Collilieux. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *Journal of Geophysical Research: Solid Earth*, 121(8):6109–6131, 2016. doi: 10.1002/2016JB013098.

[10] Gérard Petit and Brian Luzum, editors. *IERS Conventions (2010) (IERS Technical Note No. 36)*. International Earth Rotation and Reference Systems Service (IERS), Verlag des Bundesamts für Kartographie und Geodäsie, 2010.

[11] Sien-Chong Wu, Gerhard Kruizinga, and Willy Bertiger. Algorithm Theoretical Basis Document for GRACE Level-1B Data Processing, v1.2. Technical Report GRACE 327-741 (JPL D-27672), NASA Jet Propulsion Laboratory / California Institute of Technology, May 2006.

[12] Brent Ware. GRACE Follow-On Project LRI FM1 Datation Test Report. Technical report, NASA Jet Propulsion Laboratory / California Institute of Technology, January 2018.

[13] Brent Ware. Re: LSM1B and LHK1B time corrections. Personal communication, June 2019.

[14] Willy Bertiger, Nate Harvey, and Robert Spero. An Alternate Formulation Of The LRI Measurement. Technical report, NASA Jet Propulsion Laboratory / California Institute of Technology, December 2018.

[15] Robert Spero. Re: KBAND with GPS. Personal communication, October 2018.

[16] Robert Spero. GRACE Follow-On Laser Ranging Interferometer Phase Jump Removal ("Deglitching"). Technical report, NASA Jet Propulsion Laboratory / California Institute of Technology, September 2018.

[17] Klaus Abich et al. In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer. *Physical Review Letters*, 123:031101, July 2019. doi: 10.1103/PhysRevLett.123.031101.

[18] Nate Harvey. GRACE star camera noise. *Advances in Space Research*, 58(3):408–414, August 2016. doi: 10.1016/j.asr.2016.04.025.

[19] Christopher M. McCullough. Overview of Calibrated GRACE-FO Accelerometer Products (ACT) - Level-1 Product Version 04. Technical report, NASA Jet Propulsion Laboratory / California Institute of Technology, May 2016.

[20] Willy Bertiger, Shailen D. Desai, Bruce Haines, Nate Harvey, Angelyn W. Moore, Susan Owen, and Jan P. Weiss. Single receiver phase ambiguity resolution with GPS data. *Journal of Geodesy*, 84(5):327–337, 05 2010. doi: 10.1007/s00190-010-0371-9.

[21] Henryk Dobslaw, Inga Bergmann-Wolf, Robert Dill, Lea Poropat, and Frank Flechtner. Product Description Document for AOD1B Release 06. Technical Report GRACE 327-750, Rev. 6.1, German Research Centre for Geosciences, October 2017.

[22] Denis Fischer. AOCS Sensor Alignment. Technical Report GFO-TN-ADSF-AO-50002328 Issue 3, Airbus DS GmbH, 88039 Friedrichschafen, Deutschland, January 2017.