Description of Calibrated GRACE-FO Accelerometer Data Products (ACT)

Level-1 Product Version 04

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Contents

1 Introduction

As referenced in the Level-1 Product Handbook [1], the accelerometer data is calibrated to enable more optimal gravity field recovery. Due to differing noise characteristics, different calibrations are required for each GRACE-FO satellite (GRACE-C and GRACE-D) and over different time spans. Additionally, note that this document only refers to the linear acceleration data; angular accelerations are set to zero for the ACT product. For GRACE-C accelerometer data, throughout the entirety of the mission, and GRACE-D accelerometer data, for all days before 2018-06-21, the primary errors mitigated through the calibrations are spurious accelerometer response to high frequency signal. This results in Phantom Accelerations (see section 4.2) and improper response at thruster firings, most notably at roll thruster firings. Additionally, for the GRACE-D accelerometer data, the noise characteristics changed starting on 2018-06-21, compounding the previously noted errors with significant bias jumps. For this reason, the GRACE-D accelerometer data, for all days on and after 2018-06-21, uses an accelerometer transplant from GRACE-C. The following will outline the specific procedure used for each of these calibration processes in more detail.

2 GRACE-C Calibrated Accelerometer Data (ACT)

Prior to use in gravity field processing, the following calibration steps are applied sequentially to the output of the accelerometer. These processing steps are applied to mitigate known errors. The primary errors, which are being mitigated through this calibration, include spurious measurements of high frequency signals, thought to arise due to aliasing when performing the analog to digital conversion, which manifest in the accelerometer response at thruster firings and as Phantom Accelerations. The calibration process, described below, yields the calibrated ACT1A data product for GRACE-C. The corresponding ACT1B data products are created using the nominal GRACE-FO Level-1 software, which performs time corrections and CRN filtering [1]. Finally, note that this calibration procedure is used for GRACE-C accelerometer data throughout the mission and GRACE-D accelerometer data (replacing references to GRACE-C with GRACE-D) for all days before 2018-06-21.

C.1 Remove thruster firings from GRACE-C ACC1A data by using GRACE-C THR1A data to identify when the thruster firings occur, removing a time span of one second, before and after, the thruster firings, and filling the gaps with linear interpolation.

C.2 Remove large, spurious accelerations (Phantom Accelerations, see section 4.2) from the intermediate GRACE-C ACC1A data created in C.1 by removing a one second time span, before and after, any outliers in the data that exceed a certain threshold (see Table 1) and filling the gaps with linear interpolation.

C.3 Create a thruster-only ACC1A time series for GRACE-C. Model the thrusts, see 4.3, derived from GRACE-C data and using the GRACE-C THR1A data. The resulting data will be zero everywhere, except where there is a roll/pitch/yaw thruster firing.

C.4 Insert the GRACE-C intermediate roll/pitch/yaw thruster-only ACC1A time series derived in C.3 to the time series C.2.

3 GRACE-D Calibrated Accelerometer Data (ACT)

Prior to use in gravity field processing, accelerometer data from GRACE-C is transplanted to GRACE-D, without explicitly using any GRACE-D accelerometer data, to model the accelerations imparted on the GRACE-D spacecraft. This is done to mitigate the primary errors in the GRACE-D accelerometer data, such as spurious measurements of high frequency signals, thought to arise due to aliasing when performing the analog to digital conversion, and, most importantly, bias jumps occurring commonly in all axes (typically during thruster firing events). The transplant process, described below, yields the transplanted ACT1A data product for GRACE-D. The corresponding ACT1B data products are created using the nominal GRACE-FO Level-1 software, which performs time corrections and CRN filtering [1]. Note that this algorithm is only used for GRACE-D accelerometer data on, and after, 2018-06-21. For days before that epoch, the GRACE-C calibration method is used.

D.1 Remove thruster firings from GRACE-C ACC1A data by using the GRACE-C THR1A data to identify when the thruster firings occur, removing a time span of one second, before and after, the thruster firings, and filling the gaps with linear interpolation.

D.2 Remove large, spurious accelerations (Phantom Accelerations, see section 4.2) from the intermediate GRACE-C ACC1A data created in D.1 by removing a one second time span, before and after, any outliers in the data that exceed a certain threshold (see Table 1) and filling the gaps with linear interpolation.

D.3 Adjust the intermediate thruster/Phantom-free GRACE-C ACC data from by rotating 180° in yaw; which results in a multiplication of the X and Z axes (in the ACC frame) by -1.0.

D.4 Create a thruster-only ACC1A time series for GRACE-D. Model the thrusts, see 4.3, derived from GRACE-D data and using the GRACE-D THR1A data. The resulting data will be zero everywhere, except where there is a roll/pitch/yaw thruster firing.

D.5 Time shift the GRACE-C ACC1A time series from GRACE-C OBC time to GRACE-D OBC time (using the TIM1B, CLK1B, and GNI1B products for GRACE-C and GRACE-D, see 4.1.2) and account for the time offset due to differences in position between GRACE-C and GRACE-D (accelerometer data transplant timing, see 4.1.1).

D.6 Insert the GRACE-D roll/pitch/yaw thruster-only ACC1A time series derived in D.4 to the time series from D.5.

4 Ancillary Descriptions

4.1 Timing Offsets

When performing the calibrations outlined in sections 2 and 3, there are some important timing descriptions which should be described in more detail. The following outlines how the time shift is computed for moving one satellite into the air space of the other (the accelerometer data transplant) and briefly touches on important time frames and conversions between them (specifically for performing item D.5 in section 3).

4.1.1 Transplant Timing

When transplanting the GRACE-C accelerometer data to GRACE-D, as outlined in section 3, the GRACE-C data is time shifted into the air space of GRACE-D by invoking a time offset, which is determined using both satellite's orbits (given in the GNI1B files or separately computed via an orbit determination process). The detailed procedure for determining this time offset, for a single data epoch, is outlined below.

1. Let the XYZ position and XYZ velocity for satellite i (C or D) be given as,

   $$\boldsymbol{r}_i(t) = [x_i(t), y_i(t), z_i(t)_i]^T$$
   $$\dot{\boldsymbol{r}}_i(t) = [\dot{x}_i(t), \dot{y}_i(t), \dot{z}_i(t)]^T$$

   respectively.

2. When transplanting GRACE-C accelerometer data to GRACE-D, the value of the time offset, t, is determined at the desired epoch, t_0, by minimizing the performance index,

   $$J = [\boldsymbol{r}_D(t_0) - \boldsymbol{r}_C(t_0 + t)]^T [\boldsymbol{r}_D(t_0) - \boldsymbol{r}_C(t_0 + t)]$$

3. The minimization is performed using Newton's method, with an initial guess for the time offset, t, equal to the epoch of interest, t_0. Assuming the iteration counter is k, subsequent iterations of the value t_k are given by,

   $$t_{k+1} = t_k - \frac{J'(t_k)}{J''(t_k)}$$

   where t_k is iterated to convergence and $'$ denotes differentiation with respect to t. Note that velocities are available with the solved for orbit (such as that given in the GNI1B) and interpolation can be used to get positions/velocities/accelerations at any arbitrary epoch.

4.1.2 OBC Time Offsets

There are 3 primary time frames of interest when dealing with the accelerometer data: OBC (Onboard Computer) Time, Receiver Time, and GPS Time. Refer to the Level-1 Handbook [1] for more details. To convert between these time systems, two data products are provided: TIM1B and CLK1B. The TIM1B product provides mapping from OBC Time to Receiver time and the CLK1B product provides mapping from Receiver Time to GPS Time (with GPS Time being common between satellites C and D). During the transplant process, the accelerometer measurements are taken through a series of time frame transformations (section 3, item D.5), using the Level-1 products, as outlined below.

1. GRACE-C OBC Time is shifted to GRACE-C Receiver Time using time offsets provided in the GRACE-C TIM1B product.
2. GRACE-C Receiver Time is shifted to GPS Time using time offsets provided in the GRACE-C CLK1B product.
3. GPS Time is shifted to GRACE-D Receiver Time by using the reverse of the time offset provided in the GRACE-D CLK1B product. Note that the GRACE-D CLK1B product provides time shifts from GRACE-D Receiver Time to GPS Time; the inverse of this time shift is required.
4. GRACE-D Receiver Time is shifted to GRACE-D OBC Time by using the reverse of the time offset provided in the GRACE-D TIM1B product. Note that the GRACE-D TIM1B product provides time shifts from GRACE-D OBC Time to GRACE-D Receiver Time; the inverse of this time shift is required.

This process, along with the time offset in section 4.1.1, enables the GRACE-C accelerometer data to be transplanted to GRACE-D and referenced in OBC Time, just as the ACC1A files are typically represented. For further details on the time frames, Level-1 products (TIM1B, CLK1B), etc. see the Level-1 Product Handbook [1].

4.2 Phantom Accelerations

The term, Phantom Accelerations, is used to denote large, spurious accelerations in the accelerometer data; which occur away from thruster firings, exhibit geographical correlation, exhibit beta angle dependent correlation, and are of unknown origin. The current hypothesis is that these accelerations may be internal accelerations, similar to twangs on GRACE, which are aliased into the nominal accelerometer measurements during analog-to-digital conversion. Since these accelerations can sometimes be quite large and do not always integrate to zero, they are harmful to estimates of the Earth's gravity field, and must be removed. These Phantom Accelerations are edited by treating deviations from the data mean exceeding a predefined threshold as outliers, removing them, and filling the gaps via linear interpolation. The values of these thresholds, in the Science Reference Frame [1], are given in Table 1.

Table 1: Phantom Acceleration thresholds for outlier removal.

SRF Direction	**Outlier Threshold**
X	$\pm 1.5 \times 10^{-7}$ m/s^2
Y	$\pm 1.0 \times 10^{-7}$ m/s^2
Z	$\pm 3.0 \times 10^{-7}$ m/s^2

4.3 Thrust Modeling

The thruster repsonse due to attitude thruster firings has been modeled, using regression of the mission's accelerometer data. This is done to more accurately represent the effect of attitude thruster firings on the linear acceleration measurements. Currently, the accelerometer provides spurious measurements for high frequency signals (such as the Phantom accelerations described in section 4.2 and the attitude thruster firings - most importantly roll thruster firings), hypothesized to be due to aliasing during analog-to-digital conversion. Therefore, long thruster firings are used to regress a thruster response model to replace the spurious accelerometer measurements. Long thruster firings, greater than approximately 750 milliseconds, are used because the prolonged firing allows for stabilization of the accelerometer's transient behavior and observation of the true steady state measurements of the accelerometer during attitude thruster firings. The thruster model assumes that the attitude thrusters impart a constant acceleration on the spacecraft over the duration of the firing (a square pulse). Due to this, the model is currently fully described by a single value (per thruster type and accelerometer direction). The model values are given in Tables 2 and 3 for GRACE-C and GRACE-D respectively.

Note that the most important of these models are for the roll thruster firings (although there is some very slight, localized improvement in the gravity fields when modeling the pitch/yaw thruster firings). When implementing these models in the ACT1A data products, the measured thruster repsonses are removed from the ACC1A data, using the the THR1A data, and linearly interpolated (yielding a thruster free time series of accelerometer data). Then the models given in Tables 2 or 3 are implemented to reintroduce the thruster responses to the accelerometer data (performed in item C.3 in section 2 and in item D.4 in section 3). Further refinements to this model, including the incorporation of pressure regulator variations, will be released when available.

Table 2: GRACE-C thruster model for the linear acceleration response to attitude thruster firings.

Attitude Thrust	**Accelerometer Direction**	**Acceleration**
Positive Roll		
	SRF X	1.5×10^{-8} m/s^2
	SRF Y	-2.5×10^{-6} m/s^2
	SRF Z	6.0×10^{-7} m/s^2
Negative Roll		
	SRF X	-2.0×10^{-8} m/s^2
	SRF Y	-2.3×10^{-6} m/s^2
	SRF Z	5.5×10^{-7} m/s^2
Positive Pitch		
	SRF X	0.0 m/s^2
	SRF Y	7.6×10^{-8} m/s^2
	SRF Z	-2.35×10^{-6} m/s^2
Negative Pitch		
	SRF X	-1.09×10^{-7} m/s^2
	SRF Y	-3.75×10^{-8} m/s^2
	SRF Z	1.55×10^{-6} m/s^2
Positive Yaw		
	SRF X	-0.7×10^{-8} m/s^2
	SRF Y	2.0×10^{-6} m/s^2
	SRF Z	5.71×10^{-7} m/s^2
Negative Yaw		
	SRF X	-2.2×10^{-8} m/s^2
	SRF Y	-3.0×10^{-6} m/s^2
	SRF Z	5.3×10^{-7} m/s^2

Table 3: GRACE-D thruster model for the linear acceleration response to attitude thruster firings.

Attitude Thrust	**Accelerometer Direction**	**Acceleration**
Positive Roll		
	SRF X	-3.0×10^{-8} m/s^2
	SRF Y	-3.7×10^{-6} m/s^2
	SRF Z	6.0×10^{-7} m/s^2
Negative Roll		
	SRF X	-4.0×10^{-8} m/s^2
	SRF Y	-3.9×10^{-6} m/s^2
	SRF Z	6.8×10^{-7} m/s^2
Positive Pitch		
	SRF X	5.5×10^{-8} m/s^2
	SRF Y	3.33×10^{-8} m/s^2
	SRF Z	-3.5×10^{-6} m/s^2
Negative Pitch		
	SRF X	-1.19×10^{-7} m/s^2
	SRF Y	0.0 m/s^2
	SRF Z	3.5×10^{-6} m/s^2
Positive Yaw		
	SRF X	1.41×10^{-7} m/s^2
	SRF Y	4.0×10^{-6} m/s^2
	SRF Z	6.0×10^{-7} m/s^2
Negative Yaw		
	SRF X	1.23×10^{-7} m/s^2
	SRF Y	-3.8×10^{-6} m/s^2
	SRF Z	5.7×10^{-7} m/s^2

5 Summary

The preceding has outlined the current algorithmic processes used in the creation of ACT1A files. To create ACT1B files, the same processes used in the conversion of ACC1A to ACC1B files (time correction, CRN filtering, etc.), described in the Level-1 Product Handbook [1], are performed. Additionally, the algorithmic processes described relate to the current, Level-1 data release, version 04, and as further data analysis, verification, and validation are performed, enhanced calibration procedures will be implemented and documented.

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References

[1] Hui Ying Wen, Gerhard Kruizinga, Meegyeong Paik, Felix Landerer, William Bertiger, Carly Sakumura, Tamara Bandikova, and Christopher M. McCullough. Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) Level-1 Data Product User Handbook. Technical Report JPL D-56935, NASA Jet Propulsion Laboratory / California Institute of Technology, May 2019.