GRACE Follow-On accelerometer data recovery

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Abstract

In Gravity Recovery and Climate Experiment (GRACE) Follow-on (GRACE-FO) mission, similar to its predecessor GRACE, the twin satellites are equipped with three-axis accelerometers, measuring the non-gravitational forces. After one month in orbit, during the in-orbit-checkout phase, the noise on GRACE-D accelerometer measurements elevated and results in systematical degradation of the data. For this reason, the GRACE-D data needs to be replaced by synthetic data, the so-called transplant data, officially generated by the GRACE-FO Science Data System (SDS). The SDS transplant data is derived from the GRACE-C accelerometer measurements, by applying time and attitude corrections. Furthermore, model-based residual accelerations due to thruster firings on GRACE-D were added, proven to improve the data quality in gravity field recovery. However, preliminary studies of GRACE-FO data during the single accelerometer months show that the low degree zonal harmonics, in particular C20 and C30, are sensitive to the current transplant approach. In this work, we present a novel approach to recover the GRACE-D ACT1B data by incorporating non-gravitational force models and analyze its impact on monthly gravity field solutions. The results show the improved ACT1B data not only contributed to a noise reduction but also improve the estimates of the C20 and C30 coefficients. The application of this new approach demonstrates that the offset between Satellite Laser Ranging (SLR) and GRACE-FO derived C30 time series can be reduced by the use of the alternative accelerometer product.

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4 Key Points:

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- Alternative processing is proposed for recovering GRACE-D accelerometer data.
- The recovered products improve overall accuracy of gravity field solutions.
- The recovered products improve the estimates of low degree zonal coefficients.

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8 Abstract

In Gravity Recovery and Climate Experiment (GRACE) Follow-on (GRACE-FO) mission, similar to its predecessor GRACE, the twin satellites are equipped with three-axis accelerometers, measuring the non-gravitational forces. After one month in orbit, during the in-orbit-checkout phase, the noise on GRACE-D accelerometer measurements elevated, and results in systematical degradation of the data. For this reason, the GRACE-D data needs to be replaced by synthetic data, the so-called transplant data, officially generated by the GRACE-FO Science Data System (SDS).

The SDS transplant data is derived from the GRACE-C accelerometer measurements, by applying time and attitude corrections. Furthermore, model-based residual accelerations due to thruster firings on GRACE-D were added, proven to improve the data quality in gravity field recovery. However, preliminary studies of GRACE-FO data during the single accelerometer months show that the low degree zonal harmonics, in particular C_{20} and C_{30} , are sensitive to the current transplant approach.

In this work, we present a novel approach to recover the GRACE-D ACT1B data by incorporating non-gravitational force models and analyze its impact on monthly gravity field solutions. The results show the improved ACT1B data not only contributed to a noise reduction, but also improve the estimates of the C_{20} and C_{30} coefficients. The application of this new approach demonstrates that the offset between Satellite Laser Ranging (SLR) and GRACE-FO derived C_{30} time series can be reduced by the use of the alternative accelerometer product.

²⁹ 1 Introduction

Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) The 30 mission (Landerer et al., 2020) was successfully started on May 22, 2018, and since then, 31 provides high-quality observations to continue the gravity field time series of its 32 predecessor, the GRACE mission (2002-2017) (Tapley et al., 2004). Similar to GRACE, 33 both satellites in GRACE-FO mission are equipped with high precision accelerometers to 34 measure the non-gravitational forces (e.g. atmospheric drag and radiation pressure), as 35 well as disturbances due to satellite's operation, such as attitude thruster activation. With 36 the aim of gravity field recovery, these measurements are essential to reduce the effects of 37 non-gravitational perturbations from the orbit and obtain the sough-after gravitational 38 components. 39

Early studies have shown that the accelerometer measurements (ACC) from both 40 GRACE-FO satellites are contaminated by different types of noise. Therefore, the 41 standard GRACE Level-1A to Level-1B processing (Wu et al., 2006) does not deliver ACC 42 Level-1B (ACC1B) products with sufficient accuracy for gravity field recovery. For this 43 reason, the GRACE-FO Science Data System (SDS) team has developed specific calibration process for the accelerometer on each satellite and has provided the calibrated 45 GRACE-FO accelerometer data (ACT) products (McCullough et al., 2019). The SDS 46 members consist of the Center for Space Research at the University Texas at Austin 47 (CSR), NASA's Jet Propulsion Laboratory (JPL), and the German Research Centre 48 Geosciences (GFZ). 49

In case of GRACE-C, the accelerometer data is calibrated throughout the mission by replacing un-realistic accelerations due to thruster firing with model-based responses and removing large geographical/orbital related accelerations, called Phantom accelerations. The same calibration process is applied to the GRACE-D data for the early days of the mission (until 2018-06-21).

⁵⁵ However, After one month in orbit, the GRACE-D accelerometer data degraded.
 ⁵⁶ Hence, its measurements were replaced by synthetic data, the so-called transplant data.

The transplant approach, initially studied and developed for GRACE, uses one satellite's 57 ACC measurement to generate the other twin satellite ACC data. The idea originates 58 from the GRACE mission in 2002 and 2003, when over two periods of several weeks, only 59 one accelerometer data was available. Save et al. (2006) showed that the transplant 60 procedure is feasible because both satellites fly in the same orbit and have a time delay of 61 25-30 s. Therefore, the change in the non-gravitational accelerations during this time delay 62 is very small, and both accelerometers would measure approximately the same signal. 63 However, it is mandatory to apply time and attitude corrections to the available 64 accelerometer measurements, to account for the variable separation between the two 65 spacecrafts and the orientation differences relative to each other. 66

Over the final months of GRACE, after the GRACE-B accelerometer was turned off due 67 to battery issues, the demand for synthetic ACC data raised once again. Bandikova et al. 68 (2019) presented an improved ACC data transplant approach, which includes the modeling 69 of residual linear accelerations due to thruster firings, in addition to the attitude and time 70 correction. The modeling of thruster spikes has been studied before both on ACC1B (Meyer 71 et al., 2011) and ACC Level-1A (ACC1A) (McCullough et al., 2015) using a statistical 72 approach. However, Bandikova et al. (2019) show that by determining the dynamic system, 73 which generates the impulse response of each thruster pair, one can improve the estimates 74 of the spikes and reduce the noise in gravity field solutions. The improved ACC transplant 75 contributes to the processing standards for final months of GRACE, and ACC transplant 76 data was included in the official Level-1B products. 77

Based on the official Level-1B products, GRACE/GRACE-FO Level-2 RL06 products, 78 are provided by the SDS members. To provide long-term gravity field time series, the 79 processing standards for GRACE-FO remained mostly consistent with GRACE. In 80 addition to the official centers, various other research institutions are also preparing their 81 processing setup for GRACE-FO gravity field solutions. Among these centers, the 82 Institute of Geodesy at Graz University of Technology (TUG) routinely provides 83 operational GRACE-FO products, consistent with ITSG-Grace2018 standards (Kvas, 84 Behzadpour, et al., 2019), which are published by the International Centre for Global 85 Earth Models (ICGEM, (Drewes et al., 2016)). 86

Preliminary analysis of GRACE-FO data during the single accelerometer months proves 87 that the derived low degree zonal harmonics, in particular C_{20} and C_{30} , are affected by the 88 transplant approach, and as recommended by SDS, are needed to be replaced by SLR-derived 89 values (Loomis et al., 2020). Figure 1 shows the absolute difference between GRACE-FO 90 derived C_{30} and SLR-derived time-series, provided in the Technical Note-14 (TN-14), and 91 compares their variations with β' angle of the orbit. The β' angle represents the angle 92 between the orbital plane of the satellite and the Sun direction. It is visible that the peaks, 93 indicating the largest deviations from the recommended values, are highly correlated with 94 the periods with β' angle close to zero. During these periods, the satellite is exposed to 95 direct sunlight for approximately half of its revolution, and the rest of the time is passing 96 through the Earth's shadow, causing large temperature differences. This orbital condition 97 with 161-day cycle has an effect on satellite's operation, specifically on the energy absorption 98 by solar panels and on the thermal control due to the heating by the Sun. 99

To further investigate the reason, the transplant approach can be evaluated in 100 GRACE mid-timespan, when both accelerometers operated nominally and provided 101 high-quality data. Meyer et al. (2011) compared the acceleration signal measured by each 102 satellite in the same orbit position during a half-cycle of β' angle between March and 103 September 2007. They showed that a difference up to 3 nm/s^2 exists between the two 104 measured signals. The most substantial difference happens for a short period of time when 105 satellites are transiting through Earth's shadow, as the solar radiation pressure (SRP) 106 changes for each satellite at the same position. Additionally, a long-term variation exists 107 mainly during periods when β' angle is close to zero. In other words, when satellites are 108 under direct Sun exposure, due to high fluctuations in the atmosphere density, they 109

Figure 1. Absolute difference between GRACE-FO estimated C_{30} and recommended values in TN-14. The largest deviations are correlated with β' angle close to zero.

experience different forces, which in this case, is the drag force. Hence, the direct transplanting of ACC data can cause large errors under these conditions.

The main purpose of this paper is to present an improved method to recover the GRACE-D accelerometer data by incorporating non-gravitational force models and analyze its impact on the recovered gravity field solutions. Within the gravity field recovery, the transplanted GRACE-D accelerometer data shows a significant impact on the low degree coefficients, in particular reduces the offset between SLR and GRACE-FO derived C_{30} time series.

The paper is organized as follows: In Section 2, we provide a brief overview about the accelerometer data and focus on different ACC data products. In Section 3, we briefly describe the non-gravitational forces acting on the satellites. In Section 4, we present the alternative GRACE-D ACC recovery. And finally, in Section 5, we discuss the results by comparing our products with the official transplant data and their impact on the recovered gravity field solutions.

124 **2** Accelerometer data

The GRACE-FO accelerometer is a three-axis electrostatic accelerometer manufactured by the Office National d'Études et de Recherches Aérospatiales (ONERA) (Christophe et al., 2015). The accelerometer provides information about the linear and angular acceleration of the satellite. The sensor has two high-sensitive axes, the radial and along-track axes exhibiting a resolution better than 0.1 nm/(s² $\sqrt{\text{Hz}}$), and one less-sensitive axis, the crosstrack axis with an accuracy of 1 nm/(s² $\sqrt{\text{Hz}}$).

The accelerometer is placed in the center of mass (CoM) of the satellite. The core of the sensor consists of a proof mass, surrounded by an electrode cage. The proof mass is suspended by electrostatic forces generated by the electrodes. The sensor measurement is determined from the usage of analog voltages, producing the electrostatic force. The electrostatic force is proportional to the sum of the non-gravitational forces acting on the satellite, including atmospheric drag, solar radiation pressure (SRP), earth radiation pressure (ERP), and other disturbances.

There are three types of science data products for the GRACE-FO accelerometer data, which in the following, will be briefly introduced.

2.1 ACC1A

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The ACC Level-1A (ACC1A) data products include the 10-Hz linear acceleration measurements, given in accelerometer reference frame (AF). The origin of this frame is defined to be the center of mass of the proof mass and the frame axes are directed as shown by Figure 2. The time frame of the data is determined by the on-board computer (OBC).

146 **2.2 ACT1A**

To obtain better gravity field solutions, a series of calibration processes is applied to 147 ACC1A, providing the calibrated accelerometer data (ACT1A) products (McCullough et 148 al., 2019). Briefly summarized, for GRACE-C, this includes substituting thruster spikes 149 with model values and removing phantom accelerations. The same process is applied to 150 GRACE-D ACC1A until 2018-06-21. Afterwards, following Bandikova et al. (2019), the 151 GRACE-D data is replaced with the transplant data from GRACE-C. ACT1A data are also 152 10-Hz linear accelerations in AF and OBC time. For more details the reader is referred to 153 Wen et al. (2019) and McCullough et al. (2019). 154

Figure 2. Schematic view of the axes alignments in the accelerometer reference frame (AF) and the science reference frame (SRF).

Figure 3. ACC compress procedure applied to linear accelerations. This procedure applies time-tag corrections and digital filter on ACT1A accelerometer data to generate ACT1B data.

155 **2.3 ACT1B**

During Level-1A to Level-1B data processing, the ACT1A linear accelerations are edited, time tagged and low-pass filtered in order to reduce the high-frequent measurement noise (Wu et al., 2006). Figure 3 describes the Level-1A to Level-1B processing for linear accelerations. The process is discussed in more details in Appendix A. The output of this process is 1-Hz ACT1B product, given in satellite reference frame (SRF) and GPS time.

As the unprocessed Level-1A data products of GRACE-FO are publicly available to all 161 processing centers, an independent Level-1A to Level-1B data processing can be set up. At 162 TUG, we have implemented standard algorithms for data screening, time synchronization 163 and data rate reduction for the raw data, which produce in-house (i.e. independent of the 164 officially released product) ACT1B data, serving as input for the gravity field recovery. To 165 validate the implementation, we compare the TUG ACT1B from GRACE-C with the SDS 166 product. Figure 4 shows time-series and power spectral densities of differences between the 167 two products. The deviations are more than one order of magnitude smaller than the signal 168 noise on each axis, which demonstrates the preciseness of our implementation. 169

Figure 4. Comparison between the TUG ACT1B and the SDS ACT1B of GRACE-C on July 8, 2018 in time domain (left column) and their differences in frequency domain (right column).

Force Model	References
Solar radiation pressure Solar flux at 1 AU (1367 W m^{-2})	Montenbruck and Gill (2000)
Visible and infrared radiation flux	Vielberg and Kusche (2020)
Physical shadow function	Robertson et al. (2015)
Thermal re-radiation	Montenbruck et al. (2014)
Earth radiation pressure	Rodriguez-Solano et al. (2011) and Knocke et al. (1988)
Earth's mean reflectivity and emmisivity* Thermal re-radiation	Wielicki et al. (1996) Montenbruck et al. (2014)

 Table 1.
 Non-gravitational force models due to radiation pressure.

*Clouds and the Earth's Radiant Energy System (CERES).

¹⁷⁰ **3** Non-gravitational force models

GRACE-FO is operating in a low-Earth orbit (LEO). The non-gravitational 171 accelerations acting upon LEO satellites are mainly due to atmospheric drag, SRP, and 172 ERP. The radiation pressure force models are summarized in Table 1. For the details on 173 the formulae applied for the radiation pressure modeling, the reader is referred to the 174 corresponding references. To model these effects, the satellites' geometry and surface 175 properties are obtained from GRACE-FO macro model (Wen et al., 2019). As the drag 176 force model plays an important role in recovering the GRACE-D missing measurements, 177 the basic equations of respective accelerations are described in the following. 178

¹⁷⁹ **3.1** Atmospheric drag

Aerodynamic force is the force acting on the satellite's surface caused by interchange of momentum with the atmosphere molecules. For LEO satellites, it is the dominant nongravitational perturbation. The aerodynamic force is modeled as:

$$\boldsymbol{a}_{aero} = -\frac{1}{2} \frac{A_{ref}}{m} \boldsymbol{C}_a \rho v^2_{TAS},\tag{1}$$

depending on the aerodynamic coefficient C_a , the atmospheric density ρ , the cross-sectional area A_{ref} , the satellite mass m, and the true airspeed v_{TAS} , i.e. the velocity of the spacecraft relative to the atmosphere. Here, the atmospheric density is obtained from the Jacchia-Bowman 2008 model (JB2008; Bowman et al. (2008)), the cross-sectional area from the macro model and the mass of the satellite are set to their launch mass values, as the MAS1B data product currently do not report the changing satellite mass.

The v_{TAS} is the relative velocity of the satellite with respect to the atmosphere, which is the sum of inertial velocity of the satellite \dot{r} , co-rotating atmosphere and atmospheric wind velocity v_w :

$$\boldsymbol{v}_{TAS} = \dot{\boldsymbol{r}} - \boldsymbol{\omega}_E \times \boldsymbol{r} + \boldsymbol{v}_w, \tag{2}$$

where \boldsymbol{r} is the satellite position and $\boldsymbol{\omega}_{E}$ is the angular velocity of the Earth sidereal rotation. The wind velocity is derived from Horizontal Wind Model 2014 (HWM14; Drob et al. (2015)). The component of the aerodynamic force toward normal velocity direction $\hat{\boldsymbol{v}}_{TAS}$ is referred to as drag and the component toward $\frac{\hat{\boldsymbol{v}}_{TAS} \times \hat{\boldsymbol{n}}}{\|\hat{\boldsymbol{v}}_{TAS} \times \hat{\boldsymbol{n}}\|} \times \hat{\boldsymbol{v}}_{TAS}$ as lift, with $\hat{\boldsymbol{n}}$ being the unit normal vector to the satellite plate. Hence, the aerodynamic coefficient can be expressed by:

Figure 5. Comparison between calibrated GRACE-C measurements (black) and simulated data on along-track (blue), cross-track (red), and radial (green) direction on 2019-12-05 (left) and 2019-09-12 (right).

$$\boldsymbol{C}_a = \boldsymbol{C}_D \parallel \boldsymbol{\hat{v}}_{TAS} + \boldsymbol{C}_L \perp \boldsymbol{\hat{v}}_{TAS}.$$
(3)

Therein, C_D and C_L are dimensionless drag and lift coefficients, respectively. As drag is the 198 major component of the aerodynamic force acting on satellites, neglecting lift and referring 199 to drag force instead of aerodynamic force is conventional. Consequently, the aerodynamic 200 coefficient can be referred to as drag coefficient, which is set to a constant value of 2.4 201 for GRACE-FO. Figure 5 shows the summation of non-gravitational models for two days of 202 mission at different β' angles. This comparison reveals that at similar altitude, the maximum 203 acceleration and deviation from model occur when β' is zero and satellite passes through 204 the day-side. 205

Due to uncertainties in the state and attitude of the satellite, interaction of the satellite's surface and atmosphere molecules affecting the drag coefficient, as well as uncertainties associated with atmospheric density models. It is not possible to model the drag force

Data	Description
ACT1A	Calibrated 10-Hz linear acceleration in AF and OBC time
CLK1B	Receiver clock offsets to convert time tags to GPS Time
TIM1B	Time conversion from OBC to receiver time with 8-s sampling
GNV1B	1-Hz satellite's position and velocity, given in Earth-Fixed Frame
SCA1B	1-Hz processed SCA data for rotation from Inertial Frame to SRF
THR1B	Thruster activations given in GPS time

 Table 2.
 GRACE-FO science data products required for GRACE-D data recovery.

accurately. Therefore, the values used for density and drag coefficient play a significant role
in drag model uncertainty (Moe & Moe, 2005; Prieto et al., 2014).

According to Equation 1, drag coefficient and density errors are not completely 211 separable without a good knowledge of at least one of them. Hence, the model exhibits a 212 multiplicative total error from these two sources. However, in case of co-orbiting missions, 213 it is convenient to assume that both satellites experience the same environment, in which 214 the drag model error for each satellite is approximately equivalent. Therefore, by having 215 one actual accelerometer measurements, in this mission GRACE-C, one can estimate the 216 model error, which then can be used to retrieve the missing measurements from the other 217 spacecraft with a malfunctioning accelerometer, i.e GRACE-D. 218

²¹⁹ 4 GRACE-D ACC recovery

In the following, the recovery processing for linear accelerations from GRACE-C ACT1A to GRACE-D ACT1B is described. Table 2 summarizes the required data products in this procedure. The input data of the process is the daily 10 Hz GRACE-C ACT1A. In the first step, we apply the standard Level-1A processing, as described in Appendix A, to convert the data to GPS time and SRF frame. Additionally, before applying the low-pass filter, we remove the thruster spikes using THR1B products with a margin of 1 s and fill the gaps with linear interpolation.

4.1 Calibration and Model reduction

The next step is computing the simulated accelerations according to Section 3 for both satellites with 1-Hz sampling. Since orbit data and SCA1B are already created with the same sampling, no interpolation is needed. Using the simulated data, we calibrate the GRACE-C data, obtained from the first step, with daily constant bias on each axis. Lastly, we reduce the simulated data a_{model} from the calibrated GRACE-C data a_{cal} , creating the unmodeled acceleration signal Δa :

$$\Delta \boldsymbol{a} = \boldsymbol{a}_{cal} - \boldsymbol{a}_{model}.\tag{4}$$

4.2 Time correction

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In this step, we transfer required GRACE-C Level-1B data, including orbit, SCA1B, and the unmodeled accelerations Δa to GRACE-D time frame by applying a transfer time correction. We obtain this correction by using satellites' positions and velocities and solving Figure 6. Time correction from GRACE-C to GRACE-D on 2018-07-01.

their equations of motions. Figure 6 shows the transfer time correction obtained for 2018 07-01.

4.3 Drag model correction

As mentioned in Section 3, the un-modeled acceleration signal contains an unknown multiplicative error $S_D = \rho \cdot C_D$, i.e. a scale factor, related to atmospheric density and aerodynamic coefficient. Within the recovery process, we estimate this scale factor based on the equation given by:

$$\Delta \boldsymbol{a} = \frac{\partial \Delta \boldsymbol{a}}{\partial S_D} \cdot S_D. \tag{5}$$

To account for temporal variations, the scale value in Eq. 5 is estimated daily, using 245 uniform cubic basis splines (UCBS) (de Boor, 2001). The UCBS is characterized by the 246 degree (d) and the number of knot (k) intervals. Here, we choose a knot interval with 247 1 min length, which results in $24 \times 60 = 1440$ knots for each daily interval (k = 1440). 248 Therefore, the total number of k + d = 1443 parameters per interval are needed for the 249 scale estimation. The outputs of this adjustment are: (a) the calculated scale, which will be 250 applied to GRACE-D drag model, and (b) the residual signal, containing errors from other 251 sources as well as the estimation process. 252

4.4 Attitude correction

The residual signal needs to be transferred to GRACE-D frame by applying attitude correction, as the orientation of each satellite with respect to SRF is different. The K-band ranging (KBR) measurement principle requires precise alignment of each satellite's KBR antenna towards each other, i.e. in the direction of the so-called line of sight (LOS). Since the antenna is mounted at the front panel of each satellite, the leading satellite is turned by 180° around its z-axis. Furthermore, both satellites fly with a pitch offset of approximately 1° with respect to the LOS. According to Bandikova et al. (2019), for GRACE accelerometer transplant, it was not possible to correct the attitude with the actual attitude variations, due to high-frequency noise on the star camera measurement. Therefore, the attitude correction was approximated by a 180° yaw and an empirical (not physical) 3.2° pitch transform.

In GRACE-FO, the attitude sensors on-board each satellite consist of three star cameras and one angular rate sensing inertial measurement unit (IMU). These attitude data are combined by means of a Kalman filter to obtain an optimal attitude product (SCA1B) (Harvey & Sakumura, 2019). According to (Landerer et al., 2020), this method reduces the noise level by approximately 2 orders of magnitude lower than GRACE. This allows us to directly use the GRACE-FO SCA1B to transfer residual accelerations from GRACE-C to GRACE-D frame.

4.5 Thruster spikes

The final step in the recovery process is to add GRACE-D modeled thruster responses 273 due to attitude thruster firings. This has been done for GRACE-D ACT1A based on 274 regression of the available accelerometer data, as reported by McCullough et al. (2019). To 275 create a Level-1B thruster-only time-series, we compute the difference between two 276 processed GRACE-D ACT1B time-series: one with modeled spikes and the other with 277 removed spikes. For the latter, we remove the thruster events with a margin of 1 s and fill 278 the gaps with linear interpolation during Level-1A processing. The resulting data only 279 includes roll/pitch/yaw thruster firing spikes with 1 s sampling. 280

281 5 Results

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In the following, we present the comparison of in-house and official ACT1B data sets in time and frequency domain as well as gravity field recovery based on these products.

5.1 GRACE-D accelerations

Figure 7 shows time-series and power spectral densities of differences of the official 285 transplanted data, SDS ACT1B, and the TUG ACT1B. A major difference is visible in 286 radial component, in particular in 1 cycle per revolution (cpr) frequency. As expected, higher 287 frequencies are less affected by the recovery process, as we used the same thruster responses, 288 which are dominant at frequencies over 3 mHz. Figure 8 reveals that the magnitude of 289 the differences between the SDS and TUG data is dependent on orbit configuration with 290 respect to Sun, i.e. β' angle. Here, for all components, major differences exist at 1-3 cpr 291 frequencies. For further details, the differences are plotted as a function of argument of latitude and time in Figure 9. It is visible that the recovery process mainly affects radial 293 and along-track components, when satellites are directly illuminated by the Sun ($\beta' \sim 0^{\circ}$). 294

5.2 Drag model scale

As depicted in Section 4, we estimate drag model scale factors during the GRACE-D ACC recovery process. Figure 10 illustrates the time series of the estimated scale. The estimates show scattered variations comparable with β' angle cycle. This behavior reflects the higher uncertainties in atmosphere density during periods with direct sunlight, i.e. with β' angle ranging from -20° to 30° . To some extent the variations of the estimated values also depends on the temperature fluctuations in these periods, which affects the gas molecular behavior and therefore, the drag coefficient.

Additionally, the high-frequency perturbations of the atmospheric density during geomagnetic storms are also expected to be absorbed by the scale factors. However, our observations are mainly collected during solar minimum (2018-2020) and, therefore, sparse solar events are visible in the data. During this period, the severest geomagnetic storm

Figure 7. Comparison of the time-series (left) and power spectral densities of differences (right) of the SDS ACT1B and the TUG ACT1B on 2020-05-13, with indirect sunlight condition ($\beta' = 71.8^{\circ}$).

Figure 8. Comparison of the time-series (left) and power spectral densities of differences (right) of the SDS ACT1B and the TUG ACT1B on 2020-07-31, with direct sunlight condition ($\beta' = -0.4^{\circ}$).

Figure 9. Differences between the SDS transplanted data and the TUG data from July 2018 to August 2020, plotted with respect to GRACE-C argument of latitude. Major differences are visible in radial direction under direct Sun exposure.

Figure 10. Temporal variations of (a) the estimated drag scale, (b) the corresponding β' angle variations, and (c) thermosphere temperature derived from JB2008 model, from May 2018 to August 2020.

Figure 11. Temporal variation of the estimated drag scale, compared to the SYM-H index during minor geomagnetic events in (a) May and (b) August 2019.

happened on 26 August 2018, whose impact on GRACE-C accelerometer measurements
has been studied by Krauss et al. (2020). Due to the gaps in GRACE-D data, this period
is not included in the scale time series. Nevertheless, few minor geomagnetic storms have
triggered atmospheric disturbances during 2019 and 2020 and subsequently affected the
scale factors.

Among a variety of indices, which characterize the geomagnetic activities, it has been shown that the SYM-H index (Iyemori et al., 2010) has one of the highest correlation with the neutral atmospheric density, with nearly zero time delay at low earth orbiters (Krauss et al., 2015). SYM-H index describes the geomagnetic disturbances at mid-latitudes with a temporal resolution of 1 minute. Figure 11 shows the time series of the estimated scale, compared to the variations of this index. For two selected events, a clear correlation exists between peaks in SYM-H and scale factor time series.

It is worth mentioning that in addition to the described effects, the estimates probably absorb other effects, which are not adequately modeled (e.g. variations in radiation pressure models).

5.3 Gravity field

This section compares the monthly gravity field solutions based on the recovered GRACE-D accelerometer data and ITSG-Grace2018 scheme (Kvas, Behzadpour, et al., 2019). We recovered monthly solutions from July 2018 to August 2020 using (a) SDS ACT1B in preliminary results, denoted as ITSG-Grace2018p, and (b) TUG ACT1B in Figure 12. Degree amplitudes of coefficient differences of the CSR RL06 solution (green), the ITSG-Grace2018 (prelim.) solution (blue), and the ITSG-Grace2018 solution (red) for July 2020 w.r.t the GOCO06s model.

final GRACE-FO operational solutions, referred to as ITSG-Grace2018. The ITSG-Grace2018 solutions are publicly available and can be downloaded from ICGEM site (http://icgem.gfz-potsdam.de/ or ifg.tugraz.at/ITSG-Grace2018).

Figure 12 shows the degree variances for July 2020 ($\beta' = -0.4^{\circ}$) with respect to the static gravity field GOCO06s (Kvas, Mayer-Gürr, et al., 2019). Compared to the preliminary solution, ITSG-Grace2018 with in-house computed ACT1B performs better in terms of noise over all spherical harmonic degrees, with the largest differences in degree 2 and 3.

Figure 13 shows the power spectral densities of the post-fit range rate residuals from 334 both solutions (ITSG-Grace2018p and ITSG-Grace2018). The post-fit residuals are the 335 differences between adjusted and original range rate observations. The residuals indicate 336 the total error sources, which are present within the gravity recovery process, as they are 337 propagated errors of all involved instruments and modeling errors. Here, strong 2 cpr and 338 3 cpr signals, existing in the preliminary scenario, are mitigated using the GRACE-D TUG 339 ACT1B. This clearly demonstrates the overall improvement of gravity field solutions and 340 better estimation of low degree coefficients, particularly C_{20} and C_{30} . 341

For more details, we compare the monthly estimates of C_{20} derived from GRACE-FO and SLR-derived values, provided in the TN-14, over the entire available period. Figure 14a shows that the bias in the estimates from ITSG-Grace2018 solutions has reduced with respect to the TN-14 values. However, similar to GRACE, the C_{20} coefficients still exhibit a strong 161-day periodic signal and should be replaced by C_{20} estimates from SLR data.

Figure 13. PSD of the post-fit range-rate residuals from the ITSG-Grace2018 (prelim.) solution (blue) and the ITSG-Grace2018 solution (red) for July 2020.

Figure 14. Comparison of (a) C_{20} and (b) C_{30} estimates from GRACE-FO monthly gravity field solutions (CSR RL06 (green), ITSG-Grace2018p (blue), ITSG-Grace2018 (red)) and from recommended SLR derived values in Technical Note-14 (black)).

Additionally, Figure 14b demonstrates the C_{30} time-series derived from GRACE-FO and SLR. The ITSG-Grace2018 estimates for the C_{30} coefficients show a higher correlation with the SLR solution. This supports the hypothesis that by mitigating 2 cpr and 3 cpr signals in transplanted data, resulting from alternative GRACE-D ACT recovery, the estimates of the C_{30} coefficients are significantly improved. The improvement is mainly visible for the months with $\beta' \sim 0^{\circ}$.

353 6 Conclusions

The results presented in this paper show the advantages of incorporating non-gravitational force models and applying drag model corrections within GRACE-D ACC recovery. The alternative ACT product contributes to an improved estimation of higher degrees of the recovered monthly gravity field solutions, as well as low zonal degrees 2 and 3. The estimates of the C_{30} coefficients represents a significant improvement with respect to SLR-derived values, with which the GRACE-FO values are recommended to be substituted.

Additionally, we were able to prove that the non-gravitational forces, in particular the corrected drag model, recover part of the acceleration signal that is missing in the direct transplant approach in radial and along-track directions. The magnitude of this missing signal is β' angle dependant and reaches its maximum during direct Sun exposure. Within the periods of passing the Earth's shadow, the modeled signal is approximately zero.

Furthermore, we show that the drag model scale correction mainly reflects the physical characterizations of changing thermospheric density. This includes long-term variations during periods with direct sunlight, as well as short-term fluctuations due to geomagnetic storms.

However, there are several issues, which have a potential for further improvements: In 370 order to avoid the effects from outliers in GRACE-C measurements, the parameterization 371 of the drag scale reflects smoothed variations longer than 1 minute. This setup may result 372 in losing high-frequency details in the satellites' changing environment. Moreover, thruster 373 spikes, which also contributes to the high-frequency spectrum of the measurements, are 374 currently modeled with simple impulse functions with constant magnitudes based on 375 As proved in GRACE mission (Bandikova et al., 2019), statistical estimation. 376 incorporating more realistic thruster responses in transplant data considerably reduces 377 noise in degrees over 15, i.e. the first orbital resonance. 378

In summary, this work contributes to an improvement of the GRACE-FO derived gravity field solutions by investigating the role of the missing GRACE-D accelerometer data. The efforts in constructing the constituents of the missing measurements not only increase the gravity field quality, but also improve our knowledge about satellites' interaction with their environment.

³⁸⁴ Appendix A ACT Level1-A processing

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In the following, the accelerometer Level-1A (ACT1A) to Level-1B (ACT1B) processing for linear accelerations is described, based on Wu et al. (2006). The ACC processing includes the following steps:

- 1. Level-1A accelerometer (ACC1A), clock (CLK1B), and time (TIM1B) data products are read and converted.
 - 2. Invalid data from (1), flagged with "no pulse sync" or "invalid timetag", are removed.
- 391
 3. The accelerometer time-tags are converted from OBC time to receiver time. In order
 to convert the OBC time to receiver time, a correction has to be applied from the
 TIM1B data product.

- 4. Linear accelerometer data is re-sampled to integer multiples of 0.1 s (10 Hz) using 394 linear interpolation. 395 5. The data gaps are filled using cubic interpolation with up to 200 data points on each 396 side of the gap. If a data gap is larger than 100 s, no filling is made. 397 6. The accelerometer time tags are converted from GPS receiver time to GPS time. 398 Computation of the time-tag corrections is by linearly interpolating the clock 399 corrections from the input CLK1B data product. If there is no valid clock correction 400 data for a time span, the clock corrections are extrapolated using the valid clock 401 corrections outside this time span. This guarantees continuity of the ACC data. Additionally, the Butterworth filter delay of nominally 0.14 s has to be considered. 403 7. Linear accelerations are re-sampled to integer multiples of 0.1 s using a Lagrange 404 quadratic interpolation over the nearest 3 data points. 405 8. The ACC data is compressed with a digital CRN filter of 7th order self-convolution 406 with 35 mHz bandwidth over a 140.7 s data span. 9. The sampling of the filtered linear ACC data is reduced from 0.1 s to 1 s by removing 408 the additional data epochs from the filtered data. 409
- 10. The ACC data is transformed from the AF to the SRF and writing the output
 accelerometer ACC1B data files.

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Figure 01.



Figure 02.



Figure 03.



Figure 04.



Figure 05.



Figure 06.



Figure 07.





Figure 08.



Figure 09.



(b) cross-track

(a) along-track



Figure 10.



Figure 11.



Figure 12.



- CSR RL06
- ITSG-Grace2018p
- ITSG–Grace2018

Figure 13.



ITSG–Grace2018p ITSG–Grace2018

Figure 14.

