Sensor systems

Analysis of Attitude Errors in GRACE Range-Rate Residuals—A Comparison Between SCA1B and the Fused Attitude Product (SCA1B + ACC1B)

Sujata Goswami$^{1,3}$, Beate Klinger$^2$, Matthias Weigelt$^1$, and Torsten Mayer-Gürr$^2$

$^1$Institut Für Erdmessung, Leibniz University of Hannover, Hannover 30167, Germany
$^2$Institute of Geodesy, Graz University of Technology, Graz 8010, Austria
$^3$Max-Planck Institute of Gravitational Physics, Leibniz University of Hannover, Hannover 30167, Germany

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Abstract—For missions such as GRACE, precise knowledge of the satellite’s attitude is a fundamental requirement for the realization of the intersatellite ranging principle. It is not only essential for the realization of the precise in-orbit intersatellite pointing but also for the recovery of accurate temporal gravity field models. Here, we present a comparative study of two attitude datasets. One of them is the standard SCA1B RL02 datasets provided by JPL NASA, and another is a fused attitude dataset computed at TU Graz, based on the combination of ACC1B angular accelerations and SCA1B quaternions. Furthermore, we also present the impact of the attitude datasets on the intersatellite range measurements by analyzing their residuals. Our analysis reveals the significant improvement in the attitude due to the reprocessed product and reduced value of residuals computed from the reprocessed attitude.

Index Terms—Sensor systems, attitude errors, GRACE, range-rate residuals, sensor fusion.

I. INTRODUCTION

The GRACE satellite mission has successfully provided gravity field products for more than 15 years (2002–2017). Gravity field solutions are computed from the intersatellite ranging measurements, provided by the K-band microwave ranging system (KBR) with micrometer precision [2]. The estimated gravity field solution computed from the range-rate ($\dot{\rho}$) measurements do not meet the requirements defined by [3] before the launch of the GRACE mission. These requirements are denoted as GRACE baseline, which is several orders of magnitude below the currently achieved precision (cf., Fig. 1).

Out of many error sources responsible for this limited precision, one of the sources is attitude errors that propagate to the estimated gravity field solutions through $\dot{\rho}$. In order to minimize them, we must know the characteristics of those attitude errors that are affecting the precision of $\dot{\rho}$ observations.

For the GRACE mission, so far, the model of the attitude errors is unknown [3] that complicates the error analysis as we do not know the frequency range where these errors dominate. One way to analyze the attitude errors would be to compare the impact of different attitude datasets on $\dot{\rho}$. However, it is again difficult to analyze the direct impact of attitude errors on $\dot{\rho}$ as they contain mass change signals and errors both, which makes it complicated to analyze the errors in details. Therefore, we analyze the attitude errors in the residuals of $\dot{\rho}$ observations that are computed after the gravity field parameter estimation using least-squares estimation as shown in (1) [8], [14]

$$\mathbf{I} - \mathbf{A}\mathbf{x} = \mathbf{e}$$  (1)

where $\mathbf{I}$ contains the range-rate ($\dot{\rho}$) observations, $\mathbf{A}$ is the design matrix, $\mathbf{x}$ contains the estimated gravity field parameters, and $\mathbf{e}$ are the range-rate residuals estimated after least-squares fit using the ITSG-2014 gravity field processing chain [12].

These range-rate residuals ($\mathbf{e}$ in (1)) reflect the errors that are partially absorbed by the estimated gravity field parameters ($\mathbf{x}$). Thus, their analysis is a good basis to understand the attitude errors affecting the range-rate observations and the gravity field parameters. Therefore, in this contribution, our aim is to present the results on the following.

1) The analysis of the attitude error characteristics by comparing the two different attitude datasets.
2) The propagation of these errors into the K-band range-rate observations by analyzing their residuals.

Fig. 1. Geoid degree amplitudes of the ITSG-2014 solutions compared with the GRACE baseline. The differences are presented with respect to GOCO05s static field. The gravity field solution is for the month of December 2008.
A. Details of the Attitude Data Used in This Letter

Before discussing the results of our findings, we discuss the datasets representing the GRACE satellite attitude used in this article.

#1 SCA1B RL02, the standard Level1B attitude data computed from the combination of the data of the two star camera heads onboard each spacecraft [7]. The data of the two star cameras are combined using the algorithm described in [9].

#2 Reprocessed fused attitude data (SCA1B quaternions + ACC1B angular accelerations), the quaternions provided in the SCA1B data product are combined with the angular accelerations provided in the 1B data product. The combination details are provided in [1]. For details about the Level1B products (SCA1B and ACC1B), refer to [7].

Here, we present the results of the analysis of two years of GRACE data, i.e., 2007 and 2008.

The attitude data is required to compute the antenna offset corrections (AOC) as shown in (2) [3], [13].

\[
\text{AOC} = \text{PhC} \cos \phi = e_{AB} \cdot (R_{\text{SRF},A} \text{PhC}_A) - e_{AB} \cdot (R_{\text{SRF},B} \text{PhC}_B).
\]

(2)

Therein, PhC_A and PhC_B denote the phase center vectors, representing the distance from the KBR phase center to the satellite's COM, \( \phi \) denotes the misalignment angle between the PhC and line of sight (LOS) vector, \( e_{AB} \) denotes the normalized LOS vector (cf., Fig. 2 for the presentation of these notations on the spacecraft), and \( R_{\text{SRF}} \) represents the rotation matrix from the science reference frame (SRF) to the inertial reference frame (IRF).

The derived range-rate AOC corrections (\( \dot{\rho}_{\text{AOC}} \)) are added to the KBR range-rates (\( \dot{\rho}_{\text{KBR}} \)) to correct for the imperfect pointing and refer the measurements to the satellite’s center of mass (COM) which are denoted as (\( \dot{\rho}_{\text{COM}} \)) in the following equation:

\[
\dot{\rho}_{\text{COM}} = \dot{\rho}_{\text{KBR}} + \dot{\rho}_{\text{AOC}}.
\]

The attitude information is also needed to rotate the linear accelerations in ACC1B product from the SRF to IRF [7]. Thus, the attitude errors propagate to the KBR observations via AOC and to the linear accelerations via rotation. Since both observations are used as input for gravity field recovery, any errors within the attitude data directly propagate to the recovered gravity field models.

In this article, we discuss the propagated errors via AOC. After estimating the gravity field parameters using (1), obtained range-rate residuals (\( \dot{\epsilon} \)) are used in this study to analyze the attitude errors in Section II.
attitude only. (cf., Fig. 4).

During periods when the SCA1B product is based on the combination of two star camera heads, the differences w.r.t. to the reprocessed fused product become small, which shows that the attitude based on star camera data only is also comparably accurate, provided that the data of both star camera heads is available.

B. Propagation of Attitude Errors to the K-Band Range-Rate Observations

The above-mentioned investigated errors in the attitude datasets propagate to the range-rate observations via AOC as shown in (3). In Fig. 3, when we compare the PSD of the pointing angles with the AOC, the differences in the two sets of AOC are visible above frequency 5.5 mHz. The two PSD of the AOC show large deviation in the high frequencies similar to the pitch and yaw angles.

Furthermore, to investigate the differences between two sets of AOC computed from the attitude data #1 and #2, we plot the observations on the argument of latitude and time plots. The differences between the two sets of AOC (cf., Fig. 6) are correlated with the differences between the pointing angles of the two GRACE spacecrafts as we can see in Fig. 4 top panel. In the AOC differences, we can see that the differences are high at the places when sun and moon intrudes into the star camera field of view. It indicates that the accuracy of the attitude data is highly limited by the intrusions blinding the star cameras field of view. Again, the high differences can be clearly seen and are consistent with the pitch angle differences, where the attitude is affected by the actuators actuated to control the spacecraft’s attitude.

There are high amplitude of residuals continuous over a full orbit, seen as vertical stripes which are mainly due to the satellite orbit and attitude control maneuvers (for example, COM calibration, yaw axis turn, thruster firings, and large magnetic torquer rod currents) and heating table related changes (so-called DSHL events [5]) which indirectly affect the attitude sensors, hence, their observations. The combined attitude data #1 improves the attitude which is affected due to such maneuvers disturbances.

The AOC when added to the range-rate observations, propagate the attitude errors to the K-band range-rate observations [cf., (3)]. The presence of these errors in the range-rate observations may affect the quality of the gravity field solutions which is the end product estimated using the range-rate observations.

An analysis of the range-rate residuals should reveal these errors, thus, revealing an insufficiency in the approach of handling the observation noise in the gravity field parameter estimation [cf., (1)]. Therefore, we analyze the range-rate residuals computed after the least-squares fit using each of the attitude dataset, respectively. We represent the range-rate residuals as \( \hat{\varepsilon}_{R2} \) and \( \hat{\varepsilon}_{R1} \) computed from the attitude datasets #1 and #2, respectively. Now, when we compare the PSD of two sets of residuals, as shown in Fig. 5, we observed that the two PSD deviate for frequencies higher than 5.5 mHz, similar to the pitch and yaw angles (cf., Fig. 3). This indicates that the pitch and yaw errors are propagated to the range-rate residuals. However, we do not see the large deviations in the high-frequency (\( \geq 10 \text{ mHz} \)) range-rate residuals. This is due to the presence of so-called KBR instrument system noise, which is the dominating noise source present within the residuals [4]. As a consequence, we confine our analysis to the differences between the two sets of residuals. The analysis shows that the differences between the residuals are highly correlated with the differences of AOC computed from the two attitude.
We show that the fused attitude computed by combining the angular accelerations along with the star camera datasets certainly improves the overall attitude quality. It especially compliments during the time periods where the standard attitude has been computed from one star camera data only. Also, it reduces the errors in the standard attitude when the accuracy of the star camera data is an important factor that has to be considered while combining it with other attitude sensors. High accurate star cameras lead to more accurate reprocessed combined attitude which has significantly less high-frequency noise, as compared with the combined data computed with less accurate star camera data. Thus, we expect that the suggested improvement of the star camera data by [10] and its combination with the angular accelerations will further improve the remaining errors in the GRACE attitude data.

The attitude data #2 significantly reduces the pitch and yaw errors and correspondingly improves the AOC. We also noticed that the AOC is largely affected by the pitch and yaw pointing errors of the spacecraft’s attitude. Thus, they propagate to the range-rate observations via the AOC as shown in (3).

The pitch and yaw errors largely propagate to the residuals, which is shown by the analysis of the residual differences. The similar magnitude of the differences between the AOC and the range-rate residuals confirms that the attitude errors largely propagate via AOC, which is also verified by their correlation coefficients.

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