Application of the matched filter method for the calibration of the accelerometer measurements in LEO missions

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Abstract

GRACE and GRACE-FO space missions aimed to monitor the Earth's gravity field for a plethora of Earth applications. For the determination of the Earth's gravity field, the accelerometer measurements are crucial since they measure the non-gravitational accelerations which are subtracted from the satellite's total accelerations. Thus, the accelerometers need to be accurately calibrated, a rather formidable task. In this study, we propose an optimal, and innovative calibration method based only on the measurements of the accelerometer and the total spacecraft accelerations estimated from the GPS precise orbits (POD), without the use of any physical non-gravitational force model. The idea behind this method lies in the matched filter, an optimal method used extensively in radar applications for the detection of known pulses in scattered signals. The total satellite accelerations are calculated via a double numerical differentiation of the GPS positions and play the role of the calibrated transmitted signal to which the accelerometer signal needs to be matched and thus calibrated. Specifically, the penumbra transitions of each spacecraft to and from the Earth's shadow induce characteristic jumps in the measurements, which are ideal for the calibration of the accelerometer in reference to the POD-derived accelerations. Following this concept, we retrieve daily accelerometer scale factors for both missions and estimate the daily accelerometer biases through a least-squares process. Long-term scale factors along the three axes of the accelerometers show an interesting periodicity strongly correlated with the β' angle variability, which determines the time a LEO satellite spends in direct sunlight.

Introduction

The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On (GRACE-FO), represent a pair of highly similar missions that are specifically designed to precisely monitor changes in the Earth's gravitational field. These missions are pivotal in assessing variations in the planet's surface mass and water distribution, thereby providing substantial insights into the realm of climate change research (Tapley et al., 2004). Each mission comprises two identical satellites, namely GRACE A and GRACE B for the GRACE mission, and GRACE C and GRACE D for the GRACE-FO mission. These satellites are placed in a near-polar orbit at an altitude of approximately 500 km, inclined at an angle of 89.5 degrees. Separated by about (or around) 220 kilometers in the along-track direction, the satellites' relative displacements are precisely measured utilizing a sophisticated K-Band microwave ranging system (Cheng, 2002).

These measured changes in the inter-satellite distance stem from the distinct gravitational forces experienced by each satellite, and they play a critical role in establishing the temporal variability of the gravitational field, alongside the concurrent utilization of accelerometer measurements.

The accelerometers measure the non-gravitational accelerations acting upon the spacecraft, arising from phenomena such as, Solar Radiation Pressure (SRP), atmospheric drag, Earth Radiation Pressure (ERP), and Thermal Radiation Pressure (TRP). In order to estimate the Earth's gravity field accurately, it is necessary to isolate the gravitational accelerations alone, thus the accelerometer measurements are subtracted from the overall spacecraft accelerations derived through precise orbit determination using Global Positioning System (GPS) data (POD). Calibration of the accelerometers proves to be a formidable challenge, as they cannot be calibrated on the ground due to the immense gravitational signal (Bouman et al., 2003).

Numerous studies have proposed diverse calibration parameters that can be employed in the process of recovering the Earth's gravity field or in the retrieval of thermospheric density and neutral winds. Typically, two distinct approaches are pursued for accelerometer calibration, both of which rely on theoretical force models that estimate, directly or indirectly the non-gravitational accelerations. These accelerations are subsequently compared against the accelerometer measurements to extract calibration factors. The first calibration approach involves the direct estimation of non-gravitational accelerations from physical models, while the second approach entails deriving these accelerations from total accelerations (via double numerical differentiation of POD data) and then subtracting the gravitational model accelerations. It is important to note that all the studies referenced herein pertain exclusively to the GRACE mission, as to the best of our knowledge, no published research has yet addressed the calibration of the GRACE-FO mission.

A study by Helleputte et al. (2009) proposed utilizing high precision reduced dynamic orbits derived from GPS data, where non-gravitational force models replace the accelerometer measurements. The authors estimated daily calibration parameters using the GPS High precision Orbit determination Software Tools (GHOST) in conjunction with GPS-derived orbital parameters. The study revealed a variable scale factor that exhibited good stability with stronger accelerometer signals, while weaker signals during decreasing solar activity led to increased calibration parameter errors. Another study by Bezděk (2010) employed double numerical differentiation of satellite kinematic positions to calculate total satellite accelerations and derive accurate calibration factors for the accelerometer. This approach incorporated satellite surface properties, thermospheric density models, and seasonal Earth albedo and emissivity models. Similarly, Calabia et al. (2015) utilized GPS positions to accurately compute the total accelerations of the satellite from which the gravitational signal was subtracted to derive non-gravitational accelerations. The latter is then used as reference accelerations for accelerometer calibration, demonstrating agreement with calibration parameters proposed for GRACE. Klinger and Mayer-Gürr (2016) employed physical force models as reference non-gravitational accelerations for initial accelerometer calibration, with subsequent estimation of calibration parameters during gravity field recovery. Thermal dependency and the impact of misalignment between coordinate systems were observed. Wöske et al. (2019) introduced high precision physical models for non-gravitational accelerations, using accelerometer measurements for model validation. They identified a correlation between temperature variations and scale factors, especially in the cross-track and radial axes. It is evident from these studies that accelerometer calibration is a challenging task, necessitating careful consideration of various parameters and constraints due to the evolving orbital environment.

In this study, we introduce an original and optimal method for accelerometer calibration that, to the best of our knowledge, has not been previously presented. Our approach leverages the concept of 'wave focusing' methodology, commonly employed in radar applications for detecting known waveforms in scattered or reflected signals within linear and nonlinear environments (Kelly and Wishner, 1965; Helstrom, 1994). By applying the time-reversal method to specific short time intervals referred to as focal regions, which occur during the spacecraft's transition through the Earth's penumbra, we achieve remarkable accuracy and robustness in accelerometer calibration. Notably, this calibration method relies exclusively on Level 1B accelerometer measurements and GPS POD-derived total accelerations, without any preprocessing or reliance on force models.

Methodology

In this study, we propose a novel and sophisticated method to calibrate the accelerometers on board GRACE spacecraft. Unlike traditional calibration approaches that require a model absolute standard, we utilize the total accelerations estimated from GPS POD positions, which have inherent "absolute" characteristics due to their reliance on the speed of light. Our method is based on two signals: the estimated total accelerations from GPS POD and the accelerometer measurements. Through rigorous signal processing, we can robustly determine calibration parameters without the need for subtracting gravitational accelerations or modeling non-gravitational forces.

To achieve calibration, we focus on specific focal regions where identifiable waveforms or pulses are present in both the accelerometer and POD acceleration data, since the total accelerations of the satellite consists of both the gravitational and the non-gravitational accelerations. We leverage the time-reversal method, known for its robustness in wave focusing, to amplify the short-duration acceleration offsets caused by solar radiation pressure in the accelerometer measurements. These offsets serve as ideal calibration waveforms due to their distinguishable characteristics. By time-reversing and normalizing the non-gravitational penumbra transitions waveform, we can align and calibrate the accelerometer measurements with the POD-derived acceleration signal. This approach is efficient and effective as it takes advantage of the reciprocity properties between the signals.

Our calibration method is applied to GRACE A and GRACE C spacecraft, considering different periods of solar activity. We calculate daily bias and scale factors, while also investigate the dependency of the accelerometer measurements on the β' angle. Figures 1 and 2 illustrate the results obtained for both GRACE missions, showcasing the stability of the scale factors. Figure 1 shows the scale factors obtained for two different periods: May 2006 – February 2007 and August 2009 – May 2010, while Figure 2 shows the GRACE C scale factors retrieved from September 2008 to August 2020.

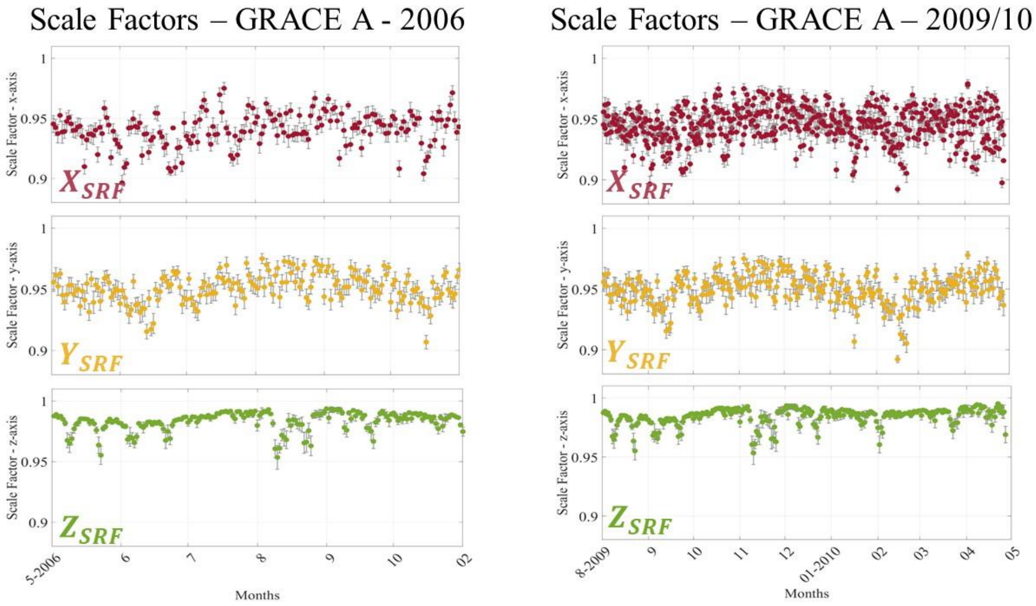

Figure 1. Left: The daily averaged scale factors of the three axes of accelerometer from May 2006 to February 2007. Right: The scale factors from August 2009 to May 2010. The standard deviations are depicted in grey.

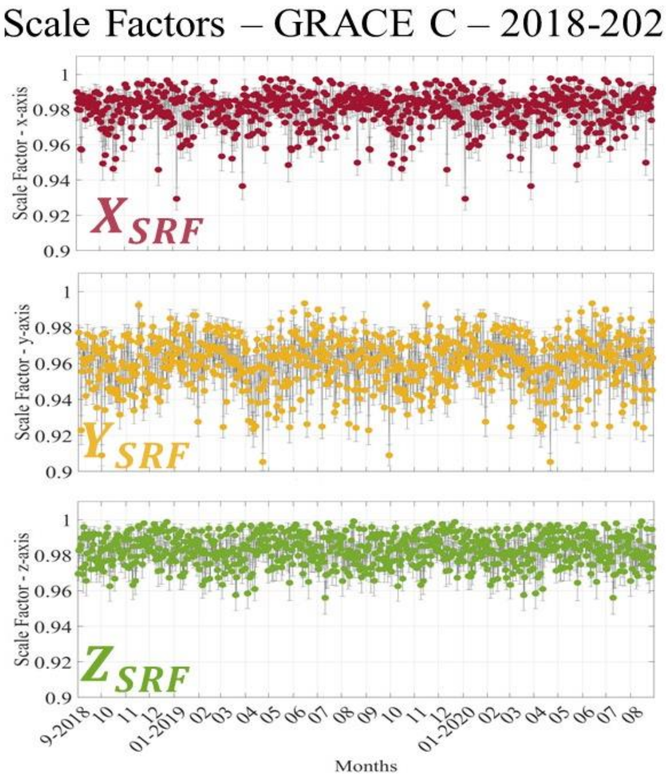

Figure 2. The daily averaged scale factors of GRACE C and their standard errors in the three axes.

The analysis of GRACE C scale factors reveals a remarkable level of consistency, indicating a higher degree of stability in comparison to GRACE A. This consistency can be attributed to the improved insulation of the instrument and its enhanced sensitivity. In addition, from the spectral analysis, a distinctive semi-annual periodicity of approximately 182.4 days manifests itself across all three axes of the accelerometer. This periodicity deviates slightly from the expected ~158 days, which aligns with GRACE C's full-sun orbit. The underlying cause of this phenomenon can be attributed to temperature variations induced by the variable distance of the satellite to the Sun.

Conclusion

This study represents a pioneering contribution by introducing an innovative method for signal detection and calibration of a vital instrument. What sets this methodology apart is its notable departure from conventional approaches that rely on physical models. Instead, the new calibration method leverages the intrinsic properties of the accelerometer measurements in conjunction with known entry and exit times of the satellite to and from the Earth's shadow. This force model-independent characteristic renders the method versatile and readily applicable to diverse accelerometer measurements, providing researchers with a powerful method for accurate calibration and analysis.

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