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Accelerometer Data Transplant for Future Satellite Gravimetry

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Key Points:

- Hybrid and transplant-based accelerometer configurations significantly improve Earth's gravity field recovery accuracy
- Quantum sensor integration (CAI) offers a promising, cost-effective solution for future satellite gravimetry missions
- Advanced accelerometer configurations enable robust gravity field recovery under sensor degradation or data gaps

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Abstract Accurate monitoring of the Earth's gravity field is crucial for understanding mass redistribution processes related to climate change, hydrology, and geodynamics. The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On (GRACE-FO), have provided invaluable satellite gravimetry data through low-low satellite-to-satellite tracking (LL-SST). However, the precision of gravity field recovery is significantly affected not only by data gaps in the accelerometer (ACC) measurements, but also by potential failures or limitations in their performance. To mitigate these issues, accelerometer data transplantation has been employed, leveraging the similarity in non-gravitational accelerations experienced by both satellites. This study presents an in-depth assessment of transplant noise and evaluates advanced accelerometer configurations, including Cold Atom Interferometry (CAI) accelerometers and hybrid electrostatic-quantum accelerometer setups for future satellite gravimetry missions. Through closed-loop LL-SST simulations, we compare four different accelerometer configurations, ranging from conventional electrostatic accelerometers (EAs) to fully hybrid CAI-EA setups. Results indicate that a dual hybrid accelerometer configuration offers the highest accuracy in gravity field recovery, while a transplant-based hybrid approach significantly enhances the performance of non-gravitational force modeling without requiring additional instrumentation. The findings underscore the potential of quantum accelerometry and transplant methodologies for future satellite gravimetry missions, offering a cost-effective solution to improve gravity field recovery, while benefitting from new sensor types.

1. Introduction

1.1. GRACE and GRACE-FO Accelerometer Observations

Precise monitoring of Earth's gravity field is fundamental to understanding mass redistribution processes associated with climate change, hydrology, and geodynamics. The GRACE mission, which operated from 2002 to 2017 (Tapley et al., 2004), and its successor, the GRACE-FO (GFO), launched in May 2018 (Landerer et al., 2020), have provided invaluable data for global gravity field recovery. These missions employ the LL-SST technique, where a pair of satellites orbit in tandem, continuously measuring variations in their relative distance as they respond to changes in the underlying gravitational field. To accurately isolate gravitational signals from other perturbing forces, both missions rely on high-precision onboard accelerometers that measure non-gravitational forces such as caused by atmospheric drag and solar radiation pressure.

Despite the crucial role of accelerometer observations in gravity field recovery, several challenges persist, including instrumental noise, bias drifts, and data gaps. To mitigate these issues, the GRACE-FO Science Data System (SDS)—comprising institutions such as the Center for Space Research at the University of Texas at Austin (CSR), NASA's Jet Propulsion Laboratory (JPL), and the German Research Center for Geosciences (GFZ)—has implemented calibration procedures to enhance the quality of the accelerometer measurements (McCullough et al., 2019). However, the premature degradation of the GRACE-FO-D accelerometer shortly after launch necessitated the development of an alternative data recovery strategy. This method, known as ACC data transplantation, reconstructs the missing data of one satellite using measurements from its twin which is possible due to their close orbital configuration and short inter-satellite separation (~220 km).

The ACC transplantation method was initially introduced during the GRACE mission following accelerometer failures that led to data gaps in GRACE-B (Save et al., 2006). This approach is based on the premise that both satellites experience nearly identical non-gravitational accelerations, allowing synthetic ACC data to be generated

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for the affected satellite after applying time and attitude corrections. However, the method has inherent limitations, particularly in cases where asymmetric environmental effects, such as variations in atmospheric drag and solar radiation pressure, become significant. These limitations became more pronounced in the final years of the GRACE mission, when biases in low-degree gravity field coefficients were observed in transplanted data (Bandikova et al., 2019; Behzadpour et al., 2021; Loomis et al., 2020). Additionally, residual linear accelerations introduced by thruster firings further contributed to errors in the reconstructed data (Meyer et al., 2011).

1.2. Advanced Accelerometers

Despite the remarkable success of GRACE and GRACE-FO missions, limitations remain at the instrument level. One key challenge is the noise behavior of electrostatic accelerometers (EAs) used in satellite gravimetry, which affects the accuracy of gravity field recovery. While EAs are well-suited for medium-to-high-frequency measurements due to their low noise characteristics, they suffer from long-term drift, making it difficult to accurately estimate time-variable biases and scale factors. To overcome these challenges, several innovative concepts and novel technologies have been proposed.

CAI has emerged as a promising alternative to traditional accelerometers. Unlike classical EAs, CAI-based accelerometers use a cloud of ultracold atoms as a test mass, manipulated by laser pulses to measure acceleration. The key advantage of CAI technology lies in its exceptional long-term stability and precise scale factor determination, which is directly linked to the frequency stability of the laser system. In CAI accelerometry, acceleration is determined by analyzing the phase shift between two atomic states after interaction with counter-propagating laser beams (Lévèque et al., 2022; Meister et al., 2022). Simulation studies (Abrykosov et al., 2019; Migliaccio et al., 2023; Müller & Wu, 2020; Romeshkani et al., 2023, 2025; Zingerle et al., 2024) suggest that CAI technology could significantly enhance gravity field recovery. However, a standalone CAI accelerometer has certain limitations, particularly due to its extended interrogation times, during which short-term variations in non-gravitational or gravitational forces may remain undetected. To address this issue, researchers have explored hybridization strategies that integrate CAI with conventional EAs. A hybrid sensor, combining the high-frequency measurement capabilities of an EA with the long-term stability of a CAI accelerometer, offers a promising solution. Studies such as Zahzam et al. (2022) and Zingerle et al. (2024) have investigated different hybrid sensor configurations and their potential benefits for space-based gravimetry.

A significant step toward the advancement of quantum accelerometry in space is the CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry) project, funded by the European Union (Lévèque et al., 2022). This initiative aims to increase the Technology Readiness Level of quantum accelerometers in space by launching a dedicated Pathfinder mission by 2030 and laying the foundation for a future quantum-based gravimetry mission. As an initial step, CARIOQA develops an engineering model of a quantum accelerometer, advances enabling technologies, and assesses spaceborne gravimetry applications using quantum or hybrid quantum-classical sensor configurations. The CARIOQA project is currently in Phase B.

This study focuses on the application of CAI technology in a GRACE-like satellite gravimetry mission and its role in the accelerometer data transplantation process. The paper is structured as follows: Section 2 presents the characteristics of electrostatic accelerometers (EAs) and CAI-based accelerometers. Section 3 discusses the non-gravitational forces relevant to satellite gravimetry missions. Section 4 provides an overview of accelerometer data transplantation methods and their implementation approaches. Section 5 describes the setup of the LL-SST simulation. Finally, Section 6 outlines the core methodology of this study and presents the validation results.

2. Performance of Accelerometers

In LL-SST missions, such as GRACE-like missions, accelerometers are essential for distinguishing gravitational forces from non-gravitational perturbations. Given the complementary advantages of EA and CAI ACC, a hybrid accelerometer is proposed as a potential sensor for future satellite gravimetry missions, aiming to enhance measurement precision and robustness.

2.1. GRACE FO Electrostatic Accelerometers

The inherent drift of EAs introduces significant errors, particularly at low frequencies (Christophe et al., 2015; Kupriyanov et al., 2024; Romeshkani et al., 2025). The Super-STAR accelerometer (EA-GFO), developed by the

French aerospace laboratory ONERA, is the reference instrument for performance assessment in GRACE-FO baseline scenarios (Kornfeld et al., 2019). Its (one-sided) amplitude spectral density (ASD) is given by

$$acc_M(f) = 10^{-10}\sqrt{1 + \left(\frac{f}{0.5\text{Hz}}\right)^4 + \frac{0.005\text{Hz}}{f}}\ \frac{\text{m}}{\text{s}^2\sqrt{\text{Hz}}} \tag{1}$$

ONERA has a long history of designing and manufacturing high-precision accelerometers for major satellite missions, including GRACE, GOCE, and GRACE-FO, significantly improving the accuracy of non-gravitational force measurements and enhancing satellite gravimetry data quality (Dalin et al., 2020). The EA-GFO is a three-axis capacitive sensor mounted at the satellite's center of mass (CoM). It consists of a proof mass ($40 \times 40 \times 10$ mm^3) enclosed within an electrode cage. Acceleration measurements are obtained by applying electrostatic forces through the cage electrodes to maintain the proof mass in a motionless state relative to the cage. These forces are proportional to the differential acceleration experienced by the cage and the proof mass. Since the accelerometer is positioned at the CoM, it primarily measures non-gravitational forces acting on the spacecraft, including atmospheric drag, solar radiation pressure, and Earth's albedo (Frommknecht, 2008; Peterseim, 2014; Touboul et al., 2004).

The EA-GFO provides measurements of both linear and angular acceleration of the satellite. It features two high-sensitivity axes—the radial and along-track axes—with a resolution better than 0.1 nm/(s$^2\sqrt{\text{Hz}}$), while the cross-track axis exhibits a lower precision of 1 nm/(s$^2\sqrt{\text{Hz}}$) (Daras & Pail, 2017). These measurement capabilities are essential for accurately characterizing external perturbations and improving satellite orbit determination.

With advancements in electrostatic and optical sensing technologies, future satellite gravimetry missions are expected to benefit from enhanced precision and stability in acceleration measurements. These improvements will contribute to a more refined understanding of Earth's gravity field dynamics, with significant implications for geophysical and climate studies.

2.2. CAI Accelerometers

CAI ACCs utilize atom clouds as test masses, manipulated by a sequence of precisely timed laser pulses that act as beam splitters and mirrors. These laser pulses, applied at specific time intervals (T), induce momentum changes in the atoms, creating quantum interference patterns that encode acceleration information (Pereira dos Santos & Landragin, 2007; Schilling et al., 2012). The phase shift observed in the atomic trajectories is directly proportional to the acceleration experienced by the system (Abend et al., 2020). A key advantage of CAI ACC lies in their high long-term stability and precise scale factor determination, which is governed by the frequency stability of the laser system. Previous studies (Abrykosov et al., 2019; Müller & Wu, 2020; Romeshkani et al., 2023, 2025) have demonstrated the potential of CAI sensors for improving Earth's gravity field recovery. However, the error characteristics of CAI ACC depend on various parameters (Beaufils et al., 2023; Knabe et al., 2022; Lévèque et al., 2022; Meister et al., 2022). In this study, we consider a CAI ACC with a distinct white noise level of $10^{-10}\frac{\text{m}}{\text{s}^2/\sqrt{\text{Hz}}}$ (CAI 10) regarding the current technology. Future satellite gravimetry missions could achieve enhanced measurement precision and long-term stability, contributing to more accurate gravity field modeling.

2.3. Hybrid Accelerometers

Hybrid accelerometers offer a promising solution for space-based inertial measurements by integrating the strengths of EA and CAI ACC. While CAI ACC provide high stability and absolute measurements, they suffer from limitations such as dead times and a constrained dynamic range (Lévèque et al., 2022). Conversely, EA exhibit established short-term sensitivity and have a proven flight heritage, but they require periodic calibration due to drift.

The synergy between these two technologies presents significant advantages. CAI ACC can be used to calibrate EA by determining their scale factor, while EA compensate for the lower temporal resolution of CAI ACC by providing continuous high-frequency measurements beyond the operational range of CAI ACC (Abrykosov et al., 2019; Knabe, 2023; Romeshkani et al., 2025). This complementary nature makes hybrid accelerometers a compelling candidate for future satellite gravimetry missions.

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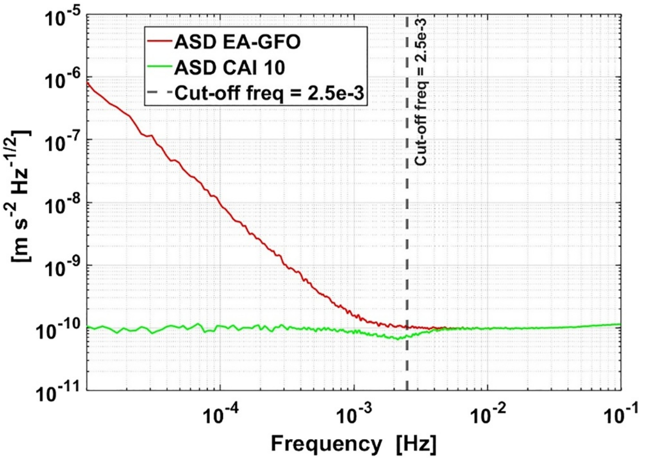

Figure 1. ASD of hybrid accelerometer noise, EA-GFO and CAI 10.

In this study, we consider hybrid accelerometers in which the noise characteristics are modeled by optimally combining an EA with a specific CAI ACC. The hybridization is performed in the frequency domain to exploit the complementary noise behavior of each sensor across different frequency bands, which can be more effective than time-domain approaches for certain applications. By integrating the stability of CAI ACC with the high-frequency capabilities of EA, hybrid accelerometers can enhance the precision and robustness of future gravity field recovery missions.

Figure 1 illustrates the hybridization of EA-GFO (SuperSTAR) and CAI 10, highlighting the methodology for determining the optimal cut-off frequency. This frequency is crucial in defining the proportional contributions of EA and CAI ACC in the hybrid ACC (Romeshkani et al., 2025; Zingerle et al., 2024). The selection process considers the intersection of the amplitude spectral densities (ASD) of EA and CAI ACC.

The cut-off frequency is determined algorithmically by identifying the numerical intersection of the EA and CAI ACC ASDs. This is done by locating the zero-crossing of $\Delta(f) = ASD_{EA}(f) - ASD_{CAI}(f)$.

Because the simulated ASDs intersect only once and show a smooth behavior, the determination of the cut-off frequency is direct and unambiguous in our study. In real mission scenarios, accelerometer ASDs may deviate from idealized forms and can exhibit multiple intersections. In such cases, the specific cut-off frequency can still be derived from the expected noise characteristics obtained through design specifications and ground calibration. As the accelerometers may show performance changes in orbit due to changing environmental (e.g., due to solar activity) or internal conditions (e.g., aging, temperature variations), in-orbit calibration is carried out in regular periods and the cut-off frequency can be updated dynamically, ensuring that the hybridization remains matched to the actual instrument behavior.

As shown in Figure 1, hybridization effectively eliminates the drift in EA-GFO while preserving its high-accuracy characteristics in the high-frequency domain. The contributions of EA-GFO and CAI 10 are approximately equal, ensuring a balanced integration of both techniques.

In our simulation framework, the accelerometer noise is represented by the nominal amplitude spectral density of the Super-STAR instrument (EA-GFO) as a baseline. It is important to note, however, that the simulated noise level does not fully reproduce the detailed behavior of real instruments in orbit. In practice, the measured noise may deviate from the nominal specification due to factors such as thermal variations, electronic drifts, and unmodeled disturbances from satellite operations (e.g., thruster spikes, heater switching events, or magnetic torquer activations) (Bandikova et al., 2019; Harvey et al., 2022; Peterseim, 2014). These effects can introduce additional low-frequency biases or high-frequency spikes that are not reflected in the simplified noise model. Consequently, the simulated results presented here represent an idealized scenario that highlights the relative performance of different accelerometer configurations, but likely underestimates the error level encountered in real-world applications.

3. Non-Gravitational Forces

GRACE and GRACE-FO operate in low-Earth orbit (LEO), where non-gravitational forces—primarily atmospheric drag, and to a lesser extent solar radiation pressure (SRP) and Earth radiation pressure (ERP)—significantly influence the satellites' motion. The magnitude of these forces depends on several factors, including atmospheric density, solar flux, satellite attitude, surface characteristics, and Earth's surface properties (Klinger & Mayer-Gürr, 2016). The satellite macro model provides the necessary satellite geometry and surface property data for accurately modeling these effects (Wen et al., 2019).

Among the non-gravitational forces, atmospheric drag is the dominant factor affecting the along-track component of linear acceleration, while SRP has the greatest influence on the radial component. ERP, on the other hand, represents the smallest non-gravitational force acting on the spacecraft (Klinger & Mayer-Gürr, 2016). The drag force model is particularly important in recovering missing GRACE-B and GRACE-FO-D measurements, as it

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directly affects the estimation of accelerations (Bandikova et al., 2019; Behzadpour et al., 2021; Harvey et al., 2022; McCullough et al., 2022).

The onboard EA-GFO measures linear accelerations along all three axes, but the data are often affected by high-frequency disturbances caused by satellite operations and environmental factors, such as thruster spikes, twangs, heater switching events, and magnetic torquer activations. These disturbances vary between satellites and must be carefully addressed during data processing.

In addition to linear acceleration, the accelerometers also provide information on angular acceleration, which can be utilized for attitude determination (Klinger & Mayer-Gürr, 2016; Sakumura et al., 2017). Unlike linear acceleration, angular acceleration measurements cannot be transferred between satellites, as they exclusively reflect the attitude variations of the individual spacecraft. Consequently, the focus of this study is solely on the analysis of linear acceleration data.

Atmospheric Drag: In low Earth orbit (LEO), satellites experience aerodynamic forces due to interactions with atmospheric molecules, resulting in momentum exchange at the spacecraft surface. This force represents the primary non-gravitational disturbance affecting satellite motion. Several atmospheric density models have been developed to estimate the variation in atmospheric conditions affecting satellite dynamics. Notable examples include the Jacchia-Bowman 2008 model (JB2008; Bowman et al., 2008), the Drag Temperature Model 2013 (DTM2013; Bruinsma, 2015), and the NRLMSISE-00 model (Picone et al., 2002). These models provide density predictions based on empirical data and physical principles, accounting for factors such as solar activity, geomagnetic conditions, and atmospheric composition.

Accurate modeling of the drag force is hindered by several factors, including uncertainties in the satellite's state and attitude, the interaction between the satellite's surface and atmospheric molecules, and the variability in atmospheric density (Moe & Moe, 2005; Prieto et al., 2014). These uncertainties contribute significantly to the overall uncertainty in drag force predictions.

In the case of co-orbiting missions, it is reasonable to assume that both satellites are subjected to the same environmental conditions, meaning that the drag model error for each satellite is approximately identical. Thus, by utilizing actual accelerometer measurements from one satellite, the model error can be estimated. This estimated error can then be applied to retrieve the missing measurements from the other spacecraft.

4. Accelerometer Data Transplant

The following outlines the procedure for recovering linear accelerations from GRACE-A to GRACE-B, which involves transplanting accelerometer (ACC) data. This method uses the near-identical orbits of GRACE-(A/C) and GRACE-(B/D), separated by ∼220 km, to facilitate ACC data transplantation. This assumption allows for the transplantation of ACC data between the two spacecraft, under the premise that the non-gravitational accelerations at any given point over the 25-s orbital separation are nearly the same.

The first transplant approach and simple one includes only time and attitude corrections, as discussed by Save et al. (2006). The time correction addresses the orbital separation between the spacecraft, while the attitude correction accounts for the differing orientations of the spacecraft relative to their velocity vectors. Another approach introduced by TUGRAZ (Behzadpour et al., 2021) incorporates drag model correction and the reduction of model forces. Bandikova et al. (2019) presented an improved ACC data transplant approach, which includes the modeling of residual linear accelerations due to thruster firings, in addition to the attitude and time correction. An alternative approach, developed at JPL and building on the methodology proposed by McCullough et al. (2022), makes use of filtered measurements from a degraded accelerometer as input to the transplantation process. A flowchart of the individual processing steps for transplant approaches is shown in Figure 2.

4.1. Model Reduction

According to the TUGRAZ approach, in the context of modeling non-gravitational forces acting on the spacecraft, it is essential to accurately determine their magnitude and direction at the precise position of the satellites. To quantify the discrepancy between modeled and observed accelerations, we employ a comparative approach. The total acceleration experienced by the spacecraft, as measured by onboard accelerometers, is denoted as a_{obs}. A simulated acceleration model, a_{model}, is generated based on theoretical and empirical force models that describe

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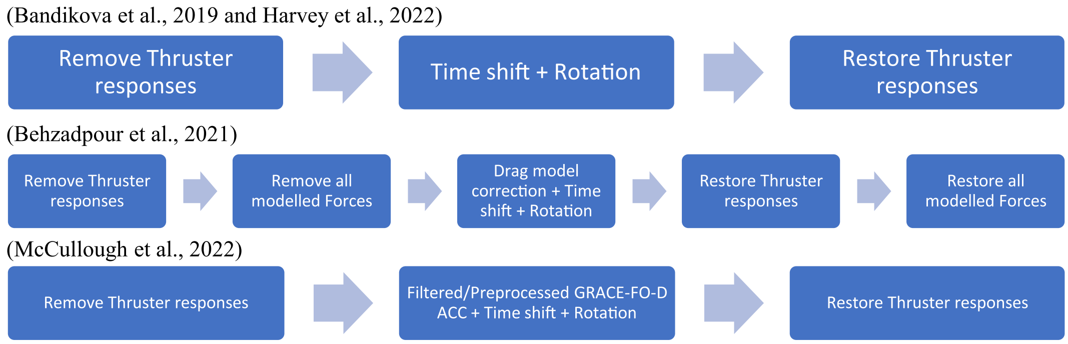

Figure 2. Three approaches for transplanting accelerometer observations from one of the twin satellites to the other.

the expected contributions of non-gravitational forces. The unmodeled acceleration component, Δa, is then obtained by subtracting the modeled acceleration from the observed data:

$$\Delta a = a_{\text{obs}} - a_{\text{model}} \tag{2}$$

This residual acceleration, Δa, represents the discrepancy between the theoretical force models and the actual measurements, capturing unaccounted physical effects, model inaccuracies, and potential instrument errors. Analyzing this residual signal provides valuable insights into the limitations of current force models and can contribute to refining future non-gravitational force modeling efforts.

4.2. Time Correction

In the process of aligning data between two spacecraft, it is crucial to account for time delays introduced by their relative motion. This step involves transferring essential data from the first spacecraft, including orbital parameters, rotational data, and unmodeled accelerations Δa, to the reference time frame of the second spacecraft. To achieve this, a transfer time correction is applied to ensure temporal consistency between the data sets. The computation of the transfer time correction relies on interpolated state vectors for both spacecraft, which provide precise orbital positions and velocities. Linear interpolation is used to obtain continuous position and velocity estimates at each epoch, ensuring smooth data transitions. The key aspect of the correction is determining the minimal three-dimensional (3D) distance between the two satellites at each time step. This correction represents the time required for a signal or force perturbation to propagate between the two spacecraft. By applying this adjustment, all relevant parameters from the first spacecraft are mapped accurately onto the time frame of the second spacecraft. Ensuring precise temporal alignment is essential for various applications, including cross-satellite data calibration, instrument bias correction, and the refinement of gravity field solutions.

4.3. Attitude Correction

To ensure accurate transfer of the unmodeled accelerations Δa from one spacecraft to the other, an attitude correction must be applied. This step is necessary because each spacecraft's orientation relative to its velocity vector differs due to the intersatellite pointing requirements of the GRACE and GRACE-FO missions. These missions utilize K-band ranging (KBR) measurements (and LRI for GRACE-FO), which demand precise alignment of the KBR antennas along the line of sight (LOS) between the two spacecraft.

The structural configuration of the satellites contributes to these orientation differences. The KBR antenna is mounted on the front panel of each spacecraft, requiring the leading satellite to be rotated by 180° about its z-axis to maintain the proper intersatellite alignment. Additionally, both spacecraft exhibit a minor pitch offset of approximately 1° relative to the LOS, further distinguishing their orientations.

To account for these orientation differences and accurately map accelerometer data between the two spacecraft, a series of attitude corrections must be applied. These corrections primarily consist of pitch and yaw adjustments:

- Yaw rotation: A 180° rotation about the radial axis compensates for the fundamental spacecraft alignment difference.

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- Pitch correction: A small pitch adjustment corrects the 1° offset relative to the LOS, ensuring precise directional consistency in the transferred accelerometer data.

The transformation of accelerometer measurements from the first spacecraft frame to the second spacecraft frame is performed using rotation matrices derived from the known attitude parameters.

5. LL-SST Simulation Setup

The simulation framework is designed to evaluate the potential impact of quantum accelerometers on future satellite gravity missions. The selected scenarios closely mimic the orbital and measurement characteristics of current single-pair missions, such as GRACE-FO, ensuring realistic conditions for assessing gravity field retrieval performance.

5.1. Orbital Configurations

For single-pair scenarios, the simulations assume a near-polar orbit with an inclination of 89° and an altitude of 463 km, mirroring the GRACE mission. This configuration is chosen to maintain a homogeneous ground-track pattern over a 7-day sub-cycle, ensuring uniform spatial coverage essential for high-precision gravity field recovery.

5.2. Forward Modeling Approach

For a realistic representation, the forward modeling process includes a static gravity field model (GOCO05s, Mayer-Gürr et al., 2015) to simulate the gravity field. The simulation accounts for gravitational signals up to spherical harmonic degree and order (d/o) 120. This approach isolates the effect of instrument noise on the gravity field solutions, allowing for a direct evaluation of quantum-based ACC performance under idealized conditions where temporal aliasing—refers to the misinterpretation or misrepresentation of rapid variations in the gravity field caused by high-frequency geophysical processes— is absent.

In our simulation framework, we have excluded geophysical background model errors such as those arising from ocean tides and atmosphere–ocean de-aliasing, as our focus was on the instrument level and we did not want to mix different error sources. But we are aware that geophysical model errors contribute substantially to the error budget of the retrieved gravity fields and may interact in complex ways with instrument noise. For example, Abrykosov et al. (2022) demonstrated that uncertainties in ocean-tide background models, particularly in coastal and high-latitude regions, can strongly affect GRACE/GRACE-FO gravity field solutions, and that their stochastic treatment significantly improves the retrieval quality when propagated into the observation domain. Neglecting such errors in our simulations implies that the reported performance levels represent an optimistic scenario, and a more realistic accuracy using real data may be lower. In future work, we will extend our framework to incorporate realistic error covariance information for tides and atmospheric/oceanic mass variations in order to fully assess the robustness of the proposed approach and to bridge the gap between idealized simulations and operational GRACE/GRACE-FO data processing.

5.3. Gravity Field Retrieval via Backward Modeling

The retrieval of the gravity field is conducted using a least-squares adjustment approach with a static spherical harmonic parameterization. The LL-SST observations are modeled as range-rate measurements using an integral equation approach based on short-arc processing (Mayer-Gürr, 2006). The stochastic properties of the LL-SST observations are represented through covariance matrices computed from the instrument noise spectral densities. The default gravity field retrieval period is set to one month, with a maximum spherical harmonic resolution of d/o 120, consistent with GRACE-like mission processing. The flowchart (Figure 3) outlines the steps of the LL-SST method applied in our computations. It begins with the simulation of the true gravity field alongside a reference field. Subsequently, the differential gravitational and non-gravitational accelerations between the two spacecraft are computed. By incorporating simulated accelerometer noise into these signals, a system of equations is established for further analysis.

All simulations and closed-loop recoveries are carried out in the center-of-mass (CM) frame of the Earth, consistent with the GRACE/GRACE-FO Level-2 conventions. Consequently, the degree-1 coefficients (C10, C11, S11)—which represent CM–CF (center-of-figure) separation—are set to zero and not recovered in our

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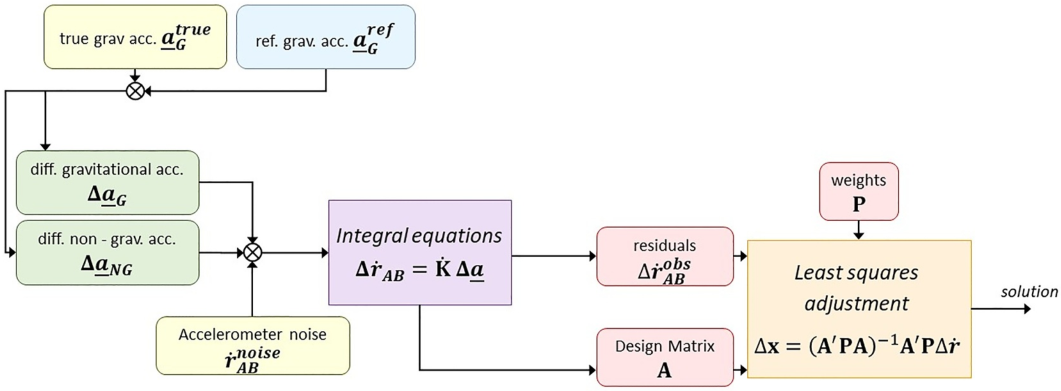

Figure 3. Closed-loop simulation in the LL-SST concept.

simulations. In applications that require geocenter motion, external degree-1 estimates (e.g., Sun et al., 2016; Swenson et al., 2008) should be added to the Level-2 solutions.

By adopting this structured simulation framework, the study aims to provide a comprehensive evaluation of quantum-based ACC technology in the context of satellite gravimetry, offering insights into its potential benefits for future Earth gravimetry missions.

6. Methodology and Validation

6.1. Methodology for Transplant Noise Estimation

The methodology used in this study (based on TUGRAZ approach) aims to quantify the impact of transplant noise in satellite gravimetry missions, particularly in scenarios where accelerometer observations are exchanged between spacecraft. The process follows a systematic approach, as illustrated in the flowchart, and involves several key steps, see Figure 4.

6.1.1. Real Acceleration and Noise Components

Each spacecraft, denoted as SAT-C and SAT-D, experiences real acceleration composed of:

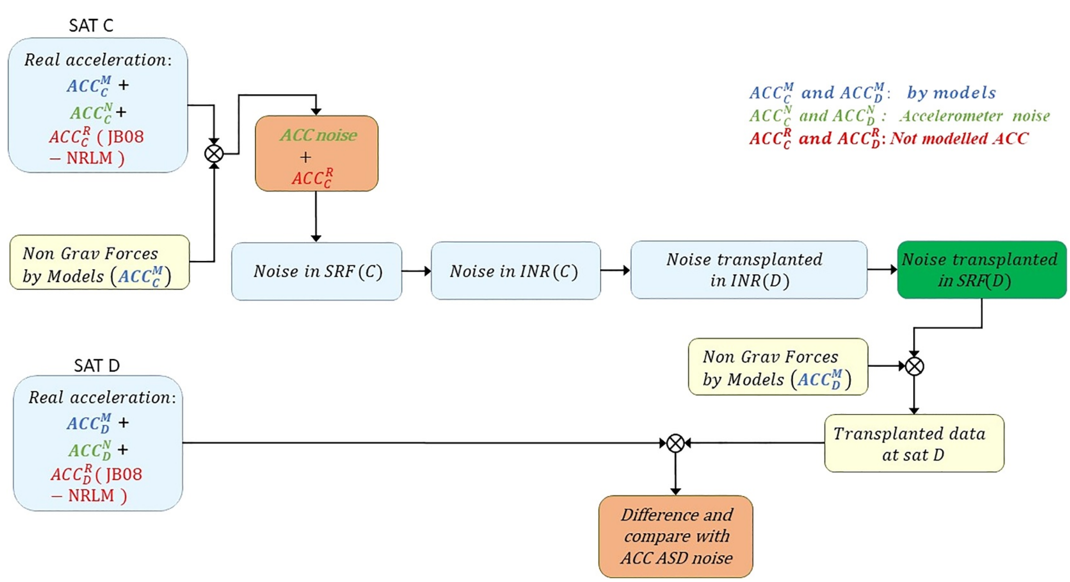

Figure 4. Methodology of transplant process of accelerometer observations.

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- *Modeled acceleration* (ACC^M): Computed from non-gravitational force models, such as atmospheric drag and solar radiation pressure.
- *Accelerometer noise* (ACC^N): Instrumental noise inherent in the onboard accelerometer.
- *Unmodeled acceleration* (ACC^R): Residual non-gravitational forces that are not accounted for in the models (e.g., mismodeling of atmospheric density variations). To estimate the unmodeled component, we use the difference between the two atmospheric drag models, JB08 and NRLMSISE-00 (NRLM).

For both satellites, the total acceleration can be expressed as

$$\mathrm{ACC}_{\mathrm{Total}} = \mathrm{ACC}^{\mathrm{M}} + \mathrm{ACC\ noise} + \mathrm{ACC}^{\mathrm{R}} \tag{3}$$

6.1.2. Noise Characterization at the Satellite Reference Frame (SRF)

The accelerometer noise and unmodeled acceleration are first processed in the SRF for SAT-C. This noise consists of a combination of random fluctuations and systematic biases that can affect the accuracy of force modeling in gravity field recovery.

6.1.3. Transformation in the Inertial Frame (INR)

To ensure consistency in data transfer, the noise components from SAT-C are transformed into the inertial frame at the time epoch corresponding to SAT-C. This step ensures that time-dependent variations in satellite orientation and motion are correctly accounted for.

6.1.4. Transplantation of ACC Noise

The noise from SAT-C is then transplanted to the inertial frame of SAT-D by applying the relative motion correction between the two satellites. This step accounts for the time difference in the data transfer, ensuring that the transplanted noise aligns with the appropriate temporal and spatial conditions of SAT-D.

6.1.5. Conversion Back to SRF of SAT-D

Once the noise is transplanted into the reference frame of SAT-D, it is converted into the SRF of SAT-D. This transformation ensures that the transplanted noise is in the same frame as the observed accelerometer data on SAT-D, allowing direct comparison with the onboard accelerometer readings.

6.1.6. Integration With Non-Gravitational Force Models on SAT-D

The non-gravitational forces modeled for SAT-D (ACC_D^M) are added to the transplanted noise to reconstruct the total acceleration data. This enables a direct comparison between the original accelerometer observations and the transplanted acceleration signal.

6.1.7. Evaluation and Comparison With ACC ASD Noise

The final transplanted data set on SAT-D is compared against the actual accelerometer noise amplitude spectral density (ASD). This comparison allows for an assessment of:

- The impact of transplant noise on the quality of gravity field recovery.
- The effectiveness of the transplant methodology in reducing accelerometer noise errors.
- The potential deviations introduced by the transplant process.

This methodology provides a framework for assessing the feasibility of using transplanted accelerometer data in satellite gravimetry. By systematically transforming, transplanting, and comparing noise components, this approach enables an evaluation of the impact of hybrid accelerometer configurations and the potential benefits of using CAI ACC in future gravity missions.

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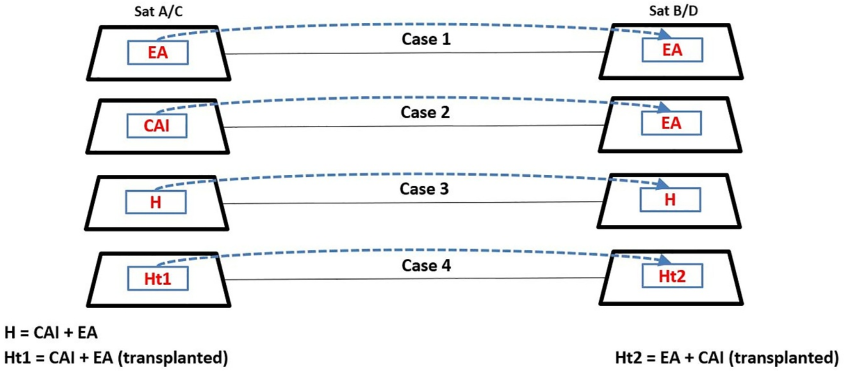

Figure 5. Four different cases from using accelerometer point of view.

6.2. Evaluation of Accelerometer Configurations for Future Satellite Gravimetry Missions

We evaluate four different accelerometer configurations for future satellite gravity missions, each designed to assess the impact of various accelerometer setups on gravity field recovery. These configurations are based on the GRACE and GRACE-FO mission architectures and incorporate conventional EA as well as CAI ACC (Figure 5).

6.2.1. Case 1: Baseline Configuration (GRACE/GRACE-FO-Like Setup)

The first scenario replicates the GRACE and GRACE-FO missions, where both the leading and follower spacecraft are equipped with conventional EAs. This configuration serves as a reference for evaluating the potential improvements offered by alternative accelerometer setups.

6.2.2. Case 2: Configuration With a Single CAI ACC

In the second scenario, the follower spacecraft is equipped with a CAI ACC instead of an EA, while the leading spacecraft retains an EA. This setup allows for an assessment of the benefits of replacing one of the conventional accelerometers with a quantum-based CAI ACC. By comparing this scenario with the baseline case, we can quantify the impact of introducing a single CAI ACC in a GRACE-like mission.

6.2.3. Case 3: Ideal Hybrid Configuration With Dual CAI ACCs and EAs

The third scenario represents an idealized case in which both spacecraft are equipped with two accelerometers: one CAI ACC and one EA, resulting in a total of four accelerometers. This setup provides redundancy and allows for a direct comparison between CAI ACC and EA data on the same spacecraft. Given the superior precision of CAI ACCs, we expect this configuration to yield the most accurate gravity field recovery among all considered scenarios.

6.2.4. Case 4: Transplant-Based Hybrid Configuration

The fourth scenario uses the transplant approach to maximize the benefits of CAI ACCs while reducing instrument redundancy. This configuration builds on Scenario 2, where the leading spacecraft carries an EA, and the follower spacecraft carries a CAI ACC. However, in addition to their independent measurements, accelerometer data are exchanged between the two spacecraft. Specifically, the CAI ACC observations from the follower spacecraft are transplanted to the leading spacecraft, and the EA observations from the leading spacecraft are transplanted to the follower spacecraft. As a result, both spacecraft have access to CAI ACC and EA data, effectively creating a “virtual” hybrid data set without requiring additional instrumentation.

By comparing the gravity field solutions obtained from these four cases we aim to assess the potential benefits of CAI ACC technology and the transplant approach for future satellite gravimetry missions. This analysis will help determine the optimal accelerometer configuration for next-generation Earth observation missions, balancing instrument performance, redundancy, and cost-effectiveness. Figure 6 shows a comparison between these four cases in recovering the time variable Earth's gravity field.

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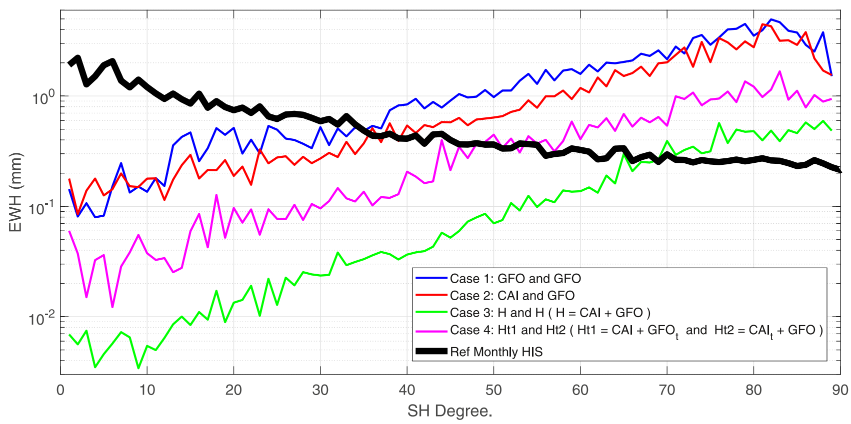

Figure 6. Comparison between four cases in recovering the time-variable Earth's gravity field.

6.3. Comparative Analysis

As expected, the third scenario, which incorporates both EA and CAI ACC on each spacecraft, yields the highest accuracy in gravity field recovery. This configuration benefits from the combined strengths of both accelerometer types, minimizing errors and maximizing precision.

A comparison between the first and second scenarios highlights the impact of replacing a single EA with a CAI ACC. The results indicate that even with only one CAI ACC, the gravity field recovery process would be significantly improved compared to a GRACE-like mission. This demonstrates the advantage of quantum accelerometry in reducing non-gravitational force modeling errors.

Comparing the third scenario (dual hybrid accelerometer configuration) with the first and second cases further reveals the substantial benefits of using a hybrid accelerometer setup. The inclusion of both EA and CAI ACCs on each spacecraft provides superior accuracy, significantly reducing uncertainties in the recovered gravity field. However, this improvement comes at the cost of requiring four accelerometers, increasing system complexity and mission expenses.

The fourth scenario, which employs the transplant approach, exhibits slightly lower accuracy compared to the ideal hybrid case (Scenario 3). This discrepancy arises due to the introduction of the transplant process noise, which affects the accuracy of the exchanged accelerometer observations. Nevertheless, when compared to Scenario 2, the transplant-based configuration demonstrates a substantial improvement. Despite both the second and fourth scenarios utilizing one CAI ACC and one EA, the transplant method effectively enhances the gravity field recovery performance by allowing both spacecraft to benefit from the combined data.

In summary, while the dual hybrid accelerometer configuration (Scenario 3) remains the optimal case, the transplant-based hybrid approach (Scenario 4) offers a viable alternative with notable improvements over the single CAI ACC setup (Scenario 2). This suggests that an optimized transplant technique could bridge the performance gap between Scenarios 3 and 4, offering a cost-effective solution for future satellite gravimetry missions.

7. Conclusions

This study presents a comprehensive evaluation of transplant noise for future satellite gravimetry missions and explores various accelerometer configurations to enhance Earth's gravity field recovery. We systematically quantify transplant noise effects by modeling real accelerations, noise components, and their transformation across satellite reference frames. Through a comparative analysis of different accelerometer setups, we assess the impact of incorporating CAI ACC in GRACE-like missions and the effectiveness of the transplant approach in hybrid configurations.

The results indicate that a dual hybrid configuration with both EA and CAI ACC on each spacecraft provides the highest accuracy in gravity field recovery. This setup minimizes errors by leveraging the complementary

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strengths of both accelerometer types. However, its increased system complexity and cost present practical challenges.

The transplant-based hybrid configuration, where accelerometer observations are exchanged between spacecraft, emerges as a promising alternative. While it does introduce some transplant noise, the approach significantly enhances gravity field recovery compared to a single CAI ACC configuration. The analysis suggests that optimizing the transplant technique could further bridge the performance gap between the ideal hybrid configuration and the transplant-based approach, offering a more cost-effective solution for future satellite gravimetry missions.

Overall, this study underscores the potential of CAI ACCs and the transplant methodology in advancing satellite gravimetry. By balancing performance, redundancy, and cost-effectiveness, these innovations pave the way for the next generation of Earth gravimetry missions, enabling more precise monitoring of time-variable gravity fields and their implications for climate change, hydrology, and geodynamics.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The recovered gravity fields for all cases are available from (Romeshkani, 2025). Simulation software cannot be shared due to intellectual property rights. However, the underlying methodology is published, and a corresponding reference is provided.

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