



Uncertainties of GRACE/GRACE-FO Satellite Gravimetry Data and Thereof Derived Products

Adrian Jäggi¹ · Andreas Güntner^{2,10} · Ulrich Meyer¹ · Alejandro Blazquez³ · Benedikt Soja⁴ · Frank Flechtner² · Felix Landerer⁵ · Christoph Dahle² · Christopher McCullough⁵ · Tamara Bandikova⁶ · Torsten Mayer-Gürr⁷ · Felix Öhlinger⁷ · Henryk Dobslaw² · Eva Boergens² · Junyang Gou⁴ · Roland Pail⁸ · Hugo Lecomte⁹ · David Wiese⁵ · Martin Lasser¹ · Ehsan Sharifi^{2,11}

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Abstract

Inter-satellite ranging by space gravimetry missions, such as from the Gravity Recovery And Climate Experiment (GRACE) mission and its successor mission GRACE Follow-On, has been established to observe mass variations in the Earth system from space globally. A complex processing chain is needed to invert the instrument data (Level-1) of space gravimetry missions into global gravity field products, either represented as a spherical harmonic series expansion (Level-2) or further processed gridded products dedicated to use for various scientific applications (Level-3), and combine them with products from other remote sensing satellite missions or assimilate them into geophysical process models (Level-4). The complexity arises from the need to use multiple background models and apply numerous corrections. Consequently, providing uncertainties for the various products is challenging. Not only is inter-satellite ranging data needed in this processing chain, but also other satellite observations, such as GPS, and geophysical background models, e.g., for de-aliasing of high-frequency signals or signal separation in the Level-3 data sets. These observations and model data sets are contributing with their specific uncertainties to the overall uncertainty budget of the final gravity fields. As long as the uncertainties of the models cannot be fully accounted for, a formal uncertainty propagation remains insufficient. Thus, an empirical error assessment remains the only reliable way of uncertainty assessment at the moment. Finally, a further source of error is signal leakage, which is related to the signal attenuation at satellite altitude and may be aggravated by spatial filtering of the Level-3 products. A comprehensive review of the current status of the uncertainty modeling of mass variation products through the whole processing chain is missing and thus is addressed in this article.

Keywords Space gravimetry · GRACE/GRACE-FO · Uncertainty modeling

Article Highlights

- Provide a comprehensive review of uncertainty sources across the full GRACE/GRACE-FO processing chain from Level-1 (instrument data) via Level-2 (spherical harmonic gravity field coefficients) to Level-3 (gridded mass-change products) and Level-4 (assimilated or merged data products).
- Discuss the complex processing chain that involves multiple background models, de-aliasing corrections, and empirical signal-separation methods, which all contribute with their specific uncertainty budget.
- Demonstrate progress on uncertainty propagation while emphasizing that uncertainty estimates routinely omit important contributions from geophysical correction models.
- Emphasize the improved observation geometry and coverage in forthcoming missions – including GRACE-C and ESA's Next Generation Gravity Mission, which together will form the MAGIC constellation – are expected to reduce uncertainties.

1 Introduction

With the launch of the Gravity Recovery And Climate Experiment (GRACE) mission in 2002 (Tapley et al. 2004), a collaboration between the National Aeronautics and Space Administration (NASA) and the German Aerospace Centre (DLR), inter-satellite ranging has been established to observe mass variations in the system Earth from space globally. The measurement principle of the GRACE mission (2002–2017) and its successor mission GRACE Follow-On (GRACE-FO, Landerer et al. 2020, since 2018), jointly pursued by NASA and the GFZ Helmholtz Centre for Geosciences, is to measure distance changes between two satellites ultra-precisely. The Earth's gravity field in space and time is derived from these distance changes. This allows us to infer the underlying mass redistributions in the Earth system at spatial and temporal scales in the order of 250–300 km and one month, respectively. Over the continents, these mass redistributions are caused mainly by changes in the terrestrial water storage (TWS). TWS encompasses the water storages in frozen and liquid states, including ice caps, glaciers, snow cover, soil moisture, groundwater, and the storage in surface water bodies. The scientific community is interested in understanding the processes of changes in global TWS on regional to global scales and the interaction with ocean mass and sea level. The significant interest of the scientific community is also reflected in the 2022 implementation plan of the Global Climate Observing System (GCOS), where TWS was introduced as a new Essential Climate Variable (ECV) for the first time.

The GRACE and GRACE-FO missions consist of two identical satellites following each other at about 220 km distance on the same near-polar low Earth orbit (LEO) at altitudes below 500 km. The satellite orbits experience varying ground track coverage through the mission durations, mainly due to atmospheric drag, which is not compensated actively, e.g., by drag-free control. Each satellite is equipped with a three-axis accelerometer to measure the sum of all non-gravitational accelerations acting on the satellites (Christophe et al. 2015), with star trackers to measure the orientation of the satellite, and a Global Positioning System (GPS) antenna and sixteen-channel receiver for 3D positioning, instrument time tagging, and atmosphere sounding. The core instrument is a K-/Ka-band ranging (KBR) instrument, which measures the distance change between the two satellites with a precision of a few micrometers standard deviation (Dunn et al. 2003; Kim and Lee 2009).

Additionally, GRACE-FO is equipped with a laser ranging interferometer (LRI) instrument as a technology demonstrator for future gravity missions. Compared to the K-band ranging, the precision of the distance change measurements is improved by at least a factor of 100 (Abich et al. 2019). Due to the continuous measurements of the distance changes, subtle differences in the gravitational potential along the orbit caused by related mass anomalies can be detected and mapped into a mean gravity field model after accumulating sufficient ground track coverage after about 30 days.

The official exploitation and dissemination of the GRACE/GRACE-FO science data are performed by the joint US–German Science Data System (SDS), consisting of NASA’s Jet Propulsion Laboratory (JPL), the Center for Space Research (CSR) at the University of Texas, and the GFZ Helmholtz Centre for Geosciences. The main task of the SDS is processing different levels of science data, i.e., from Level-0 (raw instrument data) up to Level-3 (gridded products), as well as their distribution and archiving. Besides the SDS, a growing number of additional analysis centers (ACs) is independently providing products derived from GRACE/GRACE-FO data. The International Combination Service for Time-Variable Gravity Fields (COST-G) of the International Association of Geodesy (IAG, Jäggi et al. 2020) combines at the time of this publication nine different GRACE-FO data products (Meyer et al. 2025). As of April 2026, a global TWS anomaly data set based on the COST-G RL02 GRACE/GRACE-FO products is operationally available through the Climate Data Store of the Copernicus Climate Change Service (C3S).

Although GRACE/GRACE-FO enabled spectacular science results, for example, summarized by Wouters et al. (2014) and Tapley et al. (2019), numerous important questions regarding the changes and dynamic processes in the continental hydrology, cryosphere, ocean, atmosphere, and solid Earth remain unresolved (Pail et al. 2015). The International Union of Geodesy and Geophysics (IUGG) thus adopted at its 28th General Assembly the IUGG Resolution No. 2 on “Sustained Terrestrial Water Storage (TWS) Monitoring by Dedicated Gravity Satellite Constellations” to urge national and international space agencies and decision makers to implement and maintain long-term sustained observing systems of the Earth’s time-variable gravity field realized by dedicated gravity satellite constellations with improved measurement technology to enable new science and applications of enormous societal benefit and to evolve them into sustainable operational services in the longer term. Currently, the GRACE-Continuity mission (GRACE-C, Landerer et al. 2020) is planned to launch in 2028, again as a NASA-DLR cooperation. Further into the future, ESA’s Next Generation Gravity Missions (NGGM, Daras et al. 2024), planned for launch in 2032, will complement GRACE-C in an inclined orbit. Together, they will form the Mass-change And Geoscience International Constellation (MAGIC).

Figure 1 illustrates the complex data processing chain, which needs to be set up to invert the GRACE/GRACE-FO instrument data (Level-1) into global gravity field products, either as a spherical harmonic series expansion (Level-2) or further processed gridded products dedicated to use for various scientific applications (Level-3). Additional combinations with products from other remote sensing satellite missions or assimilation into geophysical process models lead to Level-4. The complexity of this processing chain arises from the need to use multiple background models and apply numerous corrections. Consequently, providing uncertainties for the various products is challenging, and a comprehensive review of the current status of the uncertainty modeling of the mass variation products is missing.

This article intends to fill this gap and is, thus, structured along the different processing levels shown in Fig. 1 to address the current status, underlying challenges, and future perspectives of the uncertainty modeling. Section 2 starts the discussion with an overview

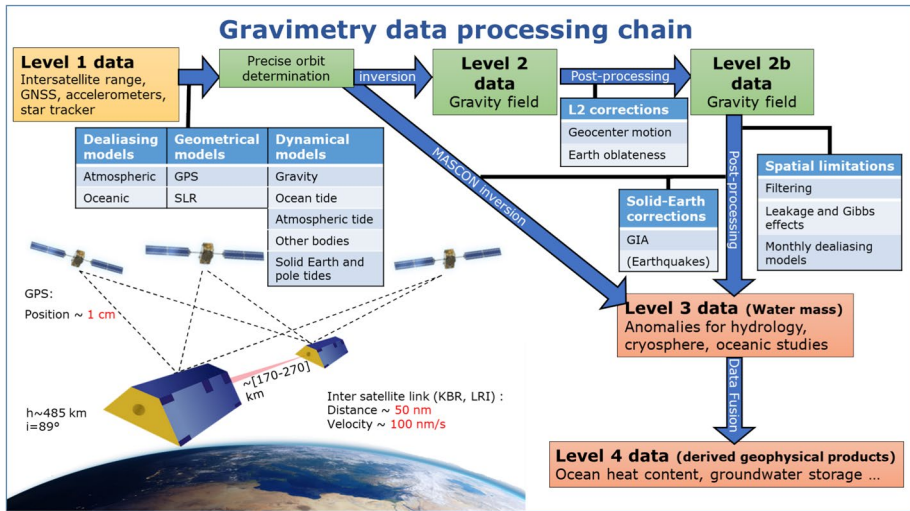


Fig. 1 Gravimetry data processing chain from Level-1 to Level-4 data, following the definitions used in this paper. Blue boxes correspond to the auxiliary data or process needed at certain steps. Black values in the observation scheme correspond to the order of magnitudes while red values to the uncertainties associated with

of the relevant instrument data (Level-1) and their associated uncertainties. Section 3 addresses the processing of the instrument data and the modeling of their uncertainties to derive monthly snapshots of the Earth's time-variable gravity field (Level-2). Section 4 focuses on post-processing the monthly solutions to derive the gridded products (Level-3) TWS, ice sheet mass changes, or ocean mass changes for different scientific applications. Section 5 discusses the exemplary use of TWS data and other remote sensing products to derive further ECV products, e.g., a global groundwater product or ocean heat content (Level-4). Section 6 concludes the article with a short summary.

2 Level-1

GRACE/GRACE-FO Level-1 data comprise the science instrument and housekeeping data products. Depending on the stage of data processing, three product levels are distinguished: Level-0, Level-1A, and Level-1B.

- Level-0 data correspond to the raw telemetry that are regularly downlinked to ground stations via the S-band communication link.
- Level-1A data are generated from Level-0 data by converting the binary-encoded measurements into engineering units. In addition, they include editing and quality control flags as well as ancillary information required for subsequent processing.
- Level-1B data represent the final form of the science instrument and housekeeping data. They are derived from Level-1A data through further processing steps, including accurate time tagging, down-sampling, filtering, and transformation into conventional reference frames. Level-1B data are the input data for gravity field computation.

Level-0 to Level-1B data processing is performed by the SDS. Details about the data products and processing algorithms can be found in Level-1 data handbooks (Wu et al. 2006; Case et al. 2010; Bettadpur 2012; Wen et al. 2019).

In general, the sources of uncertainty related to sensor performance and data processing can be categorized as follows:

- True instrument performance under real environmental conditions, where the measurement noise exceeds the nominal noise specifications provided by the manufacturer under laboratory conditions;
- Uncertainties in calibration parameters, as several parameters cannot be reliably estimated during ground-based calibration and therefore require in-flight calibration and parameter estimation;
- Imperfections in Level-1 data processing, arising from both algorithmic limitations and implementation issues in the processing software. These deficiencies are progressively identified and corrected, resulting in successive data releases (e.g., for GRACE: Level-1B V00–V04 has been already released, V05 is now in preparation).

Any error in the sensor data inevitably propagates into the gravity field estimates and must therefore be identified, characterized, modeled, and corrected in order to meet the science and mission requirements defined in Stanton (2000) for GRACE and in Kornfeld et al. (2019) for GRACE-FO. Details on the essential measurements needed for the estimation of gravity field parameters are discussed in the following subsections.

2.1 K-band and laser ranging interferometer

The primary observable in satellite-to-satellite tracking (SST) missions, such as GRACE/GRACE-FO, is the inter-satellite ranging. For GRACE/GRACE-FO, the primary ranging observations are acquired via the KBR system. The KBR system utilizes a concept known as dual one-way ranging (DOWR), where each of the two satellites transmits a carrier signal and measures the phase of the carrier generated by the other satellite relative to its local signal, which it is transmitting (Dunn et al. 2003). The sum of these phases is then proportional to the range change between the two satellites to micron-level precision. Measurement of the DOWR at two frequencies enables the removal of ionospheric effects, which in the worst case can be up to approximately 13 mm (Yan et al. 2021). After correction, using two frequencies, the ionospheric effect is reduced to picometer level (Yan et al. 2025). A vital component of the micron-level precision provided by the KBR is the accurate alignment of time tags between the spacecraft. This is achieved via GPS and is discussed further in Sect. 2.3. Finally, two further corrections are required to convert the DOWR measurement to instantaneous range: the light time correction and the phase center correction. These corrections account for the conversion of the DOWR into instantaneous range and the conversion of the instantaneous range measurement between the spacecraft KBR antenna phase centers into a measurement between the spacecraft centers of mass, respectively. Further details on the KBR measurement, including a detailed breakdown of each of the individual corrections (specifically light time and phase center), can be found in Yan et al. (2025), Dunn et al. (2003), and Wu et al. (2006).

For GRACE-FO, a laser ranging interferometer (LRI) is also flown as a technology demonstration, the first of its kind flown in space, and provides an independent source of inter-satellite ranging to the KBR, but with much higher precision, by more than two

orders of magnitude. The LRI instrument uses a different measurement concept than the KBR, essentially two-way range, where one spacecraft transmits frequency-stabilized light to the other spacecraft, where the light is offset and phase locked and transmitted back to the original spacecraft. There, the phase change corresponds to the round-trip range change between the two satellites.

In addition to the more than two orders of magnitude improvement from the KBR, the LRI removes the need for an antenna offset correction, as the vertex of the triple mirror assembly (TMA) is designed to be at the spacecraft center of mass to enable satellite tracking between the spacecrafts' center of mass; however, to account for small misalignments between the TMA vertex and the spacecraft center of mass, a tilt-to-length correction can be applied, with detailed analysis given by Wegener (2022). Further corrections required for the LRI measurement include a scale factor correction, to account for errors in the absolute laser frequency, described in detail by Misfeldt et al. (2023) and a light time correction, to convert the two-way range measurement from the LRI into an instantaneous range, described by Yan et al. (2021).

Finally, due to the narrower beam width of the LRI, approximately 140 micro-radians, half-cone angle, compared to the KBR beam of approximately 30 mrad (Abich et al. 2019), increased pointing accuracy is required to enable tracking of the inter-satellite range. This is enabled through a combination of the attitude and orbit control system (AOCS) and a fast steering mirror (FSM), which steers the beam toward the distant spacecraft. Nevertheless, it has to be noted that the need for increased pointing accuracy leads to increased consumption of propellant and consequently reduces the mission lifetime. Abich et al. (2019) describe the in-orbit performance of the LRI instrument in detail.

2.2 Accelerometer (ACC)

Each GRACE/GRACE-FO spacecraft is equipped with an ultra-precise electrostatic three-axis accelerometer (ACC) manufactured by the Office National d'Études et de Recherches Aéronautiques (ONERA) (Touboul et al. 1999, 2004; Christophe et al. 2015). The ACC provides information about the non-gravitational forces acting on the spacecraft, such as atmospheric drag, solar radiation pressure and Earth albedo with a nominal precision of $10^{-10} \text{ ms}^{-2}/\sqrt{\text{Hz}}$ in the along-track and radial axes and $10^{-9} \text{ ms}^{-2}/\sqrt{\text{Hz}}$ in the cross-track axis (the cross-track axis is less sensitive due to the manufacturing under a 1 g environment). Ideally, the accelerometer noise is independent between axes; however, due to correlated disturbances measured by the accelerometer and imperfect manufacturing there is observable correlation between axes. Empirical examination by Harvey and Sakumura (2019) has shown that there is observable cross talk from linear acceleration into angular accelerations and gravity field processing by Klinger and Mayer-Gürr (2016) shows that empirically accounting for cross talk between accelerometer axes in the accelerometer scale matrix improves gravity field estimates. The effect of non-gravitational forces needs to be reduced from the GNSS observations in order to obtain orbit perturbations caused solely by the gravitational attraction of the Earth's mass (Kang et al. 2006a).

In addition to the non-gravitational forces, the ACC senses also linear accelerations caused by the spacecraft operation and environment, which result in twangs, thruster spikes, heater switching spikes, magnetic torque spikes, temperature-dependent variations and other disturbances (Flury et al. 2008; Peterseim et al. 2012; Peterseim 2014; Meyer et al. 2012; Klinger and Mayer-Gürr, 2016; McGirr et al. 2022). These disturbing accelerations are unique for each spacecraft and most of them can be filtered out or corrected

for. One of the corrective processing methods, necessary only due to significant instrument malfunction or inoperability, is the so-called ACC data transplant that became part of the official processing standards for GRACE for months of Nov 2016—June 2017 due to power limitations necessitating the powering down of the GRACE-B ACC instrument (Bandikova et al. 2019) and for GRACE-FO for the whole missing duration due to the underperformance of the GRACE-D ACC instrument (McCullough et al. 2019; Harvey et al. 2022, 2024; Behzadpour et al. 2021). Note that significant Level-1 processing strategies enable the use of a subset of the GRACE-D data in operational processing for GRACE-FO (Harvey et al. 2022, 2024).

2.3 GPS and Orbit Determination

Pseudo-range and carrier phase measurements of Global Navigation Satellite Systems (GNSS) are providing the positioning information to determine the orbits of satellite gravimetry missions and to recover, together with the inter-satellite ranging observations as the main observable, the Earth's time-variable gravity field. The GRACE mission is equipped with the so-called BlackJack GPS receivers, advanced codeless dual-frequency space receivers manufactured at JPL (Dunn et al. 2003), while on GRACE-FO the further developed TriG receivers (Meehan et al. 2012) are employed. The receivers are collecting dual-frequency carrier phase and pseudo-range measurements on sixteen channels and served three GPS antennas: one zenith-viewing crossed dipole POD antenna equipped with a choke ring, and two limb-viewing antennas: a backup crossed dipole POD (GPS BKUP) antenna and a helix (GPS OCC) antenna for atmosphere sounding. The receiver firmware allows for tracking of up to twelve GPS satellites for POD, but the limit was set to no more than ten to keep the number of resets low (Dunn et al. 2003). Note that the GRACE GPS BlackJack receiver is capable as well to collect the dual-frequency phase measurements from the K-band ranging system, to time-tag the accelerometer data, and to read out the two CCD-based star cameras. It is therefore also referred to as the instrument processing unit (IPU).

Relying on precise orbits and clock corrections of the GPS satellites, which are commonly assumed to be error-free external products, e.g., from the International GNSS Service (IGS, Johnston et al. 2017), the GPS high–low satellite-to-satellite tracking (hl-SST) data of GRACE/GRACE-FO are the primary observables for reduced-dynamic orbit determination (Wu et al. 1991) or kinematic orbit determination (Švehla and Rothacher, 2005). Moreover, the GPS hl-SST data are used to support gravity field determination from the primary K-band or LRI low–low satellite-to-satellite tracking (ll-SST) in a generalized orbit determination problem where arc-specific parameters for all satellites and dynamic parameters common to all arcs and satellites are jointly estimated (Beutler et al. 2010b). Early studies report an accuracy of reduced-dynamic GRACE orbits of about 1.0 cm in the radial direction and better than 2.5 cm in the along-track and cross-track directions when relying only on undifferenced GPS carrier phase data (Kang et al. 2006b) and space baseline precisions of better than 1 mm when relying on doubly differenced, ambiguity-fixed GPS carrier phase data (Jäggi et al. 2007). For GRACE-FO, an absolute orbit accuracy of better than 2 cm in the 3D position is achieved based on estimated noise levels of 4.2 mm for GRACE-C and 4.5 mm for GRACE-D when 30 s undifferenced ionosphere-free GPS carrier phase observations are used (Kang et al. 2020).

Kinematic orbits are derived in a precise point positioning (PPP, Zumberge et al. 1997) from the GPS code and carrier phase observations by geometric means only, i.e., without

using any further a priori information on the GRACE/GRACE-FO satellite orbital dynamics as for reduced-dynamic orbits (Švehla and Rothacher, 2005). Kinematic positions may therefore serve as pseudo-observations instead of the original GPS hl-SST data for orbit reconstruction and gravity field recovery (Jäggi et al. 2011). As opposed to GPS hl-SST data, however, the kinematic positions are correlated, which requires to take into account covariance information resulting from the kinematic orbit determination by a formal variance propagation (Jäggi et al. 2011). For most gravity field determination processes, only epoch-wise covariance information is eventually used to model the variances and the covariances of the x, y, z components of the kinematic positions provided in the Earth-fixed coordinate frame (Zehentner and Mayer-Gürr, 2016; Lasser et al. 2020).

Limiting factors for orbit and gravity field recovery based on GPS hl-SST data are encountered by modeling the carrier phase center location of the GNSS receiver antennas (Jäggi et al. 2009) and the transmitter antennas (Schmid et al. 2016), which give rise to systematic errors. They are of particular relevance for reference frame applications (Haines et al. 2015), but also impact gravity field determination based on GPS hl-SST data or thereof derived kinematic positions (Jäggi et al. 2009). Environmental disturbances such as ionospheric scintillations or systematic errors along the geomagnetic equator may be a relevant error source as well, but was shown for GRACE to be less critical than for other satellite missions (Jäggi et al. 2016).

2.4 Star cameras and Attitude Determination

Precise attitude determination is crucial for mission operation (Herman et al. 2004; Cosavella et al. 2022) and for processing of data from other sensors that serve as input for the gravity field recovery (Bandikova 2015; Wen et al. 2019). The geometric correction that converts the distance measured between the K-band antennas into the distance between the centers of mass of the two GRACE resp. GRACE-FO satellites fully relies on the attitude information. Horwath et al. (2010) empirically derived K-band phase center corrections at the mrad level and showed the positive impact on the GRACE science results.

In GRACE/GRACE-FO missions, the main sensors for fine attitude determination are the star cameras that provide information about spacecraft's orientation with respect to the inertial reference frame. The star trackers were manufactured by the Technical University of Denmark (DTU) (Jørgensen and Pickles 1998; Jørgensen, 2000). The star cameras are characterized by an anisotropic noise distribution, where instrument performance along the boresight is approximately 10 times worse than across the boresight, and as optical devices are subject to blinding resulting in invalid measurement when the Sun or the Moon are in the field of view. This is compensated by measurements taken by multiple star camera heads. The GRACE star camera assembly consisted of two star camera heads, whereas GRACE-FO consists of three star camera heads. The GRACE-FO design increases attitude data availability and accuracy about all spacecraft axes by ensuring consistent operation on at least two star camera heads. The attitude accuracy is not only affected by the sensor sensitivity itself, but also affected by the accuracy of the calibration parameters such as the alignment of the star camera with respect to accelerometer and the KBR antenna reference frame and time tag correction. Harvey (2016) found twice-per-revolution signals in the biases between the two GRACE star camera heads that could be traced to miscalculated stellar aberration corrections, as well as a drift at the order of 100 arcsec over the GRACE mission duration, which seems to be related to thermal conditions, and a dependence on celestial longitude that points to field-of-view-dependent errors at the tens of arcsec level.

For more information about the star camera noise, see Liebe (2002); Bandikova et al. (2012); Inácio et al. (2015); Bandikova (2015); Harvey (2016); Cossavella et al. (2022).

The satellites also carry an inertial measurement unit (IMU), which provides information about the relative spacecraft attitude in terms of angular rates. While GRACE carried a medium performance IMU, that was never operationally used in flight, GRACE-FO carries a high-performance IMU that consists of four fiber optic gyroscopes. Fusion of the star camera and IMU data results in significantly reduced high-frequency noise (Harvey and Sakumura 2019). With each Level-1 data release, an improvement in the SCA1B product has been achieved by correcting known processing errors or by fine-tuning the data fusion method (Romans 2003; Bandikova and Flury 2014; Harvey and Sakumura 2019; Wen et al. 2019).

In addition to the star cameras and IMU, attitude solutions may also incorporate additional sensors. For GRACE, the angular acceleration data from the ACC was combined in a Kalman filter to improve high-frequency noise. Unfortunately for GRACE-FO, the unfavorable noise characteristics in the ACCs necessitated dropping the ACC data and only incorporating the star cameras and IMU. However, experimental GRACE-FO solutions have been made by incorporating the LRI fast steering mirror data and/or the magnetorquer data. Note that magnetorquer data is highly experimental and requires knowledge of the Earth's magnetic field and spacecraft moments of inertia to accurately incorporate into the attitude determination solution. While these solutions are not currently officially released, they will likely be incorporated operationally in the future as a way to tackle high-frequency noise.

3 Level-2

In this chapter, the determination of the monthly gravity field solutions in spherical harmonic coefficients (Level-2 products) is outlined. The processing of Level-1 into science-ready Level-2 gravity field products involves several steps, e.g., orbit determination and signal separation, where the orbit parameterization and the choice of background models, which have evolved over the course of the successive generations of the Level-2 products, have a major impact on the uncertainty budget of the gravity field solutions. This section explains common choices and current practices in more detail.

In Sect. 3.1, the underlying equations of motion of the satellites and the inversion process by a least-squares adjustment (LSA) are introduced. Section 3.2 provides an overview over the available gravity field solutions by the different ACs of GRACE/GRACE-FO data. In Sect. 3.3, the basic principles defining the spatial and temporal resolution of the gravity field solutions are explained. A major contribution to the uncertainty budget of the gravity field coefficients originates from the uncertainties of geophysical background models, addressed in Sect. 3.4. Section 3.5 is dedicated to empirical noise modeling techniques, and finally, in Sect. 3.6 the combined gravity field products of the Combination Service for Time-variable Gravity fields (COST-G, Jäggi et al. 2020) of the IAG (Poutanen and Rózsa, 2020) are introduced. The chapter closes with an outlook on future gravity field missions and advanced processing strategies that will lead to improved spatial and temporal resolution and a further reduction of temporal aliasing errors (Sect. 3.7).

3.1 Satellite Gravimetry: Observations and Other Error Sources

The main observations deployed in satellite gravimetry are the GRACE/GRACE-FO orbits derived from the supporting GPS hl-SST data, or alternatively from GPS-derived kinematic positions (see Sect. 2.3), and the primary K-band or LRI ll-SST data measured by the K-band microwave link or the laser interferometer, respectively (see Sect. 2.1). GPS hl-SST mainly contributes to the determination of the absolute orbit positions of the two satellites, whereas K-band/LRI ll-SST mainly determines the relative orbit positions of the two satellites (Beutler et al. 2010a). It has to be noted that the Level-1B K-band range-rate observations used for gravity field determination are derived from the high-rate (Level-1A) biased range observations applying a CRN-class digital filter (Wu et al. 2006) with a fit interval of 70.7 s. By the differentiation, the high-frequency noise is increased, but low-frequency errors are reduced. The correlations introduced by the filtering process have been studied by Beutler et al. (2010b). They are usually neglected in the analysis of the Level-1B data.

The observations are linked to the gravity field coefficients by the equations of motion of the satellites

$$\ddot{\mathbf{x}}_i = \mathbf{R}_t^i \nabla V_t + \nabla V_{3rd} + \mathbf{R}_s^i \mathbf{a}_{surf}, \quad (1)$$

where $\ddot{\mathbf{x}}_i$ are the total resulting accelerations of the center of mass of the satellite, the first term on the right-hand side accounts for the acceleration due to the Earth's potential, the second term for third body accelerations, and the third term for the surface forces acting onto the satellite. The subscript i indicates a non-rotating (quasi-inertial) frame. The satellite's position $\mathbf{x}_i$ is derived by numerical integration of the equations of motion, which is performed in the quasi-inertial frame to avoid the impact of apparent forces on the satellite's motion.

The observation equations are derived from the equations of motion (Beutler et al. 2010b). The observed satellite positions or inter-satellite range-rates enter the observation equations on the left-hand (observation) side. The surface forces $\mathbf{a}_{surf}$ acting on the satellites, which are measured by the three-axis accelerometer in the center of mass of the respective satellite (see Sect. 2.2), are needed to separate the gravitational forces of interest from the overall forces acting on the satellites. They enter Eq. 1 resp. the observation equations derived therefrom on the right-hand (i.e., model) side and are commonly applied as noise-free corrections. The same is true for the attitude observations by the star cameras (see Sect. 2.4), which define the rotation matrix $\mathbf{R}_s^i$ between the satellite body frame (subscript s), where the surface forces are measured, and the quasi-inertial frame. All observations naturally come with their specific uncertainties (Inácio et al. 2015; Flury et al. 2008). An approach to model the accelerometer and attitude observation noise has been described by Chen et al. (2016).

The gravitational potential V_t of the Earth including atmosphere and oceans is commonly provided as a truncated series of the spherical harmonic expansion (for the discussion of an alternative parameterization as Mascons, see Sect. 4.3) of the Earth's gravity field (Kaula 1966)

$$V_t(r, \phi, \lambda) = \frac{GM}{R} \sum_{l=0}^{l_{max}} \left(\frac{R}{r}\right)^{l+1} \sum_{m=0}^l P_{lm}(\sin\phi) (C_{lm} \cos m\lambda + S_{lm} \sin m\lambda), \quad (2)$$

where r, ϕ, λ are spherical coordinates in an Earth-fixed (subscript t for terrestrial) reference frame, e.g., the International Terrestrial Reference Frame (ITRF, Altamimi et al.

2023), GM is the product of the gravitational constant and the Earth's mass, R is the equatorial radius of the Earth, and P_{lm} are the fully normalized associated Legendre functions of degree l and order m . The information about the gravity field is given by the fully normalized spherical harmonic coefficients C_{lm} and S_{lm} . The series expansion is truncated at maximum degree l_{max} .

The gravitational acceleration enters Eq. 1, as ∇V_t , the gradient of the terrestrial gravitational potential. The transformation between the terrestrial and the quasi-inertial frame is provided by the rotation matrix $\mathbf{R}_t^i$, which is a function of the instantaneous Earth orientation parameters (EOPs). The EOPs are also taken as error-free from external sources, e.g., the International Earth Rotation and Reference System Service (IERS, Poutanen and Rózsa, 2020). ∇V_{3rd} are third body accelerations due to the Sun, Moon and major planets of the solar system, which are commonly modeled as point masses. Their positions are derived from the planetary ephemeris (Park et al. 2021).

Observation equations can be derived, using various approaches, from the equations of motion (Eq. 1). All versions of the observation equations have in common that they describe an overdetermined, inverse problem where the number of observations varies between 500000 (K-band range-rate observations and kinematic satellite positions) and 3000000 (in case of the use of the original GPS code and phase observations) per month, and the number of parameters includes $(l_{max} + 1)^2 - 4$ gravity field coefficients, i.e., 9405 in case of $l_{max} = 96$, and an AC-specific number of orbit and nuisance parameters, which may vary between 5000 and 54000 per month (for details on the AC-specific parameterizations, see Meyer et al. (2019)).

Solutions of the spherical harmonic coefficients of the monthly average gravity fields (Level-2 products) are determined by a LSA process, where the linearized observation equations $\Delta \mathbf{y} = \mathbf{A}_0 \Delta \mathbf{p} + \mathbf{e}$ including observation noise $\mathbf{e}$ are based on the nonlinear equations of motion of the satellites (Eq. 1). The design matrix $\mathbf{A}_0$ containing the partial derivatives of the observations $\mathbf{y}$ with respect to the unknown parameters $\mathbf{p}$, typically holding both gravity and orbit parameters, is evaluated at the Taylor points given by the a priori parameters $\mathbf{p}_0$. $\mathbf{y}$ are the GPS hl-SST (or kinematic position) observations and the K-band/LRI ll-SST observations, the term $\Delta \mathbf{y} = \mathbf{y} - \mathbf{y}_0$ with $\mathbf{y}_0 = \mathbf{F}(\mathbf{p}_0)$ is commonly addressed as “Observed minus Computed (O-C)” where $\mathbf{F}(\mathbf{p}_0)$ denotes the functional model of the observations evaluated with the a priori parameters $\mathbf{p}_0$. The corrections $\Delta \hat{\mathbf{p}}$ to the a priori parameters $\mathbf{p}_0$ are determined as

$$\Delta \hat{\mathbf{p}} = (\mathbf{A}_0^T \mathbf{P} \mathbf{A}_0)^{-1} \mathbf{A}_0^T \mathbf{P} \Delta \mathbf{y} \quad (3)$$

and minimize the weighted square sum $\mathbf{v}^T \mathbf{P} \mathbf{v}$ of the a posteriori (linearized) residuals $\mathbf{v} = \Delta \mathbf{y} - \Delta \hat{\mathbf{y}}$ with $\Delta \hat{\mathbf{y}} = \mathbf{A}_0 \Delta \hat{\mathbf{p}}$. The solution $\hat{\mathbf{p}} = \mathbf{p}_0 + \Delta \hat{\mathbf{p}}$ critically depends on the weight matrix $\mathbf{P} = \mathbf{Q}_y^{-1}$ with the cofactor matrix $\mathbf{Q}_y$, comprising the uncertainty information of the observations $\mathbf{y}$, which due to the limited knowledge on the observation noise (see Sect. 2) is still approximated as diagonal matrix per observation type by many ACs, whereas a smaller but increasing group of ACs is taking into account empirically determined correlated noise characteristics (see Sect. 3.5). The uncertainties of the observations are propagated to the parameters $\mathbf{p}$ by a formal variance propagation, which leads to

$$\mathbf{Q}_p = (\mathbf{A}_0^T \mathbf{P} \mathbf{A}_0)^{-1} \quad (4)$$

with matrix $\mathbf{P} = \mathbf{Q}_y^{-1}$, where $\mathbf{Q}_y$ represents the accumulated variance–covariance information, expressed as cofactor matrix, of the observation noise and of errors in the

background models that are needed for signal separation (see Sect. 3.4). The background model errors either manifest themselves in the observation residuals or as correlated errors in the estimated parameters and are still a limiting factor for the quality of the monthly gravity field solutions (Flechtner et al. 2016). In the spatial representation of the gravity field solutions, the noise causes North–South stripes, related to the along-track observation geometry of the II-SST observations.

3.2 Monthly Gravity Field Solutions and Formal Uncertainties

The official gravity field solutions are provided by the ACs of the GRACE/GRACE-FO SDS, i.e., JPL, CSR, and GFZ (Dahle et al. 2019a). Further time series are generated, e.g., by the ACs associated to COST-G. The COST-G ACs currently contributing to the operational GRACE-FO combination are the Astronomical Institute of the University of Bern (AIUB, Meyer et al. 2016), the Centre National d'Études Spatiales/Groupe de Recherche de Géodésie Spatiale (CNES/GRGS, Bruinsma et al. 2010), the Institute of Geodesy at Graz University of Technology (ITSG, Kvas et al. 2019), the Leibniz Universität Hannover (LUH, Koch et al. 2021), and since a recent expansion of COST-G now also the Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences (APM), the HuaZhong University of Science and Technology (HUST, Zhou et al. 2024a), the Southern University of Science and Technology, Department of Earth and Space Science (SUST), and the Tongji University, College of Surveying and Geo-informatics (Tongji, Chen et al. 2019). An overview over the ACs mentioned above and their most recent releases of monthly gravity fields is provided in Table 1, and a classification of the different approaches applied by the individual ACs can be found in Nie et al. (2022).

The gravity field coefficients are generally estimated in the frame of an extended orbit determination problem (Beutler et al. 2010b), together with the satellite orbits and instrument parameters like accelerometer biases and scale factors, and empirical or pseudo-stochastic parameters that are designed to absorb deficiencies in the background models. The choice of the parameters for instrument calibration and noise absorption varies among the ACs and between different releases of the same AC. A striking example is the accelerometer calibration. While early during the GRACE mission the estimation of daily

Table 1 GRACE/GRACE-FO analysis centers associated with COST-G and their most recent gravity field releases with data DOIs (where available)

AC	GRACE	GRACE-FO
AIUB	AIUB-GRACE-RL02	AIUB-GRACE-FO-RL02 (Lasser et al. 2023)
CSR	CSR-RL06 (GRACE, 2018a)	CSR-RL06.3 (GFO) (GRACE-FO, 2019a)
GFZ	GFZ-RL06 (Dahle et al. 2018)	GFZ-RL06.3 (GFO) (Dahle et al. 2019b)
CNES	CNES-RL05 (Lemoine et al. 2019)	CNES-RL05 (GFO)
ITSG	ITSG-Grace2018 (Mayer-Gürr et al. 2018)	ITSG-Grace_op
JPL	JPL-RL06 (GRACE, 2018b)	JPL-RL06.3 (GFO) (GRACE-FO, 2019b)
LUH	LUH-GRACE–2020	LUH-GRACE-FO-2020 (Koch 2020)
APM	APM-SYSU	
HUST	HUST-2024	HUST-2024 (Zhou et al. 2024b)
SUST	SUSTech2025	
Tongji	Tongji-Grace2022	Tongji-Grace2022

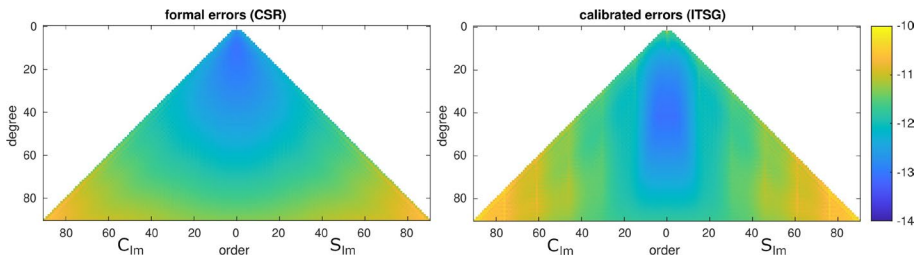


Fig. 2 The effect of using empirical noise modeling techniques on the diagonal errors, comparing the mean (2018–2023) diagonal errors of the CSR-GFO (left) and ITSG-GRACE_op (right) monthly gravity field models

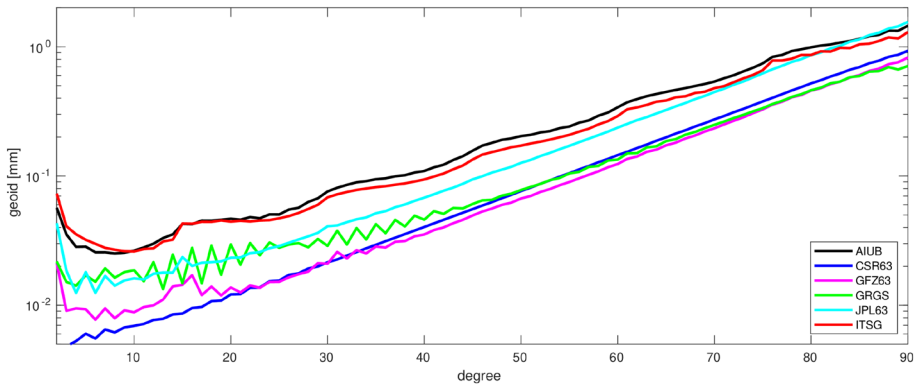


Fig. 3 Mean degree amplitudes of formal errors (2018–2024) of monthly GRACE-FO gravity field solutions of different ACs. ITSG and AIUB uncertainty estimates are calibrated by empirical noise modeling techniques and can be rated most realistic

accelerometer biases and monthly accelerometer scale factors in the three axes of the satellite body frame was considered appropriate, with the switch-off of the satellites' heaters to save energy in 2011, and with the increase of solar activity during the extended GRACE mission phase, the accelerometer parameterization had to be adapted. The estimation of daily scale factors (Meyer et al. 2016) or even daily full scale factor matrices (Klinger and Mayer-Gürr, 2016), and polynomials instead of daily constant accelerometer biases, was introduced. The adapted accelerometer parameterization was shown to significantly reduce spurious variations at 161 day frequency in the C_{20} estimates, but nevertheless the GRACE- and GRACE-FO-derived results for C_{20} are generally considered too noisy for geophysical interpretation and are routinely replaced by values determined from Satellite Laser Ranging to geodetic satellites (SLR, Cheng and Ries 2017). The same is true for the C_{30} estimates (Loomis et al. 2020) during periods, where the accelerometer measurements on one of the two satellites have to be replaced by transplant products from the other satellite (Bandikova et al. 2019; Behzadpour et al. 2021) due to the underperformance of one of the accelerometers (see Sect. 2.2).

Additionally, empirical noise modeling techniques may be applied to derive realistic covariance information ((Ellmer 2018), see Sect. 3.5 for a more detailed discussion). The impact of the calibration of the covariance model on the formal errors is illustrated by the

comparison of Fig. 2 left and right, where the formal errors of all coefficients of a truncated gravity field expansion in spherical harmonics are shown sorted by degree and order in the so-called triangle plots. By the covariance calibration resonance orders at integer multiples of the daily orbit repeat rate (see Sect. 3.3), where aliasing errors tend to accumulate (Seo et al. 2008), become visible. Due to the very diverse error sources, the poorly known noise characteristics, and the inconsistent parameterizations applied by the different ACs, the formal errors provided with the gravity field coefficients (see Fig. 3, where uncertainty degree amplitudes $\sigma_l = \sqrt{\sum_{m=0}^l \sigma_{lm}^2}$ of the mean uncertainties σ_{lm} of the coefficients of all monthly solutions of the respective time series are shown) differ by about one order of magnitude. Due to the over-optimistic noise models applied by most of the ACs and the empirical or stochastic parameters designed to absorb instrument or model deficiencies and thereby increase consistency (i.e., reduce the weighted square sum of the post-fit residuals), the formal errors are much too optimistic and cannot be used without calibration, neither for the derivation of relative weights in the combination of the gravity field solutions of different ACs (see Sect. 3.6), nor for the propagation to global grids (Level-3 products, see Sect. 4) in the physical quantity of equivalent water height (EWH) for the users (Boergens et al. 2020).

In this context, it should also be mentioned that regularization techniques may be applied to reduce the uncertainty of the estimated parameters. Regularization may either be realized in a direct way by the introduction of pseudo-observations of the gravity field parameters that are not well determined by the observations (Koch and Kusche 2002). Alternatively, the solution space may be adapted, e.g., by a truncated singular value decomposition (TSVG, Hansen 1987), in the inversion of the normal equation (NEQ) matrix $\mathbf{N} = \mathbf{A}_0^T \mathbf{P} \mathbf{A}_0$ (Lemoine et al. 2026). A more subtle way of regularization is the so-called two-step approach, where a subspace of the parameter space, e.g., the satellite orbits, are determined in a first step based on a priori knowledge of the gravity field. In the second step, the previously determined parameters, i.e., the satellite orbits, are introduced as fixed for the determination of the gravity field parameters (Meyer et al. 2015; Zhang et al. 2026). As a direct consequence of regularization not only the noise of the solution is reduced, but also geophysical signal may be attenuated (Swenson and Wahr 2011). While most ACs today provide unconstrained spherical harmonic gravity field solutions, spatial constraining is a key feature of Mascon solutions (see Sect. 4.3).

3.3 Spatial and Temporal Resolution of Gravity Field Solutions

The spatial and temporal resolution of the gravity field snapshots are closely interlinked and depend mainly on the orbit geometry and the sensitivity of the satellites' motion on the gravity field variations, i.e., on the orbit altitude. To cover the whole globe by observations, most Earth observation satellites orbit on near polar and almost circular orbits. The altitude of the satellites is a compromise between sensitivity, which decreases with satellite altitude, and lifetime requirements, because at low orbits the atmospheric drag causes a decrease of orbital altitude and finally the end of the mission. The GRACE/GRACE-FO satellites were launched into an orbit altitude of almost 500 km, which is reduced due to atmospheric drag by about 5–30 km per year,¹ depending on the solar activity which

¹ <https://www2.csr.utexas.edu/grace/operations/configuration.html>

affects the atmospheric density at satellite altitude, and the orbit maintenance maneuvers carried out to extend the satellites' lifetime.

At the given altitude, the satellites revolve about 15.3 times per day around the Earth. A regular coverage of the Earth's surface with ground tracks of the satellite orbits is achieved at integer multiples β of this basic frequency: $\beta = \alpha \text{ days} \cdot 15.3 \text{ revolutions/day}$. Due to the dense observation sampling in along-track direction, the spatial resolution of the solvable gravity field is mainly limited by the separation of the ground tracks in cross-track direction (Watkins et al. 2015) which depends on latitude, with the densest cross-track sampling near the poles. According to these purely geometrical considerations, often referred to as Colombo–Nyquist rule of thumb (Colombo 1984), a global gravity field up to degree and order $l_{\max} = \beta/2 = 46$ would be solvable after a repeat cycle of $\alpha = 6$ days. Weigelt et al. (2013) found that due to the alternation of ascending and descending tracks, this rule of thumb is too conservative. But the usefulness of a gravity field solution is also limited by its signal-to-noise ratio and it turned out that several sub-cycles have to be accumulated to reduce the noise level. The commonly generated monthly solutions up to a spherical harmonic degree and order of 96 are a compromise of these geometrical and sensitivity considerations. Vishwakarma et al. (2018) study the impact of different filtering techniques (see Sect. 4.2) on the signal content of small basins and conclude that GRACE is able to sense some catchments smaller than the spatial resolution corresponding to degree and order 96, and that a spherical harmonic resolution of 120 or higher may still contain usable signals.

While the orbit geometry is given, the signal-to-noise ratio, and consequently the useful spherical harmonic or spatial resolution of the monthly gravity field solutions, may be increased by effective noise modeling or absorption techniques (see Sect. 3.5), and by the combination of the solutions from different ACs, which differ in their stochastic noise content because the ACs use their specific analysis tools and apply diverse parameterizations (see Sect. 3.6).

3.4 Background Model Uncertainties

Temporal variations in the Earth's gravity field at periods shorter than 60 days cannot be resolved with monthly mean gravity fields that are typically inverted from the GRACE/GRACE-FO sensor data. Dynamic processes causing such variations include ocean tides, weather-related variations in atmosphere and oceans, and (to a lesser extent) also water storage variations associated with individual precipitation events. In order to avoid temporal aliasing artifacts (Han et al. 2004) in the gravity fields, such signals need to be removed with time-variable a priori background models.

Background information for the global ocean tides relies heavily on satellite altimetry data. The orbit repeat pattern of TOPEX/Poseidon (and its follow-up missions) have been selected in a way that the major tidal lines can be clearly discerned from the non-tidal variability. Tidal information from altimetry is either assimilated into hydrodynamic tide models based on the shallow water equations (Lyard et al. 2021), or evaluated directly to arrive at empirical ocean tide atlases (Hart-Davis et al. 2021). In addition, unconstrained numerical models are particularly important for smaller partial tides with sometimes complicated excitation mechanisms, like atmospheric wind and pressure contributions (Balidakis et al. 2022), or the third degree of the tide-generating potential (Sulzbach et al. 2022). With an increasing accuracy of the available global solutions for minor ocean tides, and a decreasing influence of other error sources in the GRACE gravity field products, it will

become necessary to expand the number of partial lines currently considered in the gravity field estimation process. Present-day knowledge about ocean tide model uncertainties have been recently condensed into spatially variable tidal error covariance matrices that can be readily incorporated into the stochastic modeling applied during GRACE data processing (Hauk et al. 2023; Abrykosov et al. 2022). Analyzing K-band range-rate post-fit residuals, obtained after estimation of monthly gravity field solutions from more than 20 years of GRACE/GRACE-FO data, revealed residual signals for more than 30 prominent tidal frequencies from different bands (Koch et al. 2024).

Although somewhat weaker than ocean tides, weather-related variations in atmosphere and ocean are more challenging to consider since those need to be represented in terms of 3 hourly sampled time series of spherical harmonics expansions complete to degree and order 180. The latest available release 07 of the official GRACE Atmosphere and Ocean Non-Tidal Level-1B (AOD1B; Shihora et al. 2022) product is based on the ERA5 global atmospheric reanalysis (Hersbach et al. 2020) and a simulation with ocean general circulation model MPIOM (Jungclauss et al. 2013). AOD1B RL07 has been thoroughly evaluated for the occurrence of possible instabilities or bias jumps (Shihora et al. 2023), that have complicated the interpretation of the RL05 GRACE time series (Fagiolini et al. 2015). AOD1B RL07 is further complemented by a series of approximated errors that can be readily used for end-to-end satellite simulation experiments, and also a static error covariance matrix suitable for stochastic modeling of residual de-aliasing errors (Shihora et al. 2024).

For completeness, we note that also sub-monthly variations in terrestrial water storage induce aliasing artifacts into the monthly mean gravity fields. Those signatures are much smaller than the atmosphere–ocean variability and are therefore normally not considered by means of background models, even though such data is readily available (see, e.g., Dill et al. 2018). With latest data from very high-resolution numerical modeling experiments with LISFLOOD that are configured globally with 0.05° (ca. 5 km) spatial resolution (Jensen et al. 2024; Dobslaw et al. 2024), it will be possible to rigorously tackle this error source as well.

3.5 Empirical Noise Modeling

The basic concept of determining monthly gravity field solutions in terms of spherical harmonics is the LSA process using the hl-SST tracking data (or kinematic orbits) and the ll-SST tracking data (KBR and LRI range-rate measurements). In order to determine an optimal solution, the stochastic characteristics of the observation data must be considered. The LSA has the advantage that the post-fit residuals can be analyzed and consequently, aggregated information about the uncertainty of the measurements and background models can be obtained. Early results of using the post-fit residuals for observation data weighting were published by Ditmar et al. (2006). The post-fit residuals, characterized by the underlying parameterization, comprise uncertainties from all observation types and the background models; however, by making certain assumptions, e.g., stationarity over the period analyzed, the different error sources can be disentangled.

The stochastic model required to obtain minimum variance estimates of the gravity field parameters can be derived for each month in a multi-step approach using variance component estimation (VCE), where the weights of the different observation groups and the structure of the covariance matrix are adjusted iteratively (Ellmer 2018).

For the kinematic orbits, a priori error information is given (at least) in the form of an epoch-wise 3×3 covariance matrix derived from the kinematic orbit determination (see Sect. 2.3). The range-rate measurements are reduced by the effect of the non-gravitational forces measured by the accelerometer located in the center of mass of each satellite. Hence, the noise of the reduced observations consists of several error sources, mainly the system noise of the instrument in high frequencies but also the noise induced by the accelerometer in the low-frequency range.

The noise of the kinematic orbits and the KBR/LRI observations is considered to be the result of a wide-sense stationary process, meaning that the covariance function of the noise does not vary within one month. A covariance function can be derived from autocorrelation up to a certain lag, often three hours, and compiled to a covariance matrix in block Toeplitz structure. Figure 4 shows exemplary a covariance function for January 2019 as estimated with the approach underlying the ITSG (orange) and the AIUB (green) solutions (see Table 1) in the time domain (left) and as amplitude spectral densities (ASD, right). The main feature is the $1/f^2$ and f^2 noise stemming from the accelerometer noise integration and the ranging system noise differentiation, respectively (Kim 2000). In the low-frequency domain corresponding to periods ≥ 15 min, the ASD of AIUB is flat in contrast to the ASD of ITSG, due to pseudo-stochastic parameters estimated at 15 min intervals by AIUB to absorb unknown long-period deficiencies. In the higher frequencies the covariance function underlying the ITSG solution shows less noise because of an incorporation of background model uncertainties which is lacking in the AIUB solution. The covariance matrix can then be used in a further iteration step of the least-squares adjustment as a new observation weight matrix (Lasser 2023). This process can be refined by expressing the covariance function by the amplitudes of the power spectrum which can be determined from the post-fit residuals for each frequency using VCE (Ellmer 2018). During this process, the covariance structure for each observation group is adjusted iteratively until the results have sufficiently converged.

An additional error source in the gravity field recovery process arises from background model uncertainties as discussed in Sect. 3.4. Even though geophysical models such as the AOD1B RL07 are consistently optimized, they still limit the solution quality of the gravity fields. To account for these deficiencies, an appropriate stochastic model can be developed

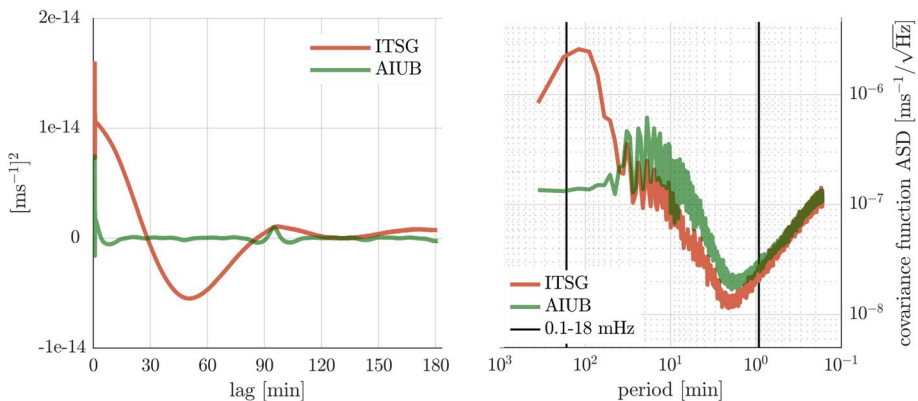


Fig. 4 Covariance functions of the AIUB and ITSG solutions in the time domain (left) and as amplitude spectral densities (ASD, right) for January 2019

using some information about these models. As mentioned in Sect. 3.4, the AOD1B RL07 additionally provides a time series of approximated de-aliasing errors. These can be used for a more realistic stochastic modeling of the observations where measurements subjected to larger model errors will be down-weighted in the LSA.

The model uncertainties can either be incorporated by augmenting the covariance matrix of the observations, or by co-estimating model corrections as stochastic parameters with a known prior covariance matrix (Kvas and Mayer-Gürr, 2019). To obtain such a model covariance matrix, the time series of the model uncertainties first has to be aligned with the parameterization defined for the model error corrections and the mean of each calendar month has to be subtracted to restrict the model uncertainties to sub-monthly variations. The underlying error process is assumed to be stationary and therefore the covariance matrix has a block Toeplitz structure. Since the direct estimation of the covariance matrix would suffer from numerical instability, an autoregressive model can be used as an approximation. This also reduces the computational burden since the NEQ system is block-banded compared to the dense block Toeplitz structure of the covariance matrix of a stationary process (Kvas 2020).

3.6 Combination of Monthly Gravity Field Models

To reliably provide the users with robust monthly gravity field solutions of favorable signal-to-noise ratio a combination of the monthly gravity field solutions of different ACs is performed by COST-G under the umbrella of the IAG. While a combination on the NEQ level would be favorable due to the correct consideration of all correlations between gravity field and orbit or instrument parameters, it suffers from the unrealistic uncertainty information in the individual NEQs (Meyer et al. 2019), as it was discussed in Sect. 3.2. Therefore, a combination on solution level is performed instead. Furthermore, a combination on NEQ level of all solutions considered by COST-G is not yet possible because not all ACs provide their NEQs.

It is assumed that the monthly gravity fields generated by the different ACs from data of the GRACE/GRACE-FO missions contain consistent signal caused by the temporal mass variability in the Earth system, because all ACs basically rely on the same observations and apply the same types of background models for signal separation. Consequently, the individual gravity fields differ only by their noise content due to the different parameterizations and noise models applied by the ACs.

The monthly gravity field solutions in the spherical harmonic domain are combined by VCE on the solution level that was specifically developed for this purpose (Jean et al. 2018). It has to be noted that no formal uncertainty information is used and all gravity coefficients up to order 60 enter the VCE with equal weight. To reduce the impact of systematic differences in the high-order coefficients, coefficients beyond order 60 are not considered in the VCE (Meyer et al. 2024).

To validate the quality of the combined gravity fields, the noise content of the individual and the combined monthly gravity fields is assessed by the non-secular, non-seasonal variability over ocean areas, where no short-term mass variations have to be expected (Fig. 5). To reduce the secular and seasonal signal content, the signal predicted by the COST-G Fitted Signal Model (FSM, Peter et al. 2022) is reduced from the monthly gravity fields. The noise level of the combination is always close to the noise level of the best individual contribution. In case of outliers, e.g., in February 2019, the combination clearly outperforms the best individual contribution.

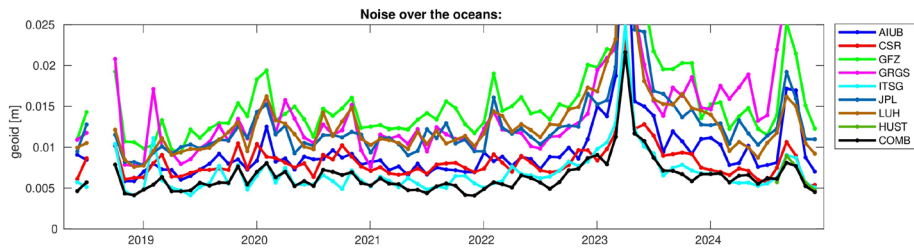


Fig. 5 Noise assessment of the individual monthly GRACE-FO gravity fields and the operational COST-G combination by the RMS of their non-seasonal and non-secular variability over ocean areas

The COST-G monthly combined gravity fields are provided with empirical uncertainty information that is derived from the spread of the individual contributions. Since all the ACs' individual gravity field solutions are derived from basically the same set of observations, notwithstanding minor differences due to individual screening procedures, and most ACs apply the same standard set of background models for de-aliasing and signal separation, these empirical uncertainties only represent the differences in the analysis noise caused by the ACs' specific choice of noise modeling or absorption strategies. As mentioned above, systematic differences mainly occur in the high-order coefficients, as also reflected in the empirical uncertainties. For the main part of the coefficients, the empirical uncertainties are overly optimistic, as is the case for the formal uncertainties of the individual solutions.

3.7 Perspectives from Future Missions

The main limiting factor of the currently achievable gravity field retrieval performance are temporal aliasing errors resulting from under-sampling high-frequency tidal and non-tidal mass variations of the atmosphere and ocean, which cannot be resolved due to the limited temporal resolution of a satellite mission (Flechtner et al. 2016) (see Sect. 3.3). In conjunction with the very anisotropic error behavior of the unidirectional in-line inter-satellite ranging system, with a very high sensitivity in along-track direction, but no sensitivity in cross-track and radial direction, this results in the typical striping patterns of GRACE/GRACE-FO gravity field solutions. However, not only short-period signal variations can generate stripes. Also long-period signals, which are sampled at different phases by neighboring ground tracks, produce these artifacts (for a detailed discussion see Abrykosov et al. (2022)). Various strategies exist to reduce the anisotropic error behavior and thus temporal aliasing effects. Pendulum orbits, where the trailing satellite makes a pendulum motion with a period of once per revolution w.r.t. the leading satellite, can measure, depending on the opening angle of the pendulum, also parts of the across-track component (Panet et al. 2013). With high-low tracking concepts between low- and high-orbiting satellites (Pail et al. 2019), also the radial gravity component can be observed. However, all of these concepts are technologically challenging. Wiese et al. (2012) proposed a technically feasible double pair concept, which is composed of a polar and an inclined in-line satellite pair. The optimum inclination regarding the retrieval performance in regions covered by the inclined pair were 45° , because of the perpendicular crossing of ascending and descending orbit ground tracks, but such an orbit leaves out big gaps toward the poles. Therefore, in the currently planned Mass-change And Geosciences International Constellation (MAGIC;

Heller-Kaikov et al. 2023), which is composed of the polar pair GRACE-C and the inclined pair NGGM, the chosen inclination of 70° is a compromise between aliasing reduction in the covered areas and (near-)global coverage. Compared to the current single-pair mission GRACE-FO, such a Bender double pair mission can improve the gravity retrieval performance by a factor of 5–7 for raw solutions, and 2–2.5 for post-processed solutions (Hauk and Wiese 2020).

Beyond the intrinsic de-aliasing capabilities of such a constellation, also enhanced parameterization strategies support a gain in gravity retrieval performance. A significant temporal aliasing reduction of non-tidal high-frequency atmosphere and ocean signals can be achieved by co-estimating short-term (daily) long-wavelength gravity fields (Wiese et al. 2011; Daras and Pail 2017), or to retrieve them as part of a two-step approach (Abrykosov et al. 2022). The second main temporal aliasing contributor are errors in ocean tide background models. In contrast to non-tidal signals, they occur at distinct excitation frequencies (Visser et al. 2010). Therefore, ocean tide model parameters can be explicitly co-estimated, provided that the observation period is sufficiently long (Hauk and Pail 2018). Beyond improved space–time parameterization strategies, another approach to reduce temporal aliasing effects is the stochastic modeling of non-tidal (Kvas and Mayer-Gürr, 2019) and tidal (Abrykosov et al. 2022) background model errors in the course of the gravity adjustment, leading to a down-weighting of observations measured in regions where background models are known to perform worse.

In Zingerle et al. (2024), it is demonstrated that even multi-pair constellations (here up to 6 pairs) are not sufficient to reduce temporal aliasing errors to a level that the benefit of better instrumentation could be exploited. This gives room for innovative processing strategies in the future, to better represent the real space–time behavior, which is generally insufficiently sampled by satellites and even satellite constellations.

4 Level-3

Level-3 data corresponds to user-friendly gridded products in 3D (latitude, longitude, and time), which might be used in hydrology, climate science, ocean science, or cryosphere research. Level-3 data is usually expressed in meters of equivalent water height as the height of a uniform thin layer of water at the surface of the Earth (*m EWH*). However, depending on the application, it may be expressed in *mGal*, *Gt/km²*, *km³/km²* or even *mm sea – level equivalent (mm SLE)* for solid Earth, cryospheric, hydrologic, or oceanic applications, respectively. Two schools of thought have been established in the last years for Level-3 data computation: First, data using the spherical harmonic conversion or synthesis of Level-2 spherical harmonic coefficients to the grid (spherical harmonic approach), and second, Level-3 data employing the direct inversion through the mass concentrated method (mascon approach) (see Fig. 1). Common to both schools is that several post-processing choices must be made to make the Level-3 data more accessible and useful for non-geodetic users.

We decided not to extend this paper in the explanation of the use of auxiliary data but to focus on the discussion of the uncertainties. However, some key papers will be cited to guide the reader through this auxiliary data. This section will first discuss the uncertainty budget of the auxiliary data commonly used in both approaches to improve and correct the low-degree harmonic coefficients of Level-2 data. Secondly, we will discuss the uncertainties in the spherical harmonic and mascon approaches. Then, we will review the

post-processing affecting both approaches and their associated uncertainties, i.e., the leakage and the Gibbs effect. Finally, we will discuss the uncertainties introduced by the signal separation of the overlapping geophysical signals observed by satellite gravimetry, namely, separating solid Earth and water mass signals.

4.1 Correction of Low-Degree Spherical Harmonic Coefficients

GRACE/GRACE-FO satellite-to-satellite tracking observations are weakly sensitive to the nodal precession due to the near-polar satellite orbits (Wahr et al. 2006; Cheng and Ries 2017). Thus, Satellite Laser Ranging (SLR) to geodetic satellites allows to estimate low-degree harmonic coefficients such as C_{20} more accurately. This low-degree harmonic coefficient is dominant at very large scales, in particular when estimating the barystatic sea level and the global water budget. Thus, it is recommended to replace it by SLR-derived estimates (Chambers 2006; Dobslaw et al. 2020). During the months where only a single accelerometer² was available on GRACE, C_{30} was also poorly determined, and, thus, needed a similar replacement based on SLR (Loomis et al. 2020). At the time of this publication, there are several C_{20}/C_{30} products available based on SLR observations or combinations of SLR and GRACE/GRACE-FO observations that include their own uncertainties (e.g., König et al. 2019; Lemoine and Reinquin 2017; Cheng et al. 2013; Loomis et al. 2019a,b). Although some studies included different SLR products, using their spread as the uncertainty on this correction, at the time of this publication, no routine Level-3 data processing include these uncertainties in the error propagation chain.

Furthermore, GRACE/GRACE-FO inter-satellite ranging data are insensitive to the geocenter motion, which is why the related spherical harmonic coefficients (C_{10} , C_{11} , and S_{11}) are also replaced by external estimates carrying their own uncertainties and correlations depending on the method used to compute this correction (Swenson et al. 2008; Sun et al. 2016; Uebbing et al. 2020; Wu et al. 2017; Couhert et al. 2020). These uncertainties have been pointed out as one of the major sources of uncertainty in the estimation of the barystatic sea level changes or in the estimation of Antarctica ice sheet mass change (e.g., Kim et al. 2022; Barletta et al. 2013; Chambers et al. 2007; Marti et al. 2022; Blazquez et al. 2018). Thus, a reliable estimate of the uncertainties of the geocenter motion should be established in the future and used in the uncertainty estimation of Level-3 data. The International Earth Rotation and Reference Systems Service (IERS) decided at its Directing Board Meeting no. 80 (April 27, 2025) to establish a dedicated campaign for the “analysis and combination of geocenter motion and degree-2 gravity field parameters” under the umbrella of the IERS, which may provide a framework to assess in a coordinated way the level of consistency of geocenter estimates derived from various approaches relying on different data sources.

4.2 Level-3 Data Derived from Level-2 Spherical Harmonic Coefficients

Currently, there are three routine Level-3 data products available using the Level-2 spherical harmonic coefficients: the Gravity Information Service (GravIS²) data set provided by GFZ based on COST-G and GFZ Level-2 data (Dahle et al. 2025), the Tellus³ data

² <https://gravis.gfz.de>

³ <https://grace.jpl.nasa.gov>

set provided by JPL based on JPL, CSR, and GFZ Level-2 data (Landerer and Swenson, 2012), and the SAGSA⁴ data set provided by CNES based on JPL, CSR, GFZ, ITSG, and CNES Level-2 data (Blazquez et al. 2018). The central processing step between Level-2 and Level-3 data is the spherical harmonic conversion or synthesis from the spherical harmonic coefficients to a grid. Thus, theoretically, uncertainties of the spherical harmonic coefficients could simply be variance propagated to Level-3, including the uncertainties of all corrections. However, even with improved Level-2 uncertainty estimations via stochastic modeling, these uncertainties are still too optimistic. Hence, the uncertainties of the spherical harmonic coefficients are currently not commonly used to estimate Level-3 uncertainties. Several studies use the spread among a selected ensemble of Level-2 data as a more realistic estimate of the uncertainty (Sakumura et al. 2014; Blazquez et al. 2018). However, variance propagation from Level-2 data to Level-3 data is feasible and may become routinely used in the coming years. Before the spherical harmonic synthesis, the spherical harmonic coefficients are usually filtered with dedicated filters to reduce the typical striping errors. Nowadays, the DDK (Kusche et al. 2009), VDK (Horvath et al., 2018), or destriping and smoothing (Swenson and Wahr 2006) filters are the most commonly used. Concerning the routine data products, GravIS uses the VDK filter, TELLUS the destriping and smoothing filter and SAGSA the DDK filter. These filters change the structure of the covariance matrix of the coefficients without introducing additional uncertainties. Including these uncertainties is feasible with the variance propagation, but it is numerically and computationally laborious.

4.3 Level-3 Data Using the Mascon Approach

There are currently three publicly available global mascon data products where the estimation of mascons coupled with prior constraints are performed during the Level-2 data processing: JPL (Watkins et al. 2015), GSFC (Loomis et al. 2019a, b) and CSR (Save et al. 2016). The output of the Level-2 mascon estimation is a subsequent Level-3 data product that does not require additional filtering to remove correlated errors. There are distinct differences between the data products which necessitate different treatment of uncertainties. The JPL Mascon data product estimates 3° spherical cap mascons from analytical partial derivatives, sampling the globe roughly at the native resolution of the GRACE/GRACE-FO observations, but it is provided with a spatial resolution of 0.5° . Conversely, mascon data sets from GSFC and CSR estimate spherical harmonic decompositions of 1° mascons, which oversamples the native GRACE/GRACE-FO resolution by an order of magnitude. Due to the different resolutions of the mascon basis functions, the uncertainties are also recommended to be treated differently.

JPL and GSFC mascons are delivered with uncertainties due to the measurement error and leakage errors (Wiese et al. 2016; Loomis et al. 2019a, b). The measurement error represents the error in the mascon estimate due to the GRACE/GRACE-FO measurement system and sampling over the solution interval. However, their approach to quantify these errors are different. In the JPL mascon, uncertainty information is derived from the formal posteriori covariance matrix of the estimation, and scaled to match levels of agreement with in situ ocean bottom pressure recorders over the ocean, and residuals relative to a climatology fit (trend, annual, semiannual) over the land, as suggested by Wahr et al. (2006).

⁴ https://catalogue.theia.data-terra.org/meta/GRAVIMETRY_TOTAL_WATER..

While in GSFC, the measurement error derivation does not make use of the formal posteriori covariance matrix due to the need to scale it; rather, it relies on fit residuals from the difference of the final mascon solution and a temporally filtered version of the solution (in a way consistent with how the posteriori covariance matrix for the JPL mascons are scaled over land; however, a different choice of filter is used). It is noted that at time of publication, the CSR mascon solution does not provide information about the uncertainties.

4.4 Uncertainty in the Leakage Effect

The leakage effect in GRACE and GRACE-FO data arises from the limited spatial resolution of the observations, which prevents the accurate representation of signals smaller than a certain scale. As a result, mass variations from one region can spread into neighboring areas, leading to signal attenuation and spatial mixing. This is a well-known and largely unavoidable limitation of GRACE-type observations (Wahr et al. 1998), primarily caused by the large distance between the satellites and the Earth's surface.

In the classical spherical harmonic approach, spatial resolution is controlled by the maximum degree and order (l_{max}), typically around 90. This corresponds to a half-wavelength resolution of approximately $\lambda = 20000 \text{ km}/l_{max}$, i.e., about 200–300 km (2°). Although many Level-3 products are distributed on finer spatial grids, this does not reflect an increase in true resolution. Moreover, additional filtering—required to suppress correlated noise—further smooths the signal and aggravates leakage.

To mitigate leakage in the spherical harmonic approach, a variety of approaches have been developed. Some methods rely on external information, such as forward models or independent observations (e.g., Klees et al. 2007; Longuevergne et al. 2010; Deggim et al. 2021). While effective, these approaches introduce additional uncertainties associated with the external data sources. Alternatively, methods based solely on GRACE data have been proposed (e.g., Dobslaw et al. 2020; Vishwakarma et al. 2017), which avoid introducing independent measurement errors but may modify the covariance structure of the solution.

The alternative representation of the mascon approach inherently mitigates leakage as part of its processing scheme. For the 3° JPL mascon solution, leakage uncertainty is primarily characterized as intra-mascon leakage, rather than inter-mascon leakage. In this framework, individual mascons are assumed to be uncorrelated, an assumption that has been validated—particularly at high latitudes—through comparisons with independent geodetic data sets (Schlegel et al. 2016). Consequently, leakage uncertainty mainly arises when user-defined regions (e.g., drainage basins) do not coincide with the predefined mascon boundaries.

Intra-mascon leakage is further addressed through dedicated corrections. Mascons that span land–ocean boundaries are treated using a coastal resolution improvement (CRI) filter, while basin-specific scale factors are provided for hydrological applications to reduce leakage within mascons. A detailed description of the derivation of intra-mascon leakage uncertainties for the 3° solution is given in Wiese et al. (2016).

In contrast, the 1° GSFC mascon solution emphasizes the quantification of inter-mascon leakage. This reflects the fact that the 1° mascon parameterization oversamples the native GRACE resolution by approximately one order of magnitude, leading to increased signal leakage between adjacent mascons. To account for this, a resolution operator is applied to estimate both the bias and the inter-mascon leakage uncertainty for each mascon, taking into account the applied a priori constraints. Further details on the derivation of

measurement and leakage uncertainties for the GSFC 1° solution are provided in Loomis et al. (2019a, b).

Overall, leakage and its mitigation are sources of uncertainty in the Level-3 data sets, which are complicated to treat. Thus, a comprehensive analysis of these uncertainties is yet to be performed. This most relevant topic is currently being addressed by working groups organized by the IAG and the International Space Science Institute (ISSI), respectively.

4.5 Uncertainties of Geophysical Domain Specific Level-3 Data

The temporally changing Earth's gravity field measured by GRACE/GRACE-FO contains a superposition of water mass change signals and solid Earth change signals. The water mass changes include ice mass changes over the continents such as from glaciers and from the Greenland and Antarctic ice sheets, liquid water mass changes as terrestrial water storage (TWS), and the ocean mass change (barystatic sea level). Solid Earth signals that affect the gravity field are mainly the glacial isostatic adjustment (GIA), the mass displacement due to large earthquakes, and the pole tides. GIA is the ongoing process of the Earth's crust and mantle responding to the loading and unloading of ice sheets and glaciers since the last glacial maximum. GIA manifests as a linear trend and affects the water mass signals specifically in regions covered by ice sheets during the last glacial maximum (i.e., North America around Hudson Bay, Fennoscandia, Greenland, Antarctica). GIA also influences regional ocean mass trends. Besides that, it may be considered negligible for hydrological studies in most of the main basins. GIA is usually corrected for through external models (e.g., Peltier et al. 2018; Caron et al. 2018). Although, uncertainty estimates might exist for some of these GIA models (e.g., Caron et al. (2018) employs a Bayesian approach to provide model uncertainties), most of the Level-3 products consider the correction as “error-free” or use the spread between the two or more GIA models as the associated error such as in SAGSA barystatic sea level. Either provided or estimated GIA model uncertainties could be included in the future in the variance propagation from Level-2 to Level-3 data.

Another solid Earth signal present in the GRACE/GRACE-FO data is mass displacement due to large earthquakes. During the lifetime of GRACE/GRACE-FO, several megathrust earthquakes have occurred (Sumatra-Andaman 2004, Chile 2010, and Tohoku Japan 2011 being the largest). To remove the influence of the earthquakes from the Level-3 data set, the signal may be empirically estimated based on prior information about the position and timing of the event (e.g., Han et al. 2013; Tang et al. 2020; Deggim et al. 2021) and subsequently removed from the GRACE/GRACE-FO data. This empirical estimation has several limitations, for example the impossibility of separating the post-seismic adjustment from a geophysical trend. So far, the uncertainties of these estimations have yet to be considered, and further, the correction leads to temporal correlations between different months. Although their impact is dominant in the regions around the earthquakes (less than 2000 km from the epicenter), their impact on the barystatic sea level has been quantified as less than 0.2 mm SLE/yr for the period from January 2003 to December 2015 (Tang et al. 2020).

For solid Earth studies, the correction of signals with hydrological loading models or oceanic loading models can be applied to reduce the influence of surface mass variation signals (e.g., Rosat et al. 2021; Lecomte et al. 2023a, b). No uncertainties estimation comes with these surface loading models and, therefore, the spread between an ensemble of the available models (different models with the same forcing, or same model with different forcing) can serve as a proxy for an upper bound estimation of the uncertainties.

Such estimated loading models uncertainties are of the order of magnitude of the theoretical upper bound amplitudes of the temporal gravity field variations originating from the Earth's core (Lecomte et al. (2023a, b)).

4.6 Practical Implementation of Level-3 Uncertainties

At the time of this publication, there is no published Level-3 data set that propagates the variances from the Level-2 data and includes all the uncertainties in the aforementioned post-processing steps. Thus, so far, the uncertainties of Level-3 data using the spherical harmonic approach are empirically estimated while users of the mascon data sets use the uncertainties provided in the data set. The most straightforward variant to estimate Level-3 uncertainties is using the open-ocean root mean square of each month after removing the trend and the periodic signals. Over the years, different spatial covariance models have been developed for the TWS data sets, e.g., by Landerer and Swenson (2012) or Zhang et al. (2016). Boergens et al. (2020, 2022) developed a more detailed spatial covariance model, which is anisotropic, latitude-dependent, and non-stationary. This model has been published as open-source code (Boergens 2021) and is implemented in the regional mean time series uncertainties of the GravIS data set. With this covariance model we can estimate latitude-dependent grid cell uncertainties for each month. Figure 6a displays one month (March 2006) of such grid cell uncertainties. The temporal variability of these uncertainties (Fig. 6c) represents, among other effects, months with short-period repeat orbits (e.g., February 2015).

In contrast, the uncertainties provided with the JPL mascons (Fig. 6 (b) and (d)) show a distinctly different spatial and temporal behavior. Spatially, the mascon uncertainties are

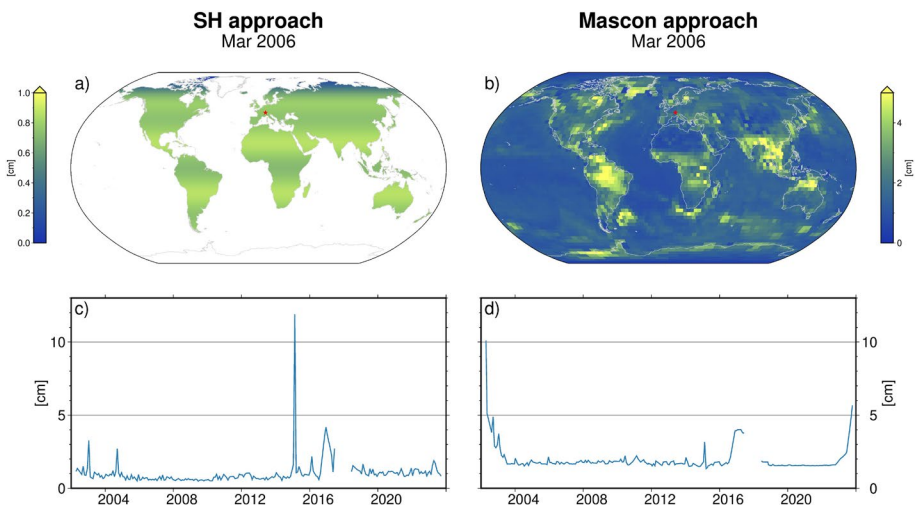


Fig. 6 Comparison of Level-3 uncertainties in the spatial and temporal domain between a SH approach and a Mascon approach. **(a)** Grid uncertainties resulting from the covariance model by Boergens et al. (2022) applied to the TWS gridded data provided via GravIS, which only covers the continents; **(b)** Grid uncertainties provided with the JPL Mascon data. **(c)** and **(d)** temporal evolution of the grid uncertainties at the location indicated by the red * in a)+b). While the overall magnitude of the uncertainty agrees between the two data sets, both the spatial and temporal patterns significantly disagree

correlated with signal amplitude, which is inversely proportional to the strength of the constraint used during the gravity solution. Temporally, the mascon uncertainties exhibit larger uncertainties at the beginning and end of the time series, which is driven by a Kalman filter implemented during the time correlation mascon solution process. There are similarities in the temporal variability between the two, including increased uncertainty during the single accelerometer months of the GRACE mission, and increased uncertainty during short-period repeat orbit phases (although the amplitude is muted in the mascons relative to the spherical harmonics).

The results of the covariance model of Boergens et al. (2022) have been compared to fully variance propagated uncertainties from Level-2 of the ITSG-Grace2018 solution of the Graz University of Technology (Kvas et al. 2019), however, without accounting for uncertainties in the correction models. The resulting time series of uncertainties for two major river basins, Yenisey and Orinoco, are shown in Fig. 7 (a) and (b)). For both river basins, the amplitude and temporal variability of the uncertainties match well. Additionally, such uncertainty time series can be compared to empirical uncertainties over desert regions such as the Sahara (Fig. 7, (c) and (d)). Here, the temporal evolution of the uncertainties is similar again. However, the formal Level-2 variance propagated uncertainties underestimate the empirical uncertainties. This comparison shows that for realistic Level-2 covariance information, the fully variance propagated Level-3 uncertainties can be very well used. However, such realistic Level-2 covariances are not yet provided by all ACs, and the uncertainties of the correction models need to be further considered.

Another approach to deal with uncertainties is the ensemble approach. Assuming the state-of-the-art corrections and the largest possible number of the different corrections, the spread of the ensemble should approach the underlying uncertainty. Based on this approach, the barystatic and manometric sea level changes with their uncertainties (Fig. 8

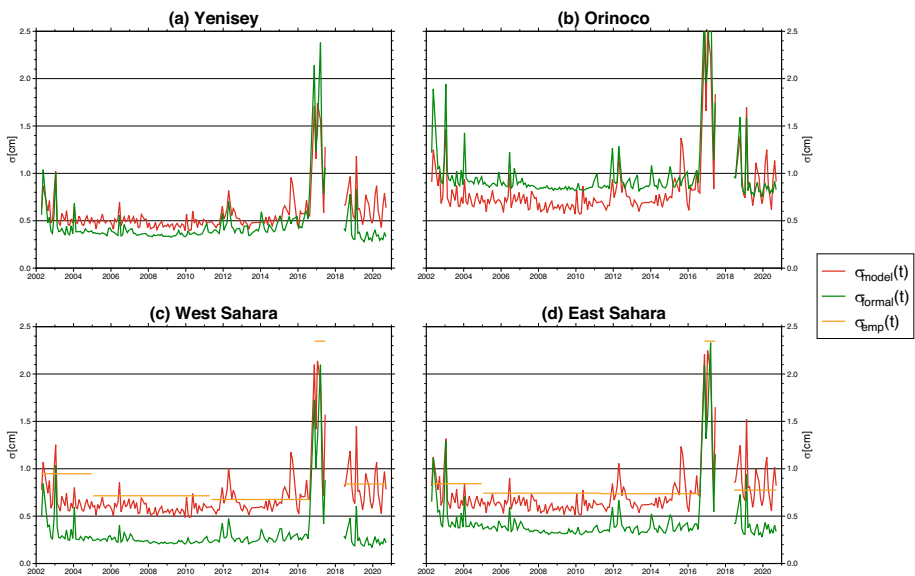


Fig. 7 Comparison of uncertainties derived by the covariance model (σ_{model}) by Boergens et al. (2022), variance propagate Level-2 uncertainty (σ_{formal}), and empirical uncertainties for ITSG-Grace2018 data (σ_{emp}). More details on the computation of the empirical uncertainties can be found in Boergens et al. (2022). The temporal patterns of the uncertainties agree well between the two/three different uncertainty estimations

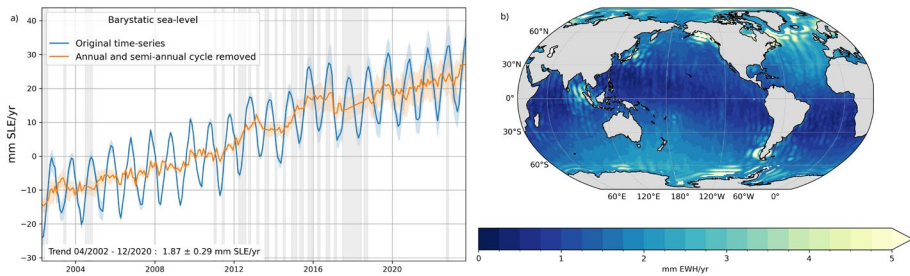


Fig. 8 (a) Barystatic sea level time series from the SAGSA Level-3 product with its associated trend in *mm SLE/yr* for the period April 2002 to December 2020. Shaded blue and orange areas corresponds to the time series uncertainties based on the spread among a selected ensemble and the gray areas correspond to the time-interpolated values. (b) Spatial uncertainties of the manometric sea level trend in *mm EWH/yr* based on the spread among a selected ensemble for the period April 2002 to December 2020

(a) and (b), respectively) are estimated and updated in a routine mode in the AVISO web-site (Blazquez et al. 2018).

5 Level-4

With Level-4 data, we refer to data products in which Level-3 mass change data sets have undergone further processing by integration with models (either statistical models, machine learning approaches or deterministic process models of Earth system components) and/or fusion with other observation data sets to derive information layers that go beyond what can be directly derived from satellite gravimetry in the Level-3 products.

5.1 Spatially Downscaled TWS Data

One of the shortcomings of Level-3 GRACE/GRACE-FO products for many applications is their limited spatial resolution of around 300 km. Therefore, various studies try to provide Level-4 estimations with a higher spatial resolution by either assimilating GRACE measurements into models (e.g., Zaitchik et al. 2008; Eicker et al. 2014; Girotto et al. 2016), or downscaling GRACE products by considering information with higher spatial resolution from other data sources (e.g., Yin et al. 2018; Miro and Famiglietti 2018; Sun et al. 2019; Gou et al. 2025). The associated uncertainty for such high-resolution products is a prerequisite for assessing their reliability, but also challenging to quantify. For example, there exists no well-established relationship between TWS and potential high-resolution predictors, while the water balance equation cannot be perfectly closed on neither local, regional nor global scales because of inherent noise in its different components (Lehmann et al. 2022; Dorigo et al. 2021). Therefore, the downscaling approaches rely on data-driven methods, including statistical methods (e.g., Vishwakarma et al. 2021; Tourian et al. 2023) and machine learning models (e.g., Irrgang et al. 2020; Gou and Soja 2024). However, the uncertainty information associated with machine learning outputs is usually not obtainable based on the law of uncertainty propagation, as the deterministic functional relationship between inputs and outputs is typically unknown and approximated by the machine learning models (Gou et al. 2026). Moreover, the high dimensionality of these models and the

probabilistic components that are typically involved further impose difficulties in the direct estimation of uncertainties (Abdar et al. 2021).

Some efforts have been dedicated to addressing these difficulties, while highlighting the importance of realistic GRACE/GRACE-FO Level-3 uncertainty information as their basis. Tourian et al. (2023) downscales GRACE-derived TWS flux by establishing non-parametric likelihood functions relying on Copula models. Within a Bayesian framework, the posterior distribution of the downscaled TWS fluxes can be obtained by considering the GRACE Level-3 data as prior information. The uncertainty of downscaled TWS flux is derived from the quantiles of the posterior distribution. However, the estimated Level-4 uncertainty may be over-optimistic due to the assumption that the relationship between low-resolution data pairs holds for the high-resolution data pairs (Irrgang et al. 2020) while the spatial correlations among high-resolution data are impractical to consider. Also Mehrnegar et al. (2021) and Forootan et al. (2024) developed and applied a Bayesian data merging approach of GRACE-based TWS data and model outputs for both downscaling and separating TWS into individual storage compartments such as groundwater. Gerdener et al. (2023) generates GRACE Level-3 covariances by propagating the Level-2 uncertainty information through the whole post-processing approaches and considers them in the ensemble Kalman filter assimilating approach, together with model uncertainties generated by aggregating multiple model parameters (Döll et al. 2024). However, they raise multiple concerns regarding the fidelity of the uncertainty estimates due to the limitations of GRACE formal uncertainty estimations. Gou and Soja (2024) provide global downscaled TWS anomalies (TWSA) by fusing GRACE mascon products with hydrological simulations using a self-supervised deep learning model. The associated Level-4 uncertainties are provided by combining the principle of deep ensembles (Lakshminarayanan et al. 2017) and Monte Carlo simulations. To this end, the input uncertainties, including GRACE Level-3 uncertainties, are needed for sampling the distributions. However, the resulting uncertainties also tend to be underestimated due to the lack of uncertainty information on hydrological simulations and over-optimistic formal uncertainty information of GRACE Level-3 products.

The above examples illustrate that several attempts have been undertaken to propagate Level-3 uncertainties into downscaled Level-4 TWSA products with higher spatial resolution. While (i) there is no generalized formal uncertainty approach for this, (ii) the resulting uncertainty estimates are case- and method-specific and (iii) not fully comprehensive due to necessary assumptions and simplifications, there is now often uncertainty information available for Level-4 data users that can be included in an uncertainty discussion of the application of interest.

5.2 Isolating Compartmental Storage Variations

Deducing groundwater storage anomalies (GWSA) from GRACE-based TWS anomalies is another common example of Level-4 data processing which has been carried out for many river basins or aquifers worldwide (see, e.g., Frappart and Ramillien (2018) for an overview). Besides separating TWS into the individual storage compartments including groundwater via data assimilation in hydrological models or Bayesian data merging approaches as also used for data downscaling (see above), GWSA is often derived based on a water budget approach in which all water storage compartments other than groundwater are subtracted from TWSA. In this case, uncertainties need to be propagated to the resulting GWSA data and accumulate in this residual term. In previous studies, this has

partially been done by a standard uncertainty propagation of the uncertainties of the individual storage components used in the subtraction process, i.e., the square root of the sum of the squared individual uncertainty values, see, e.g., Richey et al. (2015); Frappart and Ramillien (2018) or Güntner et al. (2026) for the Global Gravity-based Groundwater Product G3P.

As seen from Fig. 9 for G3P, root zone soil moisture has the largest contribution to GWSA uncertainty on global average while glacier mass changes have the lowest on a global average (Fig. 9). However, given the varying contribution of individual water storage compartments to TWSA at regional scales, the magnitude of uncertainty and the relative contribution of individual water storage compartments to the regional GWSA uncertainty may differ markedly from these global average values. For instance, in cold or mountainous regions, snow and glacier uncertainties become the dominating contributions. Figure 9 also illustrates that the uncertainty varies seasonally or biannually for most storage compartments. At the same time, TWS exhibits more time-varying uncertainties that are related to GRACE/GRACE-FO mission performance, including repeat orbits, solar activity and system degradation toward the end of the GRACE lifetime. Additional uncertainties in the GWSA estimates that originate from differences between various data sets that could be selected for each storage compartment can be large but are hardly accounted for (Akl and Thomas 2024).

In summary, when separating out the variations of individual water storage compartments from the integral GRACE/-FO-based Level-3 TWSA data, uncertainties of the individual components accumulated in the residual Level-4 signal of interest. This applies to groundwater separation as illustrated above as well as to any other storage compartment such as glacier mass, snow storage or permafrost changes, for instance. While Level-4 data producers are encouraged to propagate the uncertainties to the final product, users can make use of growing uncertainty information for their Level-4 data application at hand. As for Level-3 mass change products, when estimating the uncertainty of a Level-4 GWSA product as area average values for larger regions such as river basins or aquifers from

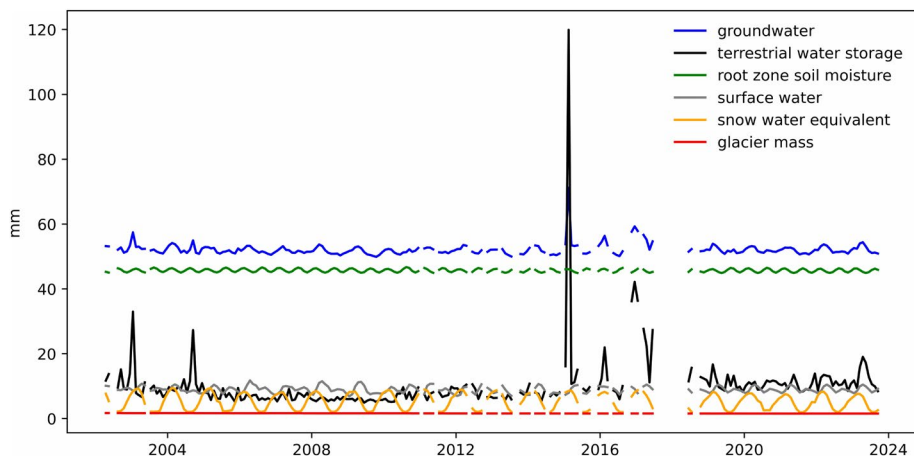


Fig. 9 Uncertainties (in mm EWH) of the individual water storage compartments and the propagated uncertainty groundwater storage anomaly for the Global Gravity-based Groundwater Product (G3P) (Güntner et al. (2026)) as global average monthly time series

gridded data sets, the fact that errors of neighboring grid cells are correlated needs to be accounted for by considering their error covariances (Humphrey et al. 2023).

5.3 Ocean Heat Uptake

Another Level-4 example is the combination of the gravimetry-based barystatic sea level and the altimetry-based sea level to excerpt the ocean heat content and, ultimately, to estimate the Earth's energy imbalance. In this approach, sea level and barystatic sea level are used to compute the changes in the ocean density caused by the heat. This approach complements in situ observations with global and periodic observations. The error propagation includes a rigorous error budget, combining satellite altimetry uncertainties derived from the Level-1 data and from all the corrections applied, as well as the uncertainties from the barystatic sea level (see Fig. 10). The uncertainties of the Global Ocean Heat content (GOHC in the figure) is then derived through the variance–covariance matrix. Furthermore, estimating the uncertainty in Global Ocean Heat Uptake (GOHU in the figure) variance–covariance matrix is done through an ensemble of GOHC created via a Monte Carlo analysis. Current estimates based on JPL Mascons and on the LEGOS/Magellium ensemble approach result in a similar global ocean heat uptake for the period from 2005 to 2019

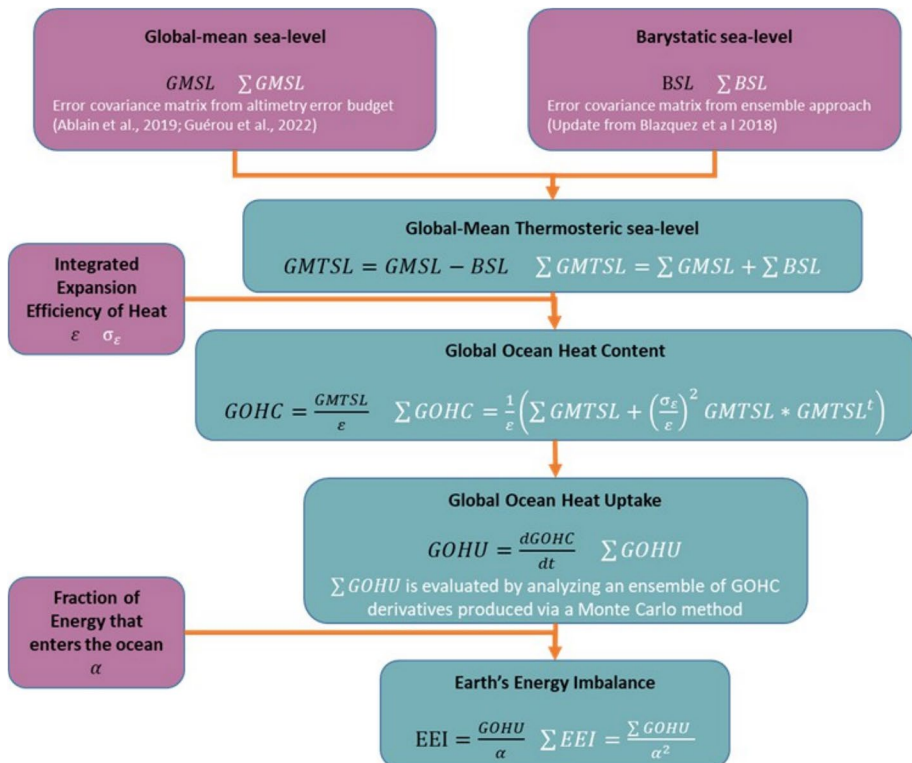


Fig. 10 Propagation of errors from the global mean sea level (GMSL) change and barystatic sea level (BSL) change time series to the global ocean heat content (GOHC) and Earth energy imbalance (EEI) time series. Updated from (Marti et al. 2022)

of $0.88 \pm 0.14 \text{ Wm}^{-2}$ and $0.89 \pm 0.11 \text{ Wm}^{-2}$, respectively (Hakuba et al. 2024; Marti et al. 2022).

6 Conclusions

Important uncertainties in GRACE/GRACE-FO data originate from the raw sensor measurements. For some sensors, particularly the ACCs, actual performance has deviated from the manufacturer's specifications. Sensor measurements undergo calibration, but various environmental disturbances further contribute to the error budget. The preprocessing to produce Level-1B data accounts for these error sources as much as possible. However, filtering during this stage often neglects correlations, leading to overly optimistic uncertainty estimates that are frequently inadequate for propagation to higher-level data processing.

Due to the different observation types contributing to the generation of global gravity field models and the many geophysical background models needed for de-aliasing and signal separation, all contributing with their specific uncertainty budget to the final gravity field coefficients, a formal uncertainty propagation remains insufficient. The problem of uncertainty quantification is aggravated by the along-track observation geometry of the main K-band or LRI inter-satellite range-rate observations and the consequently inhomogeneous observation coverage of the globe, which can exacerbate aliasing by geophysical model errors.

Unless the observation geometry and coverage is improved by the future satellite missions NGGM resp. MAGIC, an empirical error assessment, e.g., based on the study of quiet ocean areas or deserts, where little short-term mass variability is expected, remains the only reliable way of uncertainty assessment for the Level-2 products.

Formal uncertainties of spherical harmonic coefficients propagated to global grids mainly reflect the latitude-dependent density of the satellite ground tracks. The temporal variability of the uncertainties is related to several reasons. First, short orbit repeat periods increase the uncertainties, where the spatial resolution is reduced due to increased ground track spacing (as, e.g., in February 2015). Second, data artifacts caused by satellite problems result in higher uncertainties. And lastly, increased ionosphere activity coupled to the 11-year cycle of solar activity deteriorates the data quality. On the contrary, in the case of mascon solutions, the uncertainties reflect the level of spatial stabilization applied in the solution of the mascons.

In addition to the satellite observation and background model uncertainties that impact the Level-2 products, the Level-3 products rely on further geophysical models to correct for GIA-induced mass trends and seismic/post-seismic deformations. The uncertainties of these corrections may be assessed by the spread of different models, but are commonly ignored in the uncertainty measures provided with the Level-3 products.

A further source of error is signal leakage, which is related to the signal attenuation at satellite altitude and may be aggravated by spatial filtering of the Level-3 products. Leakage is commonly assessed by forward modeling approaches or by comparison of the effect of different filters, but remains a major error source.

The stochastic noise of Level-3 products may be quantified empirically by the study of quiet ocean areas or deserts but this type of error assessment is of limited use when errors in secular signals of geophysical models like GIA are under question.

To derive Level-4 products by merging of the Level-3 products derived mainly from satellite gravimetry with other data sets, the limited spatial and temporal resolution of the

TWS grids is overcome, e.g., by machine learning models. But formal uncertainty propagation is not possible without the analytical relationship between the input and output data of the machine learning models, which is usually unavailable. Uncertainty assessment of the Level-4 products, therefore, relies on statistical methods, which again depend on realistic Level-3 uncertainty information.

When different compartments are accumulated, as is the case for groundwater, often the uncertainties of, e.g., root zone soil moisture by far exceed the TWS uncertainty, thus relaxing the demands on TWS uncertainty modeling.

Since gravity missions have turned out to be a central element of Earth system monitoring, it would be desirable to lift the concept from a still somewhat experimental stage to a fully operational mass change monitoring system as stated by the IUGG Resolution No. 2 on “Sustained Terrestrial Water Storage (TWS) Monitoring by Dedicated Gravity Satellite Constellations” at the 28th IUGG General Assembly. Already the MAGIC constellation is considered to serve as a demonstrator in this respect, and the logical next step on European side would be to adopt gravity missions as a future element of the European Earth Observation program Copernicus in terms of a Sentinel series. Eventually, only long measurement time series of mass change will enable robust climate trend estimates and the separation of anthropogenic contributions to climate change from natural processes. As already discussed, sustained gravity observation from space can also make important contribution to operational services such as drought and flood monitoring and water management. Especially for these operational applications, high temporal resolution is required, which can only be achieved by further extending the constellations even beyond the planned double pair mission MAGIC. In order to be economically feasible, this would also mean to reduce the complexity of future mission designs compared to the current stage, together with at least a certain degree of miniaturization.

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Data Availability The used data sets are declared in the text with proper references.

Code Availability The used open-source codes have been declared in the text.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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Authors and Affiliations

Adrian Jäggi¹  · Andreas Güntner^{2,10}  · Ulrich Meyer¹  · Alejandro Blazquez³  ·
Benedikt Soja⁴  · Frank Flechtner²  · Felix Landerer⁵  · Christoph Dahle²  ·
Christopher McCullough⁵  · Tamara Bandikova⁶  · Torsten Mayer-Gürr⁷  ·
Felix Öhlinger⁷  · Henryk Dobslaw²  · Eva Boergens²  · Junyang Gou⁴  ·
Roland Pail⁸  · Hugo Lecomte⁹  · David Wiese⁵  · Martin Lasser¹  ·
Ehsan Sharifi^{2,11} 

✉ Adrian Jäggi
adrian.jaeggi@unibe.ch

Andreas Güntner
andreas.guentner@gfz.de

Ulrich Meyer
ulrich.meyer@unibe.ch

Alejandro Blazquez
alejandro.blazquez@utoulouse.fr

Benedikt Soja
soja@ethz.ch

Frank Flechtner
frank.flechtner@gfz.de

Felix Landerer
felix.w.landerer@jpl.nasa.gov

Christoph Dahle
dahle@gfz.de

Christopher McCullough
christopher.mccullough@jpl.nasa.gov

Tamara Bandikova
tamara.bandikova@c2sm.ethz.ch

Torsten Mayer-Gürr
mayer-guerr@tugraz.at

Felix Öhlinger
felix.oehlinger@tugraz.at

Henryk Dobslaw
dobslaw@gfz.de

Eva Boergens
boergens@gfz.de

Junyang Gou
jungou@ethz.ch

Roland Pail
roland.pail@tum.de

Hugo Lecomte
hugo.lecomte@nls.fi

David Wiese
david.n.wiese@jpl.nasa.gov

Martin Lasser
martin.lasser@unibe.ch

Ehsan Sharifi
ehsan.sharifi@gfz.de

- ¹ Astronomical Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
- ² GFZ Helmholtz Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
- ³ Université de Toulouse, LEGOS (CNES, CNRS, IRD, UT), 14, Avenue Edouard Belin, 31400 Toulouse, France
- ⁴ Institute of Geodesy and Photogrammetry, ETH Zürich, Robert-Gnehm-Weg 15, 8093 Zurich, Switzerland
- ⁵ Jet Propulsion Laboratory, California Institute of Technology, Oak Grove Drive 4800, Pasadena 91109, USA
- ⁶ Center for Climate Systems Modeling, ETH Zürich, Universitätsstrasse 16, 8092 Zurich, Switzerland
- ⁷ Institut für Geodäsie, Graz University of Technology, Steyrergasse 30/III, 8010 Graz, Austria
- ⁸ School of Engineering and Design, Technische Universität München, Arcisstraße 21, 80333 Munich, Germany
- ⁹ Finnish Geospatial Research Institute, National Land Survey of Finland, Vuorimiehentie 5, 02150 Espoo, Finland
- ¹⁰ Institute of Environmental Science and Geography, University of Potsdam, Karl-Liebknecht-Strasse 24-25, 14476 Potsdam, Germany
- ¹¹ Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT), Wolfgang-Gaede-Straße 1, 76131 Karlsruhe, Germany