GENESIS PHASE A/B1

GENESIS data product
About what can GENESIS bring for science and society

GENESIS VLBI Transmitter

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CHANGE RECORDS

ISSUE V.x.y[1]	DATE (dd/mm/year)	CHANGE RECORDS	Reason for change
V1.1(1) draft	30/07/2024	New document	Following ERC PoC REFERSOC and Julian Mathe Internship.
V1.1(2)	19/11/2024	Changes related to several email exchange and Visio conferences	Adding information gathered from Sylvain Loyer, Anne Barnoud, Paul Rebischung, Leonid Petrov
V1.1(3)	25/11/2024	Improving English	Improving English, avoiding repetitions, and adding some illustrations; also considering geocenter results of Klopotek et al. (2020)
V1.1(4)	28/11/2024	Additional sentences after discussions with H. Sert (ROB) and considering recent results from Schunck et al. (2024)	Clarifying the added value on EOP of using VT in the GENESIS data processing, and insisting on the scheduling effects
V1.1(5)	09/12/2024	In part 3.1, we have added characteristics of the new release of ITRF 3 years after ITRF2020	New release of the ITRF2020 → 2023
V1.1(6)	23/12/2024	In part 3.5, we have added recent results on sea level change	Recent presentations at AGU 2024 on sea level change

[1] Vx.y ==> x = version number, y = issue number

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1. GENERAL INFORMATION

1.1 Scope of the Document

The document aims at evaluating the possibility for the observations of the GENESIS mission to enhance the precision of reference frames and to respond to the society challenges such as determining the mean sea level or the geocenter at 1 mm level and with long-term stability better than 0.1 mm/year.

1.2 Applicable documents

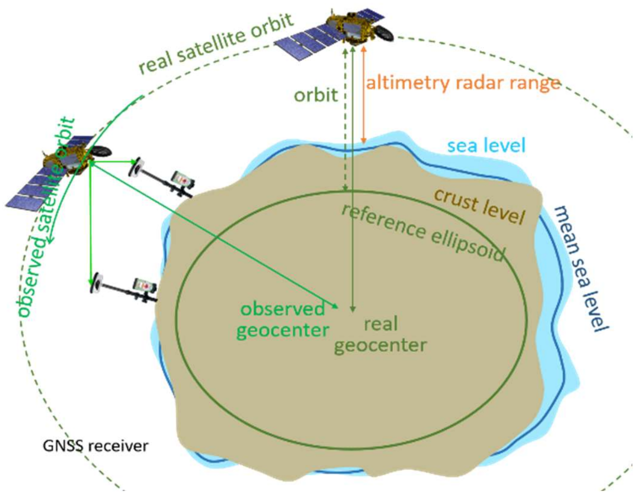
Title	*Reference*
GENESIS-ROB-AA-0001-Abbreviations-Acronyms_v1.1(6) provides the abbreviations and acronyms used in this context.	GENESIS-ROB-AA-0001

1.3 Reference documents

Title	*Reference*
Technical Note for Precise Orbit Determination (POD) for GENESIS	GENESIS-ROB-TN-0001

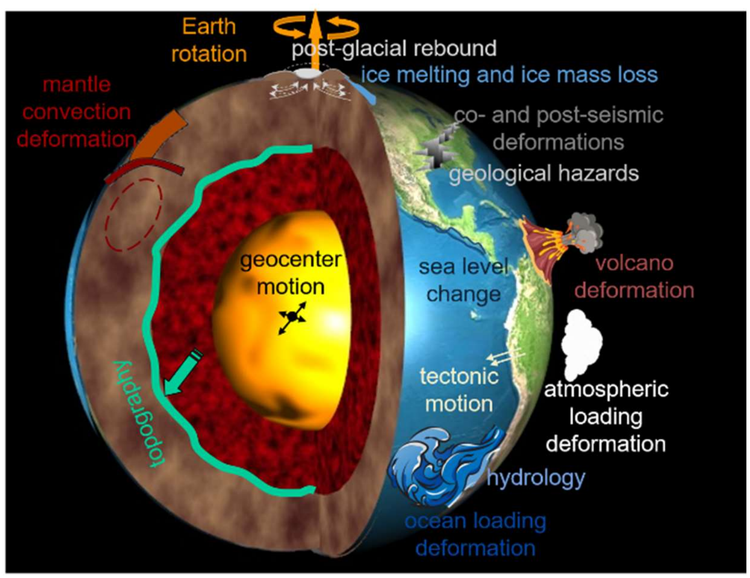
2. MOTIVATION

2.1 Motivation



Satellite altimetry for measuring sea level change. Presently based on the observed satellite orbit and observed geocenter that differ from the real ones.

Improving and homogenizing Earth's reference frames with an accuracy of 1 millimeter (mm) and a long-term stability of 0.1 mm/year are relevant for numerous scientific and societal applications. For instance, quantifying **sea level change** from satellite altimetry strongly depends on an accurate determination of the geocenter motion and the orbits of the satellites (see Figure on the left). Sea level change is also determined from tide gauges that need to be precisely located with respect to continental and island reference stations. Reaching millimeter level accuracy in sea level change needs positioning the satellites and the reference frame with even better accuracy and with a long-term stability of 0.1 mm/year. Numerous other applications in geophysics require also such absolute accuracy. This is the case, for instance, when monitoring **tectonic motions** or **crustal deformations**. It is thus important to reach high accuracy and precision in such observations in order to advance our understanding of the physical processes involved in the Earth dynamics (see Figure on the right), as well as to contribute to a better understanding of **natural hazards**. Reaching such low errors in the measurements is also essential for **positioning and navigation** in the civilian applications and for proper geo-referencing of geospatial information.



All kinds of deformations requiring at least mm-level precision in their observation.

Needs. The reference frame accuracy to be achieved represents the consensus of various authorities, including the International Association of Geodesy (IAG). Moreover, the United Nations Resolution 69/266[2] states that the

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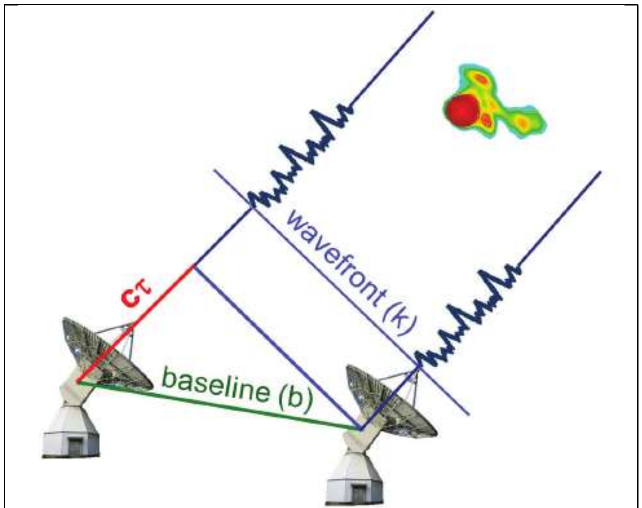
[2] UN resolution 69/266 https://ggim.un.org/documents/A_RES_69_266_E.pdf

full societal benefits in developing satellite missions for positioning, remote sensing, and *in-situ* measurements are realized only if they are referenced to a common global accurate reference frame at the national, regional and global levels. Today we are still far from these ambitious accuracy and stability goals (Delva et al., 2023, and the references therein).

2.2 The problem

The reference frame attached to the Earth, the ITRF (International Terrestrial Reference Frame), is mainly realized and maintained by using GNSS satellites (Global Navigation Satellite System). The positions and velocities of the ground stations are derived from using GNSS satellite orbits that are determined from Earth tracking stations. These orbits, as well as the associated geocenter, have important biases, as they are not directly observed from space. To accurately position them in space, it is necessary to correct for the Earth's rotation and orientation in space.

Very Long Baseline Interferometry (VLBI) is used to determine the Earth rotation parameters. This technique is based on the observation of quasars, which are objects with very stable positions in the sky and emitting in all wavelengths including microwaves. Large antennas on Earth observing them and recording the time correlation of the signal arriving at different stations allows us to determine the evolution of the time delays (see Figure enclosed). Together with physical models, these observations are used to provide critical information about Earth rotation and orientation parameters, which are essential for determining the orbits of GNSS satellite or of any other satellite.

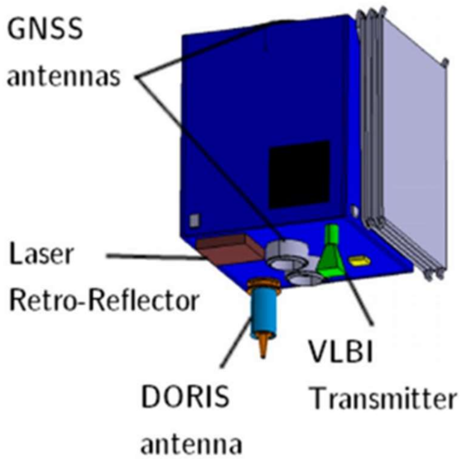


Principle of VLBI observation: The primary observable is the difference (τ) in the arrival times of a plane wavefront emitted by an extragalactic radio source at two VLBI telescopes forming a baseline (b). © Teke et al. (2012)

For that reason and for many other reasons, such as errors in the local ties between the techniques at the ground stations (see more details below in Section 3.1), the ITRF is not determined with the UN-prescribed resolution accuracy.

2.3 The solution

In the future, we will benefit from the ESA GENESIS mission (to be launched in 2028), a spacecraft co-locating four geodesic techniques enabling serving a more precise realization of the reference frames that will meet UN resolution requirements.



Spacecraft GENESIS containing the four geodetic techniques (GNSS, SLR, DORIS and VLBI Transmitter). © ESA

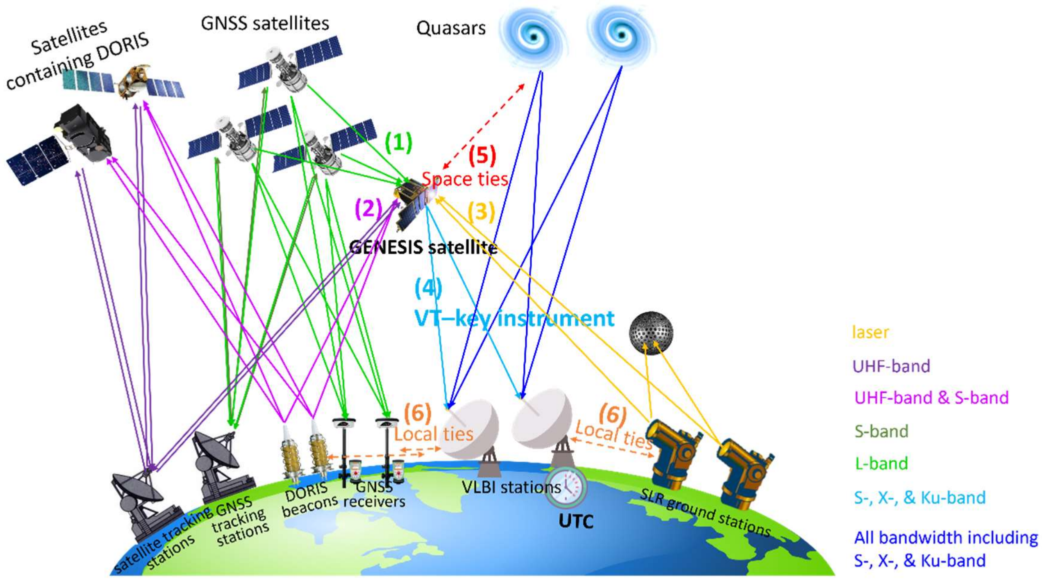
ESA's GENESIS satellite will combine and co-locate the four existing geodetic techniques used for the ITRF on a single platform for the first time (see Figure below). GENESIS will be developed and launched as the first-ever satellite with all four space-based geodetic techniques on-board. In so doing, it will serve to identify and subtract inherent biases within each of these techniques, allowing, in turn, improvements in the accuracy and consistency of the reference frame (ITRF) that is used to organize much of the underlying functions of our civilization as mentioned above.

Conceptually, both the new Earth rotation modeling and the accuracy expectation of GENESIS mission will enable the determination of the geophysical observables with unprecedented accuracy, addressing key societal needs (Delva et al., 2023). The four geodetic techniques are:

- Global Navigation Satellite System (GNSS);
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), a radio satellite tracking system;
- the Satellite Laser Ranging (SLR) technique;
- and the Very Long Baseline Interferometry (VLBI) technique.

In typical operations, VLBI involves capturing signals from quasars. However, GENESIS will include a VLBI "transmitter" (VT), an innovative Belgian instrument that mimics a quasar by emitting noise or pseudo-noise in the same frequency bands observed by the ground-based VLBI stations (primarily the VGOS stations, which have a rapid slew able to follow the satellites).

As outlined earlier, there are numerous innovative applications that benefit from improved Earth rotation modeling, orientation data, and reference frame accuracy. The GENESIS mission aims to refine reference frames to an accuracy of 1 mm and a long-term stability of 0.1 mm/year. By co-locating four space geodetic techniques (namely GNSS, SLR, DORIS, and VLBI) on one satellite platform, the mission will create direct space ties between the techniques (see the Figure below). The GENESIS platform will function as a dynamic space geodetic observatory, where all instruments are precisely referenced to each other through carefully calibrated space ties. This co-location in space aims to resolve inconsistencies and biases among the techniques, achieving the accuracy and stability targets set by international scientific bodies and authorities.



GENESIS satellite and all the geodetic techniques (together with the frequency bands involved).

3. STATE-OF-THE-ART

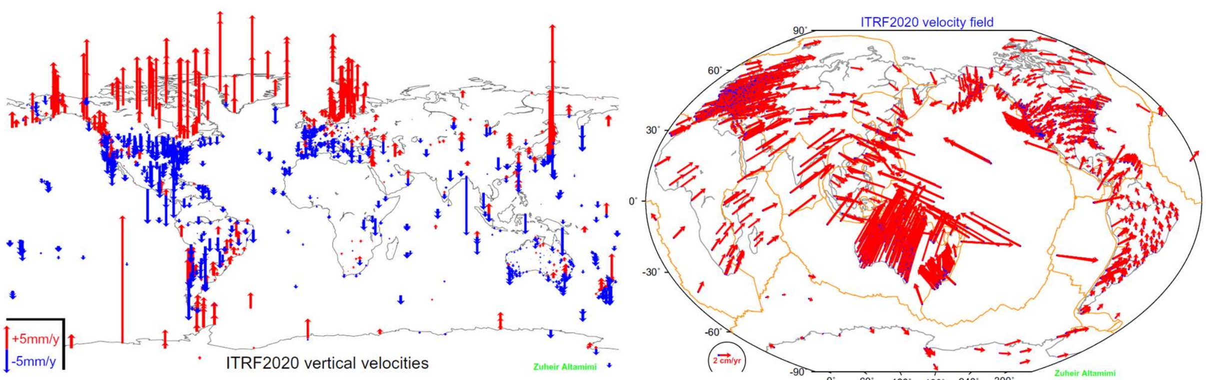
3.1 ITRF, its Center of mass and its scale

Today, the TRF is realized by station positions and velocities of a globally distributed network of ground stations. This is accomplished through a combination of the four major space geodetic techniques mentioned earlier. In practice, the TRF consists of a **set of coordinates and velocities of reference points** on Earth's surface, whose positions are precisely measured over time. These points create a realization of the terrestrial reference system, allowing not only for the relation between geodetic measurements from different stations but also linking these measurements over space and time. Since Earth's **tectonic plates** are constantly moving, both horizontally and vertically, the **TRF must be updated regularly**, typically every five to six years. These updates are called ITRFxxxx, where xxxx represents the date of the realization.

To create a unique, consistent and accurate TRF, the four techniques are combined and linked using **co-location sites** located on the ground, i.e. sites where multiple space geodetic techniques operate simultaneously. These stations have also topometrically measured **local ties** between the techniques, which are utilized in ITRF calculations. The global distribution of co-location sites remains nevertheless sparse. Almost all SLR and VLBI stations, and about two-thirds of the DORIS stations are co-located with GNSS. However, only 32% to 50% of these co-location sites (with time spans of more than three years) show agreement between the terrestrial tie vector and the difference between the station positions estimated from each space geodetic independently, to better than 5 mm to 1 cm in all three components (Delva et al., 2023). This significantly impacts the accuracy of the ITRF (Altamimi et al., 2023).

Note that a new promising technique to measure the ties uses small-baseline GNSS interferometry near VLBI ground station. Skeens et al. (2023) designed a radio interferometer consisting of a GNSS antenna and a VLBI radio telescope. This approach can achieve sub-millimeter accuracy, provided modeling errors for the radio telescopes are kept minimal during experiments.

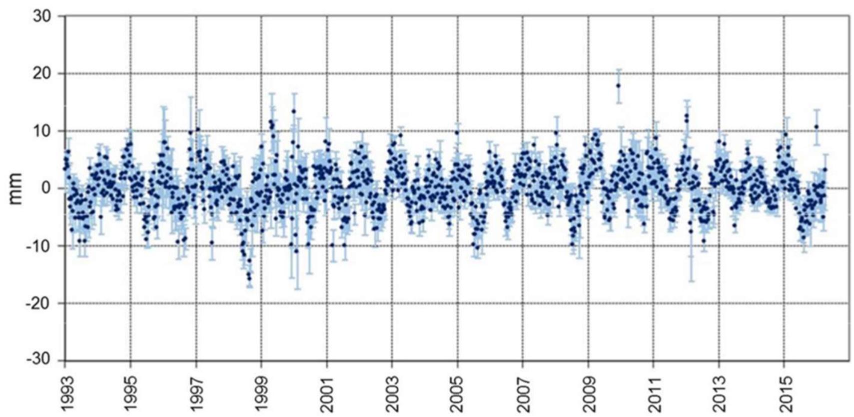
All TRF realizations include **station positions and velocities**, modeling the long-term changes in Earth's crust due to plate tectonics. Efforts are made to ensure continuity between successive TRF realizations by adopting consistent conventions for ITRF definitions. For example, the ITRF2020 site velocities, with formal errors less than 1 mm/year, are visualized in the Figure below from Altamimi et al. (2023). Their analysis shows that the horizontal components standard deviations are approximately 0.7 mm/year for VLBI and SLR and 1.2 mm/year for DORIS. The standard deviation values for the vertical components range from 1.3 mm/year to 1.6 mm/year for the three techniques (VLBI, SLR, DORIS), compared with GNSS. Because of the number and repartition of their stations, the DORIS and GNSS techniques play a crucial role in constraining the rotation coefficients that are associated with tectonic motions.



Vertical (left) and horizontal (right) ITRF2020 site velocities. © Altamimi et al. (2023)

The ITRF is anchored at the **Center of Mass (CM)** for long-term periods, and at the **Center of Figure (CF)** otherwise (CM and CF definitions are provided in Section 3.2). The **long-term origin of the ITRF** is defined solely by SLR input data from the ILRS (International Laser Ranging Service) and satisfies the conditions of no translation and no translation rate between the ITRF and the SLR long-term frame. This method has been applied for the ITRF2020 (Altamimi et al., 2023), which provides seasonal signals in the CM or in the CF (see Section 3.2). For instance, the origin of the ITRF2020 expressed in the CF frame shows seasonal signals and is defined in such a way that the weighted sum of the seasonal signals of a selected subset of stations (approximating an integral over the Earth's surface) is zero. In practice, the ITRF2020 origin is established with zero translation parameters at epoch 2015.0 and zero translation rates between the ITRF2020 and the ILRS (International Laser Ranging Service) SLR long-term frame over the timespan 1993.0-2021.0, using the concept of internal constraints in the computation. The origin of the ITRF2020 seasonal signals expressed in the CM (as sensed by SLR) frame are defined in such a way that there is no seasonal translation between the ITRF2020 seasonal signals and the input SLR solutions over the timespan 1993.0-2021.0, using the concept of internal constraints.

One way to assess the accuracy and performance of the ITRF2020 origin is to estimate the translation components with respect to past ITRF solutions, namely ITRF2014, ITRF2008 and ITRF2005 whose origins were also defined by SLR data series (Altamimi et al., 2007, 2011, 2016). Differences range between -1.4 mm and 3.3 mm for the translations at epoch 2015.0, and between −0.1 mm/year and 0.3 mm/year for the translation rates. These variations are thus generally within a little bit more than 3 mm range and 0.3 mm/year for stability. To adopt a more conservative approach, they are at the level of or better than 5 mm and 0.5 mm/year. In other words, the origins of the successive ITRF solutions stand roughly within a sphere of 5 mm in diameter and 0.5 mm/year for their time variation. Current precision for geocenter or satellite absolute positioning is around 1 to 2 cm for a single measurement, improving to 4 mm after a week's observation, as noted from the Figure below from Delva et al. (2023). It is mainly based on the SLR-derived geocenter motion as explained also in Section 3.2.



SLR-derived geocenter motion, X component (ILRSA combined solution, ASI/CGS). © Delva et al. (2023).

The scale of a reference frame is counted in part per billion (ppb), where 1 ppb equals 10^{-9} in the TRF scale, translating to a 6.4 mm height offset for all stations. The ITRF **long-term scale** is an average of the SLR and VLBI intrinsic scales. It is defined to have no scale factor or scale factor rate with respect to the mean of VLBI and SLR long-term solutions obtained by stacking their respective time series. However, SLR and VLBI are subject to systematic biases that affect scale measurements, such as range biases for SLR stations and unknown antenna deformations for VLBI. Given the limited number of co-located SLR-VLBI stations and the absence of a common satellite, assessing the agreement between the SLR and VLBI scales is challenging. For instance, Altamimi et al. (2023) observed unexpected VLBI scale drift post-2014 and an SLR scale offset before 1997.75. These anomalies remain under investigation by the IVS (International VLBI Service) and ILRS.

On this topic and in a complementary way, studies by Thaller et al. (2011, 2017) have demonstrated that the SLR-based scale can be well transferred to the GNSS network, if a satellite is used as co-location platform. In these studies, the GNSS satellites tracked by SLR were employed as co-location platforms, however, being limited to GNSS and SLR only.

In summary, for the ITRF2020, the SLR constrains the center of mass (see Section 3.2), VLBI (mainly) and SLR constrain the scale factor, and DORIS and GNSS mainly the rotation coefficients related to tectonic motions.

The strategy adopted for generating ITRF2020 consists in rigorously **stacking** the **time series** of solutions from the **four space geodetic techniques all together**, adding **local ties** and ensuring consistent station velocities and seasonal signals at co-location sites. To that end, intermediate steps (see ITRF IGN website, https://itrf.ign.fr/en/solutions/itrf2020) were applied in order to identify and reject outliers and properly assign and handle discontinuities and post-seismic deformation models for stations subject to major earthquakes.
The key intermediate steps prior to the overall ITRF2020 combination include:

- Apply minimum constraints to all loosely constrained solutions (meaning broad enough to efficiently evaluate the parameters);
- Implementing No-Net-Translation and No-Net-Rotation constraints to IVS solutions in the form of normal equations (requiring no-net-translation/rotation of the lithosphere while constraining relative plate velocities to equal those in global plate motion model NUVEL-1, a kinematic model of rigid tectonic plates derived from geophysical observations over millions of years, considering non-rigid surface deformations, e.g., in seismic zones);
- Using minimally constrained solutions as they are for IGS (International GNSS Service) daily and IDS (International DORIS Service) weekly solutions;
- Correcting for post-seismic deformation using GNSS/IGS data for earthquake sites;
- Forming long-term solutions per technique by stacking time series and solving for the TRF station positions and velocities, the Earth Orientation Parameter (EOP), and 7 transformation parameters (translation, rotation and scale) for each technique. In addition, the process estimates annual and semi-annual signals for stations with sufficient time-spans, as well as, for the particular case of IGS time series, periodic signals at the first 8 GPS draconic[3] harmonics.

After applying all these steps, Altamimi et al. (2023) analyzed the translational origin components between ITRF2020 and past ITRF versions (ITRF2005, ITRF2008, and ITRF2014) and found that the current accuracy and stability of the ITRF long-term origin using SLR data stands at or is better than **5 mm in position** and **0.5 mm/year in stability**, as mentioned previously. Weighting the SLR and VLBI scale time series, Altamimi et al. (2023) ended with a **scale agreement at the**

[3] The nodal period (or draconic period) of a satellite T_n is the time interval between successive passages of the satellite through either of its orbital nodes, typically the ascending node. It is distinct from the sidereal period, which measures the period with respect to reference stars seemingly fixed onto a spherical background, since the location of a satellite's nodes precess over time. The oblate figure of the Earth has important effects of the orbits of near-Earth satellites.[6] An expression for the nodal period (Tn) of a near circular orbit, such that the eccentricity (ε) is almost but not equal to zero, is the following:

$$T_n = \frac{2\pi a^{\frac{3}{2}}}{G^2}\left(1 - \frac{3J_2(4-5\sin^2 i)}{4\left(\frac{a}{R}\right)^2\sqrt{1-\varepsilon^2}\,(1+\varepsilon\cos\Omega)^2} - \frac{3J_2(1+\varepsilon\cos\Omega)^3}{2\left(\frac{a}{R}\right)^2(1-\varepsilon^2)^3}\right)$$

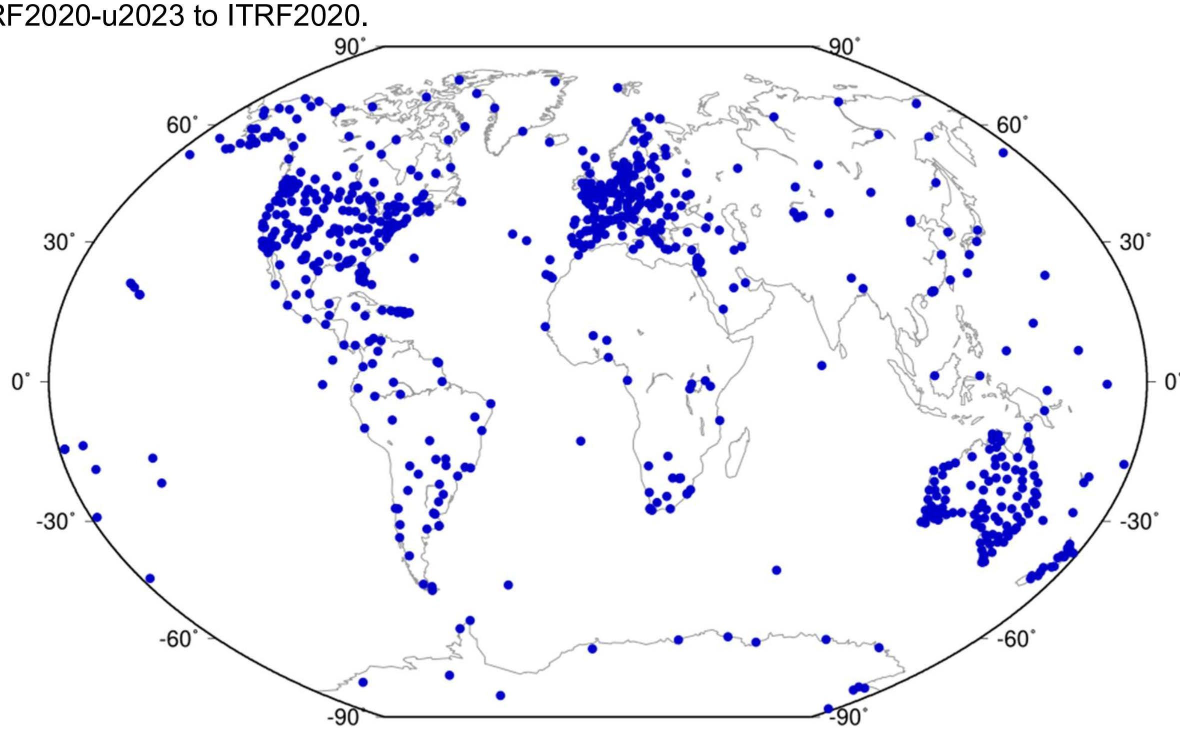
where a is the semi-major axis, G is the gravitational constant, J_2 is a perturbation factor due to the oblateness of the Earth, i is the inclination, R is the radius of the Earth and Ω is the argument of the perigee.

level of 0.15 ppb (corresponding to about 1 mm at the equator) at epoch 2015.0, with no significant rate.

In 2024, Altamimi et al. (IERS message, https://itrf.ign.fr/en/solutions/ITRF2020-u2023) have computed a new solution, ITRF2020-u2023 solution, the first ITRF2020 update, generated by adding three years (2021.0-2024.0) of data after the end of the ITRF2020 input data. The ITRF2020-u2023 web site contains the most important results and information regarding the ITRF2020-u2023 combination. It will be updated regularly to add more details and results useful to the ITRF users. This release was motivated by reasons including

- the stability of the ITRF long-term origin, evaluated to be at the level of or better than 5 mm and 0.5 mm/yr for its time evolution,
- the agreement in scale between VLBI and SLR, at the level of 1-2 mm, with no drift,
- the growth of extrapolation errors of the ITRF2020 coordinates beyond the end of the ITRF2020 input data,
- changes in the positions of certain ITRF2020 stations (due to, e.g., earthquakes and equipment changes) that occurred after the end of the ITRF2020 input data.

The computation strategy of ITRF2020-u2023 is identical to that of ITRF2020 (see here above and https://itrf.ign.fr/en/solutions/itrf2020#computation-strategy). For instance, ITRF2020-u2023 is aligned in origin, scale and orientation to ITRF2020 by means of no-net-translation, no-net-scale and no-net-rotation constraints. These constraints were applied to both the ITRF2020-u2023 long-term linear station coordinates and seasonal station motions. A reference network of 815 stations (see Figure below), whose linear coordinates and seasonal motions were hardly affected by the addition of three more years of input data, was used for the alignment of ITRF2020-u2023 to ITRF2020.



Reference stations used for the alignment of ITRF2020-u2023 to ITRF2020.

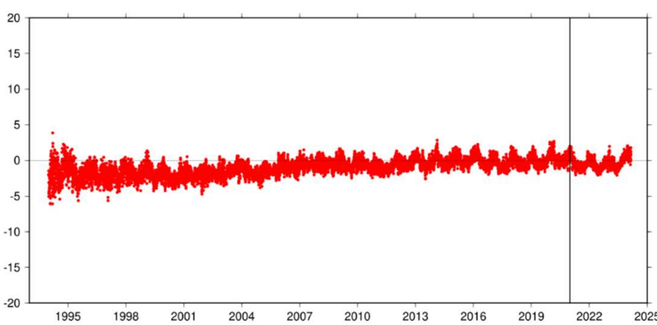
The alignment of ITRF2020-u2023 to ITRF2020 implies that there is no Helmert transformation between the two solutions, i.e., all transformation parameters between ITRF2020-u2023 and ITRF2020 are zero. Unlike individual seasonal station motions, the ITRF2020 seasonal geocenter motion model was not updated with ITRF2020-u2023. The table below contains the parameters of the ITRF2020 seasonal geocenter motion model. The sign and phase conventions used are such that the seasonal motion of the Earth's CF with respect to the Earth's CM, along any X, Y, Z axis, is obtained by:

$$A_1 \cos\left(2\pi t - \frac{\pi}{180}\varphi_1\right) + A_2 \cos\left(4\pi t - \frac{\pi}{180}\varphi_2\right)$$

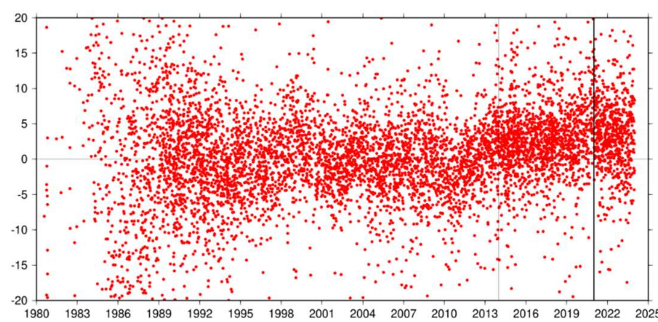
where A_1 is the annual amplitude, φ_1 the annual phase, A_2 the semi-annual amplitude, and φ_2 the semi-annual phase, all given in the table below.

	Amplitude (mm)	Phase (Degrees)
Annual X	1.23 ± 0.16	-123.2 ± 7.2
Annual Y	3.48 ± 0.15	152.9 ± 2.5
Annual Z	2.76 ± 0.33	-139.5 ± 6.8
Semi-annual X	0.49 ± 0.15	107.2 ± 18.1
Semi-annual Y	0.22 ± 0.15	1.6 ± 39.0
Semi-annual Z	1.19 ± 0.33	30.5 ± 15.5

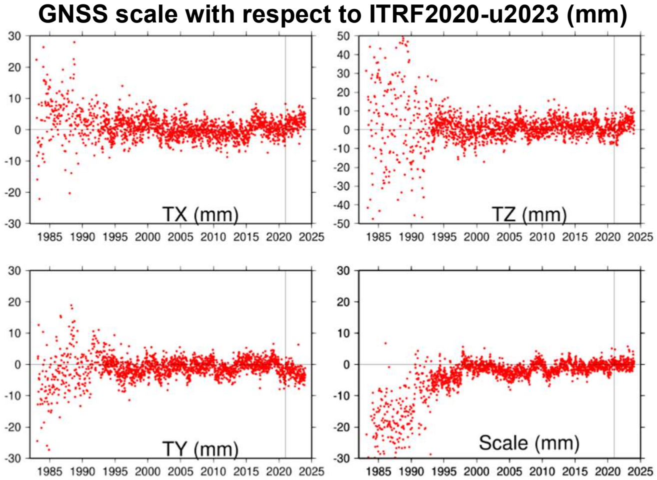
The different scales with respect to ITRF2020-u2023 are shown in the Figure below.



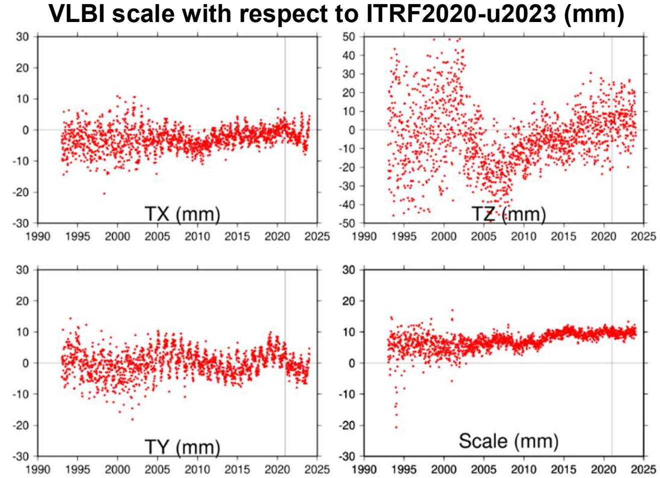
GNSS scale with respect to ITRF2020-u2023 (mm)



VLBI scale with respect to ITRF2020-u2023 (mm)



SLR scale and geocenter with respect to ITRF2020-u2023 (mm)



DORIS scale and geocenter with respect to ITRF2020-u2023 (mm)

Further improvement in the TRF (as well as in the Celestial Reference frame (CRF)) could result from better atmospheric corrections. The current models use zenith path delay and its gradient, capturing limited atmospheric details (see e.g., Davis et al., 1991). Temporal variations in VLBI residuals correlate with atmospheric conditions, suggesting that residual noise is not purely random. For VLBI, the background noise is still at 70 microarcsecond (μas) in right ascension and 120 μas in declination, which is 1.5 to 3 times the instrumental noise. The only way to improve that is to use a precise Water Vapor Radiometer (WVR) or a cluster of GNSS around the VLBI station. For ITRF2020, these errors are absorbed by adding **range biases** independent of the epoch of observation and measurement conditions. According to L. Petrov (personal communication, 2024), the uncertainties in scale and CM from different techniques are largely due to atmospheric errors, which first manifest in spherical harmonics of degree 0 and 1. Petrov also mentions that, to improve this, a highly precise WVR or a cluster of GNSS stations around VLBI or other geodetic stations would be needed.

One other way to further improve the TRF is to improve the orbits of the satellite used by using space ties. As discussed in Sections 4.10 and 4.9, combinations of the different geodetic methods have been performed on the Jason-2 and Sentinel-6 satellites, which however do not contain a VLBI Transponder (VT). Orbits have been determined at the centimeter level. Simulations including a VT, like on E-GRASP (see Biancale et al., 2017; and see Section 4.11) or GENESIS (see Delva et al., 2023; and see Section 0), show that the orbit can be determined at better than the cm, but is not yet at the millimeter level (Ait-Lakbir et al., 2024).

Future strategies should also aim to integrate data holistically, without relying solely on individual solutions. Parameters like CM or scales should be derived using combined data, not only SLR data. Furthermore, when working on all the data together, the strategy should free more parameters including the orbits of the GPS and Galileo for instance.

Currently, ground station **tie accuracy** is limited to the centimeter level. There are **scale** and **CM biases** between the realizations of reference frames by the four different geodetic techniques at the level of a few mm. The TRF origin (CM) accuracy is at the level of **3 mm**, its stability at **0.3 mm/year**, and the scale accuracy is at the level of **0.15 ppb**, with a stability of **0.02 ppb/year**. SLR constrains the CM of the ITRF, while VLBI (mainly) and SLR constrain the scale factor. Doris and GNSS (mainly) and VLBI constrain the rotation coefficients. The GENESIS aims to enhance these measurements by providing **space ties** in addition to the local ties, with goals of 1 mm accuracy and 0.1 mm/year stability for the origin and 0.10 ppb for scale, with a stability of 0.01 ppb/year. The objectives of the geodetic scientific community are, for the origin accuracy, 1 mm, with a stability at 0.1 mm/year and the scale accuracy, 0.10 ppb, with a stability of 0.01 ppb/year.
Significant effort is needed to refine atmospheric corrections and to combine data in an integrated manner, moving away from isolated solutions. Parameters like CM or scales must be determined using all the data together, not only SLR data. The strategy should free more parameters including the orbits of the GPS and Galileo for instance.

3.2 Geocenter

These first paragraphs are largely based on Wu et al. (2012).

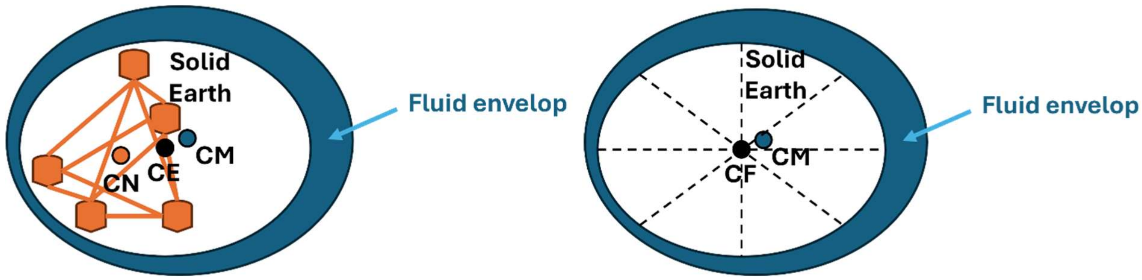
The **center-of-mass (CM)** of the total Earth system, which includes the solid Earth and its fluid envelope, is commonly referred to as the **geocenter** (Petit and Luzum, 2010). The geocenter is crucial for describing Earth's motion in inertial space and serves as the orbital center for all Earth satellites. The term "**geocenter motion**" refers to the movement of the CM relative to the **center of figure (CF)** of the solid Earth (e.g., Ray, 1999). In practice, it is the solid Earth (with its CF origin) that moves within the reference frame when the origin is defined at the CM.

Understanding geocenter motion is essential for interpreting and applying the ITRF. Because the ITRF is derived from a combination of all space geodetic solutions, its definition and realization are intimately linked to the geocenter and its movement relative to the surface of the Earth. The ITRF's origin of coordinates is theoretically defined as the long-term mean CM rather than as any quasi-instantaneous CM (e.g., Dong et al., 2003; Wu et al., 2012; Meindl et al., 2013). Consequently, the **origin** of the ITRF (Altamimi et al., 2007, 2011, 2016, 2023) is a **long-term average of satellite CM realizations**. This means that any geodetic tracking system having its coordinates origin fixed at the origin of the ITRF requires **corrections for instantaneous geocenter motions** unless they are explicitly estimated through degree-1 gravitational field coefficients. Independently determined geocenter motion time series can be adjusted in various geodetic coordinate time series and combined, providing ultimately a globally unified displacement time series in the instantaneous CM frame.

Geocenter motion is driven by global mass redistribution processes such as sea level rise, atmospheric and ocean circulation, present-day ice mass imbalance, continental hydrology, ocean tides, glacial isostatic adjustment (GIA), and geodynamic processes of the Earth's core and mantle. These phenomena are often characterized by degree-1 gravitational potential, resulting from surface or internal loads in the spherical harmonic domain (Greff-Lefftz and Legros, 1997). The response of the solid Earth to loading varies with time scales:

- On short-term (sub-daily to decadal), the Earth behaves elastically, adapting to loads.
- On Long-term (1,000 to 1,000,000 years), the Earth exhibits viscoelastic properties, behaving more like a linear Maxwell viscoelastic body.

Although the magnitudes of geocenter motion are generally small (about 1 cm due to diurnal and semi-diurnal ocean tides, a few millimeters from non-tidal annual water and atmospheric mass shifts, and less than 1 mm/year on a secular scale) reliable estimates remain challenging due to limited uncertainty assessments. While geocenter motion can be directly observed by tracking satellites orbiting around the CM, the accuracy needed to detect such mm movements is highly demanding due to stringent precision and consistency requirements in the tracking data and due to the imperfections in the dynamic modeling of geodetic systems. The requirement for millimeter precision in many applications of geodetic observations means that the effect of geocenter motion can no longer be ignored.



Simplified illustration of the different reference frames used in geodesy. The Black solid circle on the lefthand side represents the center of mass of the solid Earth (CE) while the dark blue solid circle represents the center of mass of the total Earth (CM), being the solid Earth plus the surface mass system in the fluid envelope. The center of network (CN, orange solid circle) is different from both CE and CM. On the righthand side, we show the theoretical situation of having geodetic sites evenly spaced over the Earth's entire surface for which the center of figure CF = CE.
Adapted from © Wu et al. (2012).

Given the finite number of sites in a geodetic network, the incremental (geometric) **center of network (CN)** is sometimes used to describe the network's translational motion (see the above Figure).

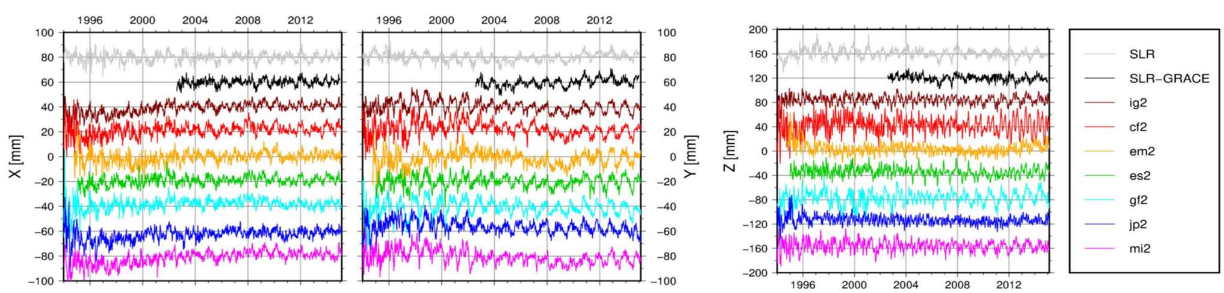
External forces, such as solar heating, drive the horizontal redistribution of continental water, oceanic, and atmospheric masses at the Earth's surface. These mass redistributions cause significant seasonal and interannual geocenter motion with amplitudes of a few millimeters. Snow and continental water are important contributors to this geocenter motion, followed by atmospheric and oceanic influences. There is a distinct annual cycle in the pattern of hemispheric water mass exchange, with the northern hemisphere having more mass during the northern hemisphere winter. Contributions from continental hydrology, oceans, and the atmosphere have been explored using geophysical models (e.g., Collilieux et al., 2009).
Horizontal transport of water in Earth's surface layer, including sea level change, deglaciation, and surface runoff, results from numerous geophysical processes like ocean and atmosphere circulation, climate change, and the hydrological cycle, all occurring on varying spatial and temporal scales. The largest atmospheric mass variations occur mostly at synoptic wavelengths (associated with weather patterns) and at seasonal time scales. The longest wavelength component of surface mass transport, the spherical harmonic degree-1, involving mass exchange between the northern and southern hemispheres, causes loading deformation of the solid Earth and induces geocenter motion between the CM of the total Earth system and the CF of the solid Earth's surface.

One of the most significant historical mass transports was the melting of the late-Pleistocene continental glaciers, which covered large parts of North America, Fennoscandia, and parts of Antarctica and Greenland. This event has caused an eustatic sea level rise (increase in the volume of water in the world's oceans) of about 120 meters over the past 21,000 years. The resulting GIA continues to influence the geocenter motion, currently less than 1 mm/year (Greff-Lefftz, 2000). Despite being informed by multiple datasets, GIA models rely on forward-fitting methods, which can introduce errors and lack comprehensive uncertainty assessments.

From all this, it is evident that geocenter motion is intimately related to the realization of the ITRF origin and plays a significant role in global change monitoring.

The **origin of the ITRF**, currently realized using **SLR data** only, is anchored at this **long-term mean CM**. Cloud-free SLR observations are based on satellites such as LAGEOS-1 (launched May 1976 at altitude 5850 km), LAGEOS-2 (October 1992 at 5625 km), Etalon 1 (January 1989 at 19,105 km), and Etalon 2 (May 1989 at 19,135 km), with near-circular orbits having inclinations of 109.84◦, 52.64◦, 65.3◦, and 65.2◦, respectively (see http://ilrs.gsfc.nasa.gov/). The SLR tracking network comprises over 40 active, permanent ground stations, predominantly located between +60.2° and -36.8° latitudes. With a concentration of sites in Europe and East Asia, the sparse distribution in the southern hemisphere presents **challenges** for accurately determining axial geocenter motions.

The accuracy and stability of the ITRF origin are directly tied to the **performance** of geodetic systems (**SLR, GNSS, DORIS**) in **measuring geocenter motion**. Achieving the target of 0.1 mm/year stability for global change monitoring requires enhancements in tracking precision, network geometry, data consistency, and modeling strategies. Although observing technology has advanced as well as models for data corrections, constraining instantaneous geocenter motion remains difficult. Nonetheless, modeling seasonal and longer-term geocenter movements shows promise.
For example, the Figure below, which is Figure 1 of Ma et al. (2020), shows time series of movement of the geocenter as seen in the solutions of different analysis centers having contributed to the 2nd IGS data reprocessing campaign (repro2).



Geocenter coordinates time series. Offsets of -20, 20 or -40, 40 mm have been added for clarity in the X, Y and Z directions. © Ma et al. (2020)

Name	Data span	Sampling	Data source
ig2	1994/01–2015/02	Daily	International GNSS Service; Rebischung et al. (2016)
cf2	1994/01–2015/02	Daily	Center for Orbit Determination in Europe; Steigenberger et al. (2014)
em2	1994/10–2015/02	Daily	Natural Resources Canada; Donahue et al. (2014)
es2	1995/01-2015/02	Daily	European Space Operations Center; Springer et al. (2014)
gf2	1994/01–2015/02	Daily	GeoForschungsZentrum; Deng et al. (2014)
jp2	1994/01–2015/02	Daily	Jet Propulsion Laboratory; Desai et al. (2014)
mi2	1994/01–2015/02	Daily	Massachusetts Institute of Technology
SLR	1994/01–2014/12	Weekly	Altamimi et al. (2016)
SLR–GRACE	2002/08–2014/12	Weekly	Altamimi et al. (2016); Lemoine et al. (2013)

The accurate determination of the CM, including its temporal motion (related to mass redistribution), is still a challenge due to **systematic biases** within each measurement technique. These biases propagate through the TRF, influencing CM determination. The ITRF2020, released in 2022 and published in 2023 (Altamimi et al., 2023), illustrates the complexities involved in ensuring accuracy. Each satellite technique (SLR, GNSS, DORIS) estimates station positions (daily or weekly) relative to the "instantaneous" CM, based on the fundamental equations of dynamics solved arc by arc in a (quasi-)inertial frame. While satellite orbits should, in theory, have CM as their origin, in practice, this remains complex. Unlike other techniques, VLBI is purely geometric and does not directly relate to the Earth's gravitational field or CM.
SLR is considered the most reliable for defining the ITRF origin, as it accurately senses the Earth's CM. This technique offers two key advantages for CM localization:

- It is an optical round-trip measurement system, **eliminating the need** to estimate **clock shifts** and **tropospheric delays**, resulting in improved CM observability (Rebischung et al., 2014; Section 6).
- Geodetic SLR satellites, such as LAGEOS and Etalon, are dense spheres, **minimizing the impact of non-gravitational forces**.

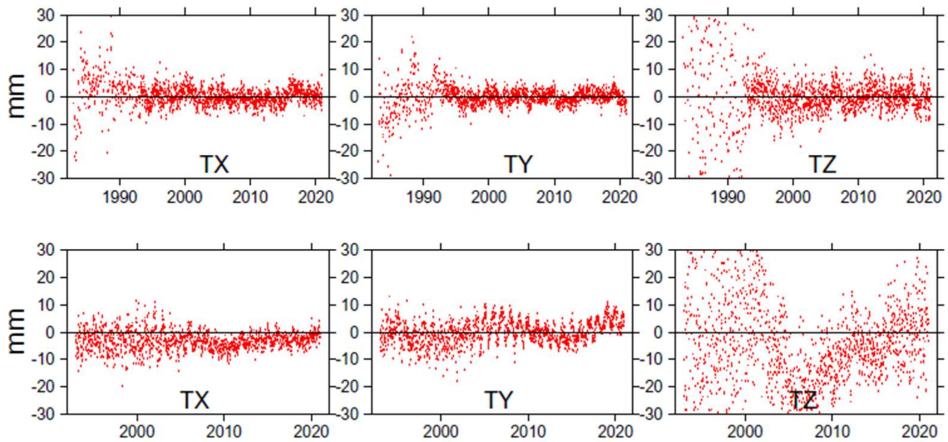
Consequently, the ITRF2020 origin is based on **CM as observed by SLR**, particularly at long-term annual and semi-annual frequencies. Observations from GNSS and DORIS, which are often labeled "apparent" geocenters, are excluded from defining the CM due to their inconsistencies.

Nevertheless, SLR data is sensitive to **observational biases** such as range errors and network inconsistencies, which can distort measurements. Recent efforts by ILRS have improved handling and estimation of station-dependent biases (Luceri et al., 2019), significantly impacting the SLR scale by up to 1 ppb (about 6 mm at the equator) (Appleby et al., 2016). In practice, one estimates range biases, which does not only compensate for ranging instrument errors, but also absorb the modeling errors such as satellite center of mass offsets, orbit force model deficiencies (see GENESIS TN 1 for explanation on why these are important), or unmodelled tropospheric delay.

The GNSS satellite orbit has a **draconic period** close to the annual frequency, which complicates the **separation of geophysical signals** from systematic errors. **GNSS-based geocenter motions** are often noisy and inconsistent, with noticeable systematic errors, including those tied to the harmonics of the GPS draconic year (~351.5 days) (Ray et al., 2008). These inaccuracies are also linked to factors such as **clock offsets**, **non-gravitational forces on the spacecraft** (e.g., solar radiation pressure), and **unmodelled tropospheric delays** (Hugentobler et al., 2006;

Rodriguez-Solano et al., 2014; Rebischung et al., 2014, 2016). Although recent GNSS data reprocessing (repro3) has improved pressure modeling for solar radiation, reliable CM determination remains elusive (Rebischung et al., 2024).

DORIS faces similar challenges, with errors even more pronounced than GNSS (e.g., Couhert et al., 2018). Analysis by Altamimi et al. (2023) highlights significant translation discrepancies between DORIS solutions and the ITRF2020 (see their Figure 8).



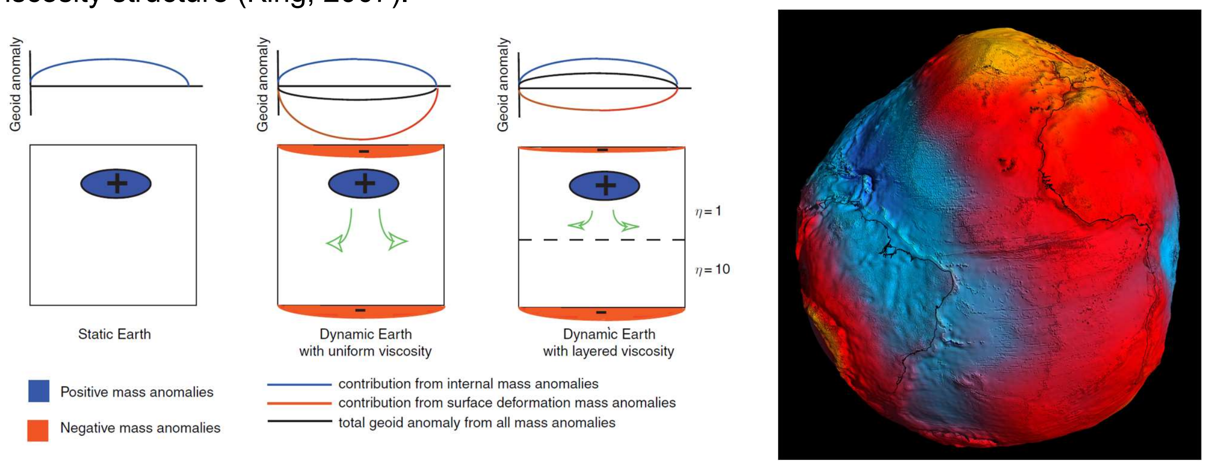
Top Figure, geocenter coordinates time series of SLR and bottom Figure, time series of DORIS. © Altamimi et al. (2023)

VLBI, which relies on distant celestial sources, is unaffected by the Earth's translation and cannot determine station positions relative to a specific origin. Therefore, VLBI data requires constraints of no-net-translation relative to the ITRF to express station positions conventionally.

The **center-of-mass (CM)** of the entire Earth system, known as the **geocenter**, moves relative to the **center of figure (CF)** of the solid Earth. The origin of the ITRF is a **long-term average of satellite CM** realizations, primarily derived from SLR observations. **Corrections for instantaneous geocenter motions** are necessary for any geodetic system tied to the ITRF. The **origin of the ITRF** is currently realized using the long-term mean CM from **SLR data**. The CM's temporal movement is linked to mass shifts and is challenging to measure accurately due to systematic biases. **GNSS**, in particular, exhibits errors related to the GPS **draconic year** (~351.5 days), complicating the separation of annual mass variations. Additional sources of noise may include **clock offsets**, **non-gravitational forces** acting on satellites (like solar radiation pressure), and inaccuracies in modeling **tropospheric delays**.

3.3 Gravity field

The **geoid** is a representation of Earth's gravity field with respect to a reference ellipsoid. Gravity is not uniform across the planet, and the Earth's gravitational force it exerts varies with changes in mass distribution. These uneven mass distributions influence satellite trajectories, as areas with higher mass exert a stronger gravitational pull than areas with lower mass. If tides and ocean currents (the dynamic ocean surface topography) were removed, Earth's mean sea level would have an undulating shape, with "hills" where mass concentrations are higher (left Figure below), causing strong gravity, and "valleys" where mass concentrations are lower, causing weaker gravity. This irregular shape is known as the geoid. With a layered viscosity increase with depth (third representation in the left Figure below), the amount of surface deformation from the same positive mass anomaly is reduced, and the resulting anomaly can change sign depending on the viscosity structure (King, 2007).



Left: Schematic representation of geoid anomalies over a positive mass anomaly for a static (first), isoviscous (center), and layered viscosity (third) mantle. The blue line is the component of the anomaly due to the internal mass; the red line is the component of the anomaly due to the surface deformation; and the black line is the sum of the components. © King (2007).
Right: Geoid from ESA's GOCE mission. © ESA

Orbiting satellites can precisely measure how Earth's mass is distributed below them. Models of **Earth's gravity field** are primarily based on data from the joint NASA/German Aerospace Center (DLR) Gravity Recovery and Climate Experiment (GRACE; operational 2002 to 2017), the joint NASA/German Research Centre for Geosciences GRACE-Follow On (GRACE-FO; launched in 2018), and the ESA Gravity field and Ocean Circulation Explorer (GOCE; operational 2009 to 2013). Additional gravitational data comes from satellite laser ranging measurements to geodetic satellites, such as the LAser GEOdynamics Satellite (LAGEOS) and the LAser RElativity Satellite (LARES). While GOCE used a gradiometer to gather data, GRACE and GRACE-FO use twin satellites flying in formation to track each other's movements. By continuously measuring tiny changes in the distance between the two satellites to an accuracy of one micron, they can identify areas of higher and lower mass concentrations. Data from GOCE, GRACE, and GRACE-FO allows scientists to determine not only where **mass** is **concentrated**, but also how mass **redistributes** as fluid moves around Earth's surface and within the planet. GRACE and GRACE-FO capture **changes in mass** over different temporal and spatial scales, including mass changes resulting from glacial rebound, hydrological changes on land surfaces and in river basins, and movement of ice sheets and glaciers. These data, including these **time-variable gravity variations**, help refine models of spacecraft trajectories. In fact, without these models, precise orbit determination (**POD**) calculations for sea level change would be off by several tenths of a millimeter per year.

As the paragraphs above illustrate, the geoid is not a static, smooth surface. It typically varies by about ± 100 meters over the globe, sometimes rising above and sometimes dipping below the reference ellipsoid.

The first three degrees of the geopotential field, expressed using spherical harmonics, are significant because they relate to fundamental global properties of Earth's mass:

- Degree 0: Gravitational coefficient (*GM*) of the Earth, where *G* is the gravitational constant and *M* the Eart's mass,
- Degree 1: Geocenter motion (see Section 3.2),
- Degree 2: Orientation of Earth's figure axis.

In addition to GRACE and GRACE FO data, geodetic tracking (primarily SLR, but also DORIS and GNSS) also contributes valuable information about the long-wavelength (low-degree) time-variable gravity field. However, there have been issues with the accelerometers and potential tidal aliasing (Chen et al., 2021).

The current *GM* value of 3.986004415 × 10^{14} m^3 s^{-2} was established by Ries et al. (1992) with an uncertainty of the order 2 ppb, equivalent to ±2 cm in the absolute radial position of high-orbiting GNSS satellites. Recent studies suggest possible adjustments to a value closer to 3.986004418 × 10^{14} m^3 s^{-2} (Couhert et al., 2020). In this study, Couhert et al. present a **self-consistent determination** of three fundamental properties of the Earth (*GM*, CM and CF). Their primary goal was to address sources of uncertainty in altimetry satellite orbits, which impacts sea surface height measurements. The study identifies modeling errors that should be mitigated when estimating the geocenter coordinates from SLR observations. Additionally, the long-term behavior of the degree-0 and -2 spherical harmonics has been observed over more than three decades using satellite laser tracking. Analysis of the evolution of these coefficients provides insights into Earth's internal properties, such as rheology, *GM* value, and moments of inertia. Limitations in these measurements include orbit precision, SLR station biases, and modeling errors related to the atmosphere and non-tidal deformations. For example, Tapley et al. (2004) demonstrated that GRACE monthly gravity field estimates have a geoid height accuracy of 2 to 3 mm at a spatial resolution as fine as 400 kilometers. Annual variations in the geoid height, peaking in spring and fall, can reach up to 10 mm in some regions. Blazquez et al. (2018) evaluated trends in global water budget components, finding consistency within uncertainties when compared to other observational sources. They estimated that the uncertainty in the global water budget is ±0.27 mm/year at the 90% confidence level for the 2005-2015 period. The largest sources of uncertainty in GRACE's global water budget estimates are due to geocenter motion and GIA corrections, contributing ±0.21 and ±0.12 mm/year, respectively. These uncertainties translate to an estimated error in the ocean's net warming and Earth's energy budget of ±0.25 W/m² when using the sea level budget approach. Further discussions on sea level changes are provided in Section 3.5.

The gravity field is of particular interest in the context of the GENESIS mission because the first degrees of its spherical harmonic expansion are linked to several GENESIS products. The **geocenter motion**, associated with **degree-1 gravitational potential**, reflects **global mass redistribution**. The degree-0 relates to *GM*, which corresponds

to Earth's total mass, while degree-2 coefficients relate to the mass influences on PM and LOD (see next Section), as well as moments of inertia.
A **self-consistent determination** of these properties Earth properties offers valuable insights for geodetic and climate studies.

3.4 Earth rotation

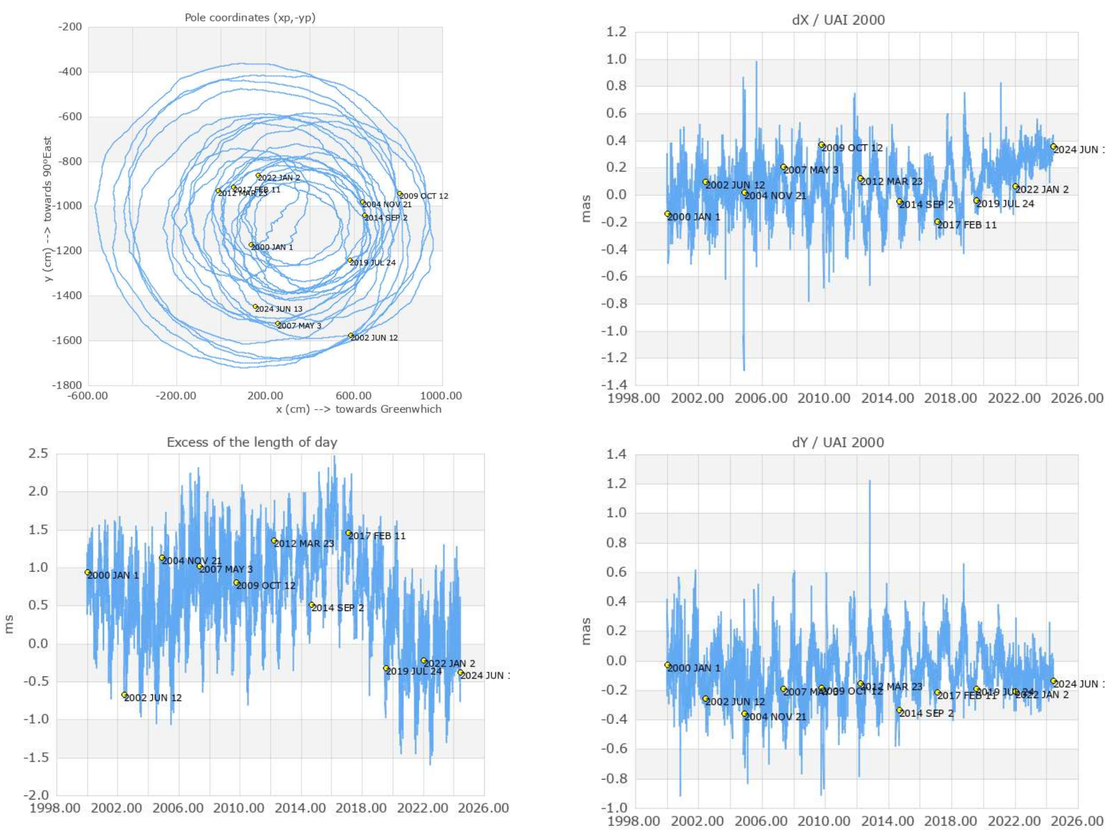
The Celestial Reference frame (CRF) is realized using the positions of extragalactic radio sources as observed by VLBI (Charlot et al., 2020). The **Earth Orientation Parameters (EOP)** describe the transformation between the TRF and the CRF. When calculating the International Celestial Reference System (ICRS), the ITRF and certain EOP are often held fixed. Conversely, when determining the ITRF, the International Celestial Reference frame (ICRF) and specific EOP are fixed. This approach can lead to **inconsistencies**, which in turn affect the EOP values that link the two reference frames when accurate determination is needed.

Length-of-day (LOD) measures variations in the Earth's rotation speed. LOD can be observed with a precision of 0.3 ms for a single measurement, improving to 0.1 millisecond (ms) after a week of observation. A 1 ms change in LOD corresponds to a shift of about 46 cm in longitude at the equator, or equivalently 0.1 ms translates to a 5 cm effect at the equator.

Polar Motion (PM), which tracks the shifting of Earth's rotational axis relative to its crust, is observed at the meter scale but determined with centimeter-level precision in single measurements (improving to 3 mm after a week of observations).

Nutations, which are small oscillations in Earth's rotational axis in space, are measured with a precision of 0.3 milliarcsecond (mas) level (equivalent to 1 cm level) for a single measurement. This precision improves to 0.1 mas after a week of observation and 0.02 mas after a year. Precession (the slow motion of Earth's rotational axis in space) and nutations are accurately modelled with precision within a few tens of microarcseconds (µas), corresponding to the millimeter level. However, the accuracy of these models is contingent upon the current understanding of core-mantle coupling, which remains at the centimeter level. Moreover, there is a free mode excitation in the nutations that is unpredictable and occurs at the centimeter scale, requiring precise observation.

All satellite-based applications must account for variations in LOD, precession, and nutations for accurate positioning and navigation.

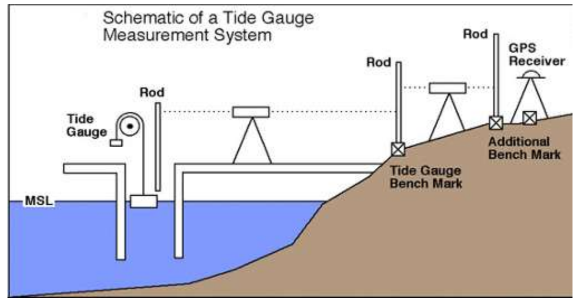


Top-left: polar motion; bottom-left: LOD variations; top and bottom right: X and Y components of nutations; from International Earth Rotation and Reference Systems Service (IERS) website.

Length-of-day (LOD), **Polar Motion (PM)** and **nutations** are critical parameters that require precise determination. LOD should be measured with an accuracy better than 0.01 ms; PM and nutations should be determined with an accuracy better than 1 cm, ideally at the millimeter level.

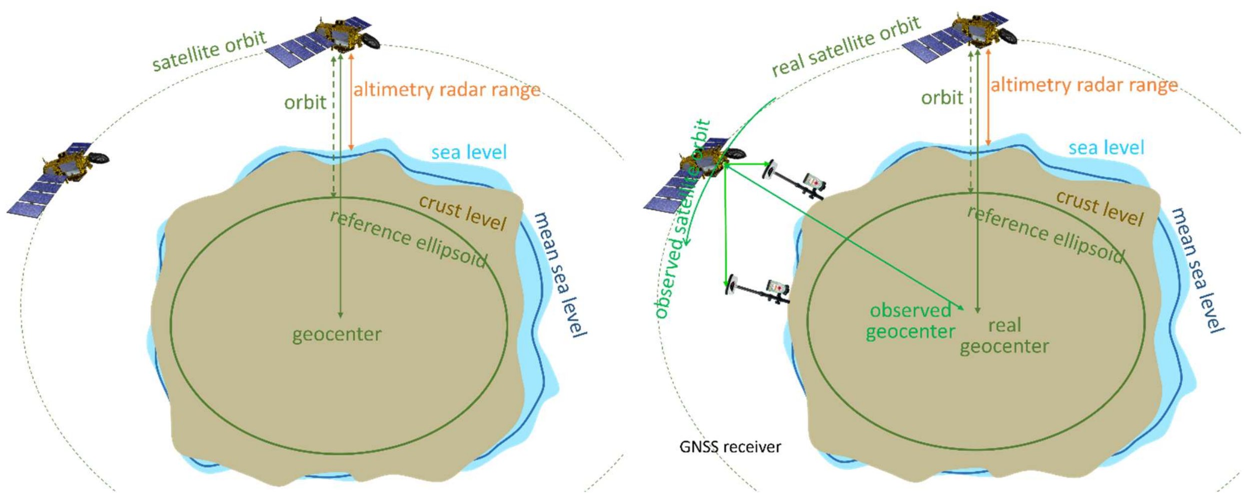
3.5 Altimetry and sea level rise

Global and regional sea levels have significant impacts on society. The geocentric global mean sea level, as measured by TOPEX/Jason altimetric missions since 1992, has been rising at approximately 3 mm per year (e.g., Lemoine et al., 2010). This rate of sea level rise is comparable to the geocenter velocity caused by GIA and the suspected current drift in the ITRF origin. Annual global mean sea level variations are also in the range of a few mm. Therefore, accurately understanding the effects of geocenter motion and improving the stability of the ITRF origin is crucial for determining sea level changes and their underlying causes.



Global sea level change from tide gauge measurements © sealevel.colorado.edu/tide-gauge-sea-level

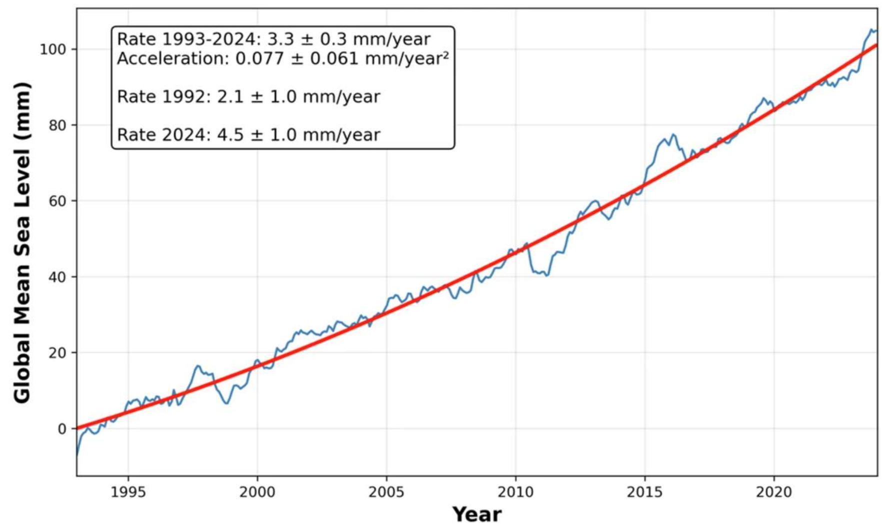
To measure sea level change within a global reference frame, the **tide gauges** are geodetically tied to the TRF using co-located GNSS stations (see Figure enclosed). Consequently, the ability to accurately observe contemporary sea level rise at global or local scales depends heavily on the stability of the TRF. In recent determinations of the TRF, a drift of 1.4 ± 0.2 mm/year was observed in the Z-component compared to the ITRF2000 origin, and a drift of −0.4 ± 0.2 mm/year compared to the ITRF2005 origin (Collilieux and Woppelmann, 2011). This affects the precision on sea level change observed through long-term tide gauge measurements relative to station positions. For the transition from ITRF2008 to ITRF2014, regional sea level trends showed changes of up to 0.4 mm/year (April 1993 to July 2008) and up to 1.0 mm/year (July 2008 to April 2015), as found by Rudenko et al. (2019). For the same transition, Zelensky et al. (2018) estimated an uncertainty in the global mean sea level trend of 0.2 mm/year.



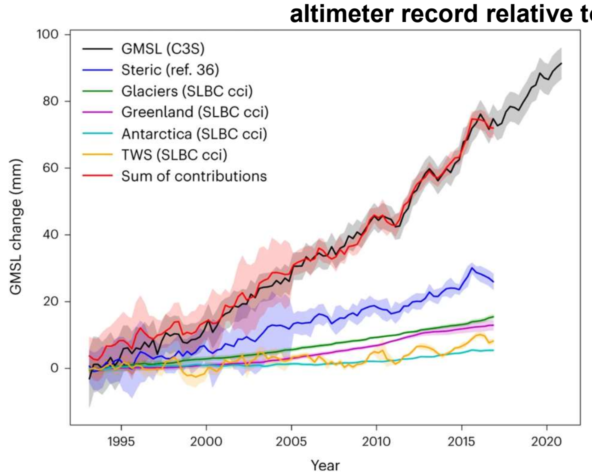
On the left, the principle of satellite altimetry; on the right, the way the orbits of the satellites are computed.

Sea-surface height is measured using radar altimetry, which considers the time it takes for radar pulses to travel from the satellite to the ocean's surface and back. Laser altimetry works similarly, using laser pulses to measure distances to land and sea ice surfaces. These methods require precise knowledge of satellite altitude and the terrestrial reference frame to ensure accuracy (see Figure above). Extensive calibration is necessary to maintain the precision of altimetry measurements. **Satellite altimeters** use **radar data** combined with precisely known orbits to determine sea level globally with high accuracy. Since these measurements are referenced to the CM frame over the long term, they are often referred to as **absolute sea levels**. Monitoring long-term global mean sea level changes provides a way to validate climate models predicting global warming.

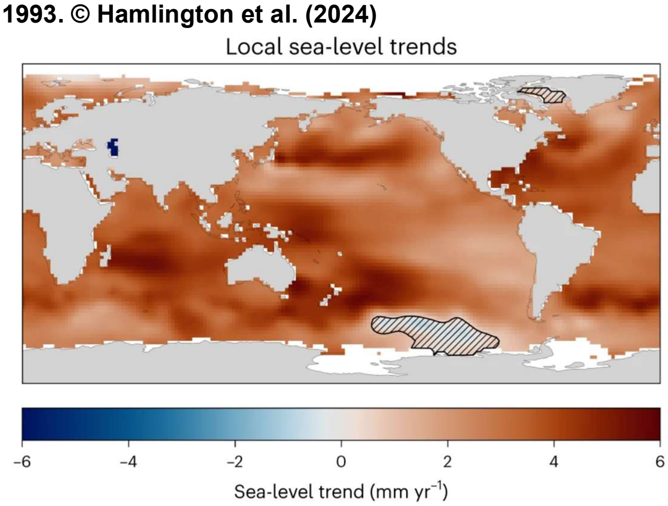
The present-day sea level rise is considered different from a trend: it resembles a quadratic curve, as presented in the figure below. Internal precision seams to be at the 1 mm/year, not yet at 0.1 mm/year.



Global mean sea level (GMSM) time series (mm) from satellite altimetry over the time period from 1993 through 2023. The solid red line is the quadratic fit to the data and indicates the sea level change over the altimeter record relative to 1993. © Hamlington et al. (2024)



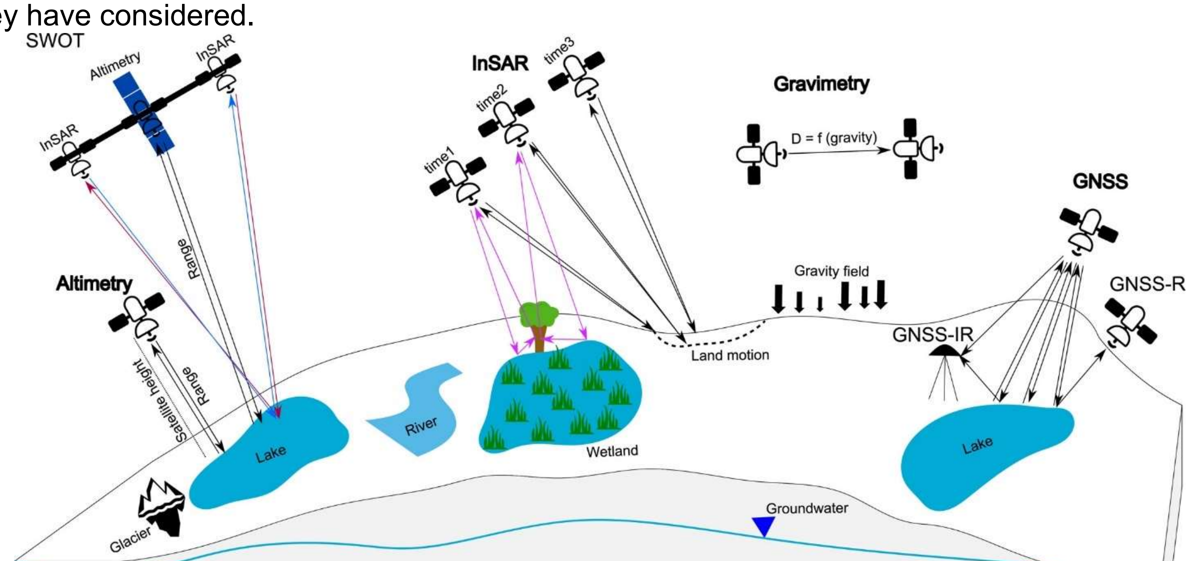
GMSL changes measured by satellite altimetry (black line) from the Copernicus Climate Change Service with uncertainties at 10 days (5–95%, indicated by the black shaded area) and the different contributions to sea-level changes from the Sea Level Budget Closure climate change initiative: thermal expansion (blue line), glacier ice melt (green line), Greenland mass loss (pink line), Antarctica mass loss (cyan line) and land water storage variations (orange curve). The red line is the sum of the contributions to sea-level rise. © Meyssignac et al. (2023)



Regional sea-level rates of rise over 1993–2019 estimated by Prandi et al. (2021) (the hatched areas are regions where regional sea-level rates of rise are not significant at the 5–95%.

The different contributions to the global mean sea level (GMSL) are shown in the above figure. The regional mean sea level changes are different and have a higher magnitude compared to GMSL as also shown in the above figure.

Note that water mass balance can be constrained using a lot of data. Jaramillo et al. (2024) have recently made a review. We reproduce here their Figure 1 summarizing all the techniques that they have considered.

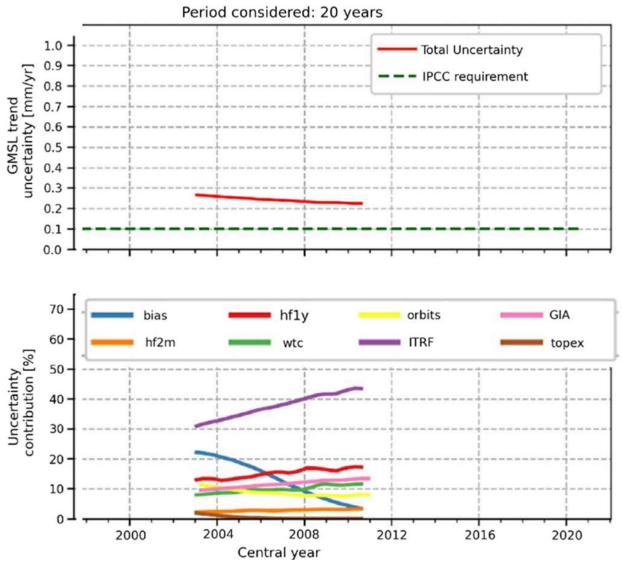


	Altimetry	InSAR		Gravimetry	GNSS		
		Repeat pass	Single pass (SWOT)		GNSS	GNSS-IR	GNSS-R
Hydrologic parameter	Surface water level	Surface water level and water storage change	Surface water level	Water storage change	Water storage change	Surface water level change	Surface elevation, soil moisture
Measuring principle	2-way travel time of radar/laser	Difference in 2-way radar travel time between multiple acquisitions	Difference in 2-way radar travel time between simultaneous acquisitions	Precise orbit determination	Correlation of satellite and receiver signals	Difference in signal-to-noise ratio from 2 GNSS signal paths	Reflected GNSS's signal travel time and backscatter
Temporal, spatial Resolution	~10- 35 days, 50-300 m (along-track)	≥6 days, 10-100 m	≤21 days, 95% of all water bodies	monthly, >300 km)	Daily, Point measurements	Seconds, 100m-100km	Seconds, 100m-100km

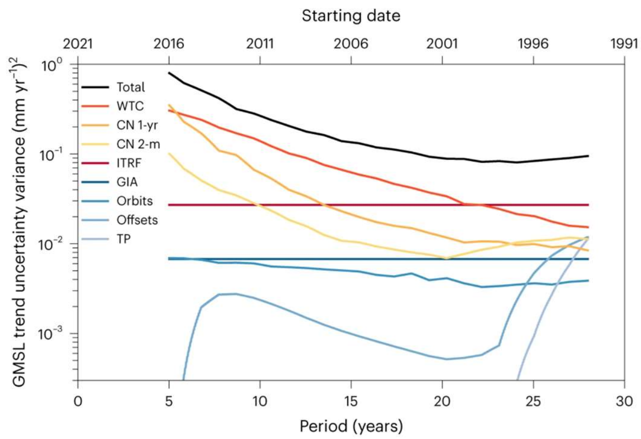
Illustration of the various technologies of Hydrogeodesy and their applications. The table includes the hydrological parameters most commonly measured in the context of Hydrogeodesy, the principle behind such measurement, and the usual temporal and spatial resolution. © Jaramillo et al. (2024)

Improving **satellite altimetry** precise orbit determination (POD) is crucial for accurately measuring sea level rise. This requires advancements in tracking system precision, reference frame stability, Earth rotation parameters, and both static and time-variable geopotential models (International Altimetry Team, 2021). For sea level and vertical land motion measurements to be reliable in long-term climate studies, they must be anchored to a reference frame that is an order of magnitude more accurate than the current observed climate change signals of 1 to 3 mm/year. Altimetry orbits are calculated within the ITRF, with corrections to align as closely as possible with the CM. However, these corrections can introduce discrepancies. Differences in orbits calculated using various geodetic techniques (e.g., SLR, GNSS, DORIS) result in biases, typically around 5 mm and 0.5 mm/year. Orbit discrepancies in the radial direction impact sea level measurements, allowing for the identification and reduction of non-geophysical sea level errors.

The **reference frame stability** is one of the main sources of error in determining global and regional sea level trends (Ablain et al., 2019; Beckley et al., 2007; Blewitt et al., 2010; Blazquez and Meyssignac, 2022), as illustrated in the Figure below.

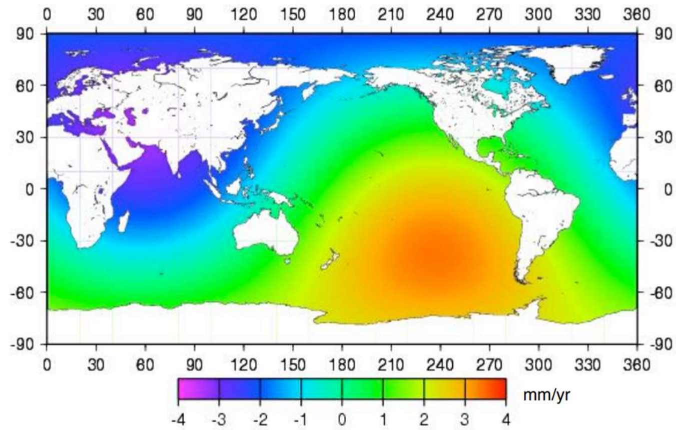


Total uncertainty in the global mean sea level (GMSL) trend and individual contributions (Blazquez and Meyssignac, 2022). The uncertainty coming from the ITRF is clearly the major contribution, which implies a total uncertainty currently well over the Intergovernmental Panel on Climate Change (IPCC) requirement. © Ablain et al. (2019) & Delva et al. (2023).



Same recomputed in 2023. © Meyssignac et al. (2023)

Improvements in reference frame realizations over time and the availability of more comprehensive data also affect orbit calculations. For instance, Morel and Willis (2005) achieved a sea level accuracy of 3 mm and a sea level rise rate of 0.4 mm/year using the ITRF97 frame. Similarly, the effect of different reference frame realizations (ITRF2000 and IGS-based realizations) on mean sea level is shown in a study by Blewitt et al. (2010) on positions and speeds of GNSS data (see Figure below).

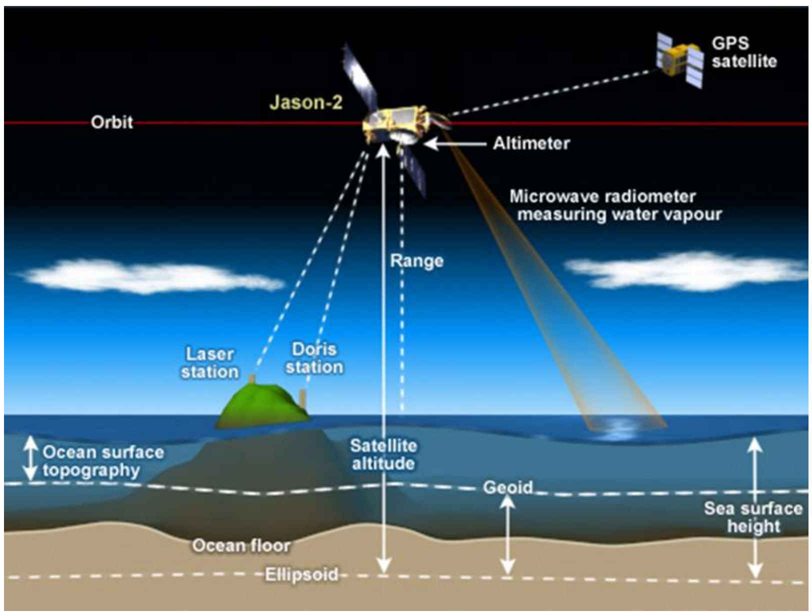


Simulated effect on sea-level error inferred by satellite altimetry caused by an error in realizing the reference frame. This example shows the effect of differences between two frames realized by the International GNSS Service (IGS): one is IGb00, which is aligned with ITRF2000; the other is the frame of the IGS precise point positioning products (Kierulf and Plag, 2006). The difference in the (X,Y,Z) motion of the geocenter of these two frames is (-1.5, -2.2, -2.1) mm/year. The difference in sea level ranges from -3 to +3 mm/year, with a mean-sea-level error of 0.4 mm/year caused by asymmetric distribution of the ocean. © Blewitt et al. (2010).

Over the past three decades, a series of satellite ocean altimetry missions (https://www.earthdata.nasa.gov/learn/articles/pod-sea-level-rise) has been monitoring sea surface height globally. Starting with the Topographic Experiment (TOPEX)/Poseidon mission (operational 1992 to 2006), followed by the Jason-1, Ocean Surface Topography Mission (OSTM)/Jason-2, and Jason-3 series of satellites (operational 2001 to present), this long-term record has continued with the launch of the Sentinel-6 Michael Freilich satellite. These missions have created a time-series of sea surface height data exceeding 30 years. Sea level change rates are derived from repeated measurements over the same orbital tracks. The precision of these measurements is within a few millimeters, reflecting changes in global mean sea level over time. The ability of satellite altimeters to provide accurate measurements of the distance between the satellite and the ocean surface, despite being thousands of kilometers above Earth and moving at high speeds (tens of thousands of km per hour), demonstrates the extraordinary precision required for reliable sea level monitoring.

For accurate sea surface height measurements, it is essential to know the satellite's position and attitude. Radar altimeters continuously transmit high-frequency signals (over 1700 pulses per second) to Earth and analyze the return signal from the sea surface to determine the round-trip travel time. This timing, adjusted for the speed of light, provides the **range measurement**. After corrections for atmospheric effects, the final range is determined to be within 2 cm precision.

The ultimate goal is to measure sea levels relative to a terrestrial reference frame. This requires independent measurements of the satellite orbital trajectory, including precise latitude, longitude and altitude coordinates. Improvements in these measurements are essential to enhance the robustness of sea level change assessments. POD is the technique used to determine the precise position of orbiting satellites by accounting for Earth's shape, gravity field, and rotation, which all vary over time (see Figure below). This process involves calculating the forces acting on a spacecraft at every time step and integrating these equations to pinpoint the satellite's position at each measurement point (see GENESIS TN 1 for more details on POD). Achieving accurate POD requires numerous data inputs and the use of multiple geodetic techniques. A retroreflector on the satellite reflects laser beams from SLR stations on the ground. Many altimetric satellites are also equipped with DORIS receivers that detect signals from ground-based beacons, as well as GNSS receivers that use signals from orbiting GNSS satellites. These combined systems ensure the satellite's position is known relative to a stable reference frame. TOPEX/Poseidon, Jason-1, Jason-3, and Sentinel-6 all carry DORIS and GNSS receivers along with retroreflectors.



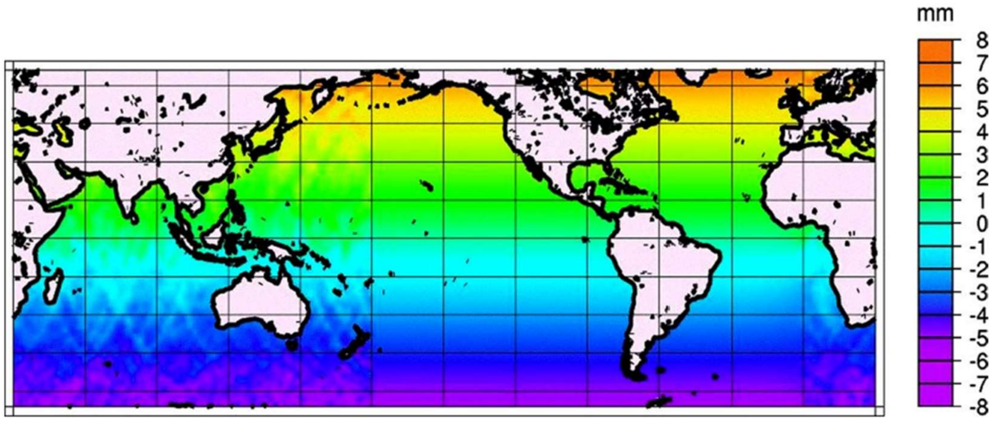
POD in the frame of altimetry (NASA's Jet Propulsion Laboratory (JPL) and available at https://sealevel.jpl.nasa.gov/missions/technology/. © NASA

The **ocean's dynamic surface topography** is the height difference between the geoid (see definition above, Section 3.3) and the actual ocean surface, influenced by factors like ocean currents, tides, and waves. The sea surface height combines the geoid and the dynamic surface ocean topography. To understand ocean currents and their temporal changes, the geoid is subtracted from the sea surface height.

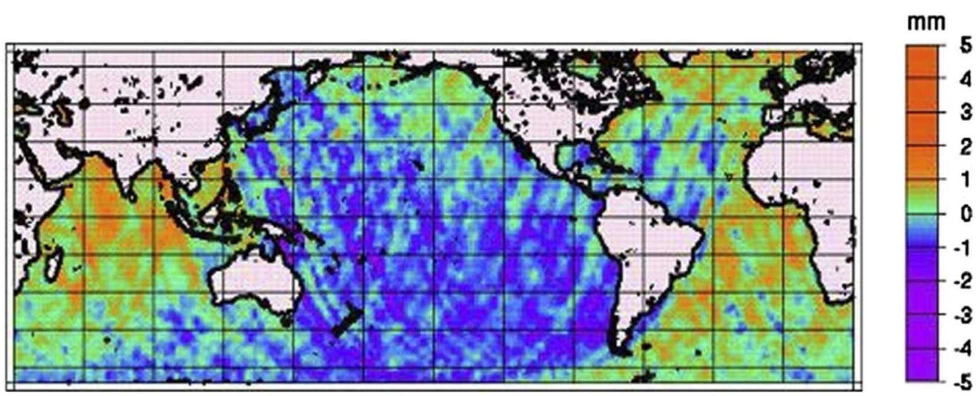
According to the IPCC, the **global average sea level** must be estimated with millimeter precision every 10 days, with **absolute accuracy limited by systematic errors**. Sea surface height reflects the combination of the geoid and dynamic ocean topography. Errors in Earth's gravity field models, which were the main source of orbit errors in satellite altimeter missions before gravimetric satellites, still impact the precision of these measurements.

Morel and Willis (2005) assessed factors contributing to sea level measurement errors, including the satellite tracking network, *a priori* orbits, TRF scale, and translation parameters. The current precision in TRF realization is about 5 mm, with a trend of 0.5 mm/year (as discussed in Section

3.1). Morel and Willis highlighted that even small biases in **geocenter coordinates** can result in systematic errors of -1.2 mm in mean sea level. These errors could be mistakenly attributed to warming, rather than inaccuracies in the reference frame.



Observed geographical mean sea level errors resulting from a 10 mm Z-translation of the TRF. © Morel and Willis (2005)



Observed geographical mean sea level errors resulting from a 10 mm X-translation of the TRF. © Morel and Willis (2005)

Morel and Willis (2005) determined that the relation between the scale and the translations in Z-direction to the mean sea level (mm) is -0.12 x TZ (mm) where TZ is the TRF error considered. Even if their effects are very small, the transfer functions estimated for TX and TY provide a mean sea level (mm) of -0.014 x TX (mm) and -0.014 x TY (mm). A 10 mm error in the TZ realization can create -1.2 mm of systematic errors in the mean sea level derived. Significant sea level rise could erroneously be attributed to a possible warming of the biosphere while they just come from systematic errors in the TRF used to generate satellite operational orbits. Using the uncertainty on ITRF1997, i.e. a scale factor at 1.5 ppb and 0.5 ppb/year levels, TX at the 10 mm level and maintained in time at the 4 mm/year level, TY at the 20 mm level and 5 mm/year level, and TZ at the 25 mm and 3 mm/year level, they computed a 3 mm precision in mean sea level with a 0.4 mm/year rate. While this is a strong approximation, **using the same scaling as they obtained and the accuracy level of the ITRF2020 (5 mm and 0.5 mm/year of TX, TY, and TZ), we obtain 0.6 mm precision in mean sea level with a 0.1 mm/year rate.** Remember that Ablain et al. (2019) have computed a 0.3 mm/year uncertainty on the global mean sea level, from which about 40% comes from the ITRF (i.e. 0.12 mm/year).

One method for validating satellite altimetry measurements of mean sea level change is by comparing them with **tidal gauge measurements**. However, this is complex. Beckley et al. (2027) have shown that sea-surface heights from the TOPEX altimeter compared against a high-quality network of tide gauges may be biased by ±5 mm with a 1 mm/yr drift. While satellite altimetry offers superior spatial coverage and accuracy compared to tide gauges, the latter provides long-term observations at specific points. Tide gauge data reflect local relative sea level changes, including vertical land motion, while satellite data provides a global perspective (see https://tidesandcurrents.noaa.gov/sltrends/). Early comparisons between altimetric and tide gauge data revealed discrepancies, largely due to instrument drift and vertical land movements (Mitchum, 1998; Cazenave et al., 1999). Recent studies using historical and reconstructed tide gauge data indicate a 20th-century sea level rise between 1.7 and 2.1 mm/year (see https://ggos.org/item/sea-level-change/ and Carson et al., 2017). Altimetry estimates from 1993–2017 show a global mean sea level trend of 3.35 ± 0.4 mm/year, with a statistically significant acceleration of 0.12 ± 0.07 mm $year^{-2}$ (Ablain et al., 2019). Despite differences in methodology, both approaches confirm that sea level rise is accelerating.
The advantage of the tide gauge measurements is their long observation period, often exceeding 75 years at sparse points on Earth's surface. When comparing regional trends, deviations from global mean trends are often larger in tide gauge reconstructions than in altimetry-based data (Carson et al., 2017), indicating that uncertainties remain in trend estimates.

The sea surface height is the combination of the geoid and the dynamic surface ocean topography. Sea level changes are measured using either **tidal gauge**, which are anchored to a well-defined continental frame, or through **satellite altimetry**. Achieving accurate **mean sea level changes** is heavily dependent on the **stability of the reference frame**, as it is one of the primary sources of error in determining both global and regional sea level rise. **Uncertainties in global mean sea level trends are largely influenced by uncertainties in the origin coordinates of the TRF**, particularly the Z-coordinate, and **its scale**. These uncertainties affect sea level changes as a function of the geometry of the satellite mission involved. Using the same scaling factors and the precision achieved in the ITRF2020 (5 mm and 0.5 mm/year of TX, TY, and TZ), a **0.6 mm precision in mean sea level**, with a **0.1 mm/year precision in mean sea level rate**, can be attained.
Comparisons with **tidal gauge data** reveal current discrepancies in mean sea level trends, showing differences of about **1 mm/year**. These differences remain unexplained, highlighting the need for further investigation to reconcile satellite and tide gauge measurements.

3.6 Determination of ice mass loss and post-glacial rebound

Accurately estimating center of mass (CM) motions has become increasingly challenging due to the impacts of climate change. Studies have shown that **global ice sheet melting** may currently be causing an accelerated shift in the CM, potentially reaching up to 1 mm/year relative to the CF, moving toward the South Pole along Earth's rotational axis (e.g., Métivier et al., 2020). Even a small error of a few tenths of a millimeter per year in the stability of the frame origin can significantly affect calculations of water mass redistribution on the surface (see Section 3.5). Today's uncertainties in long-term geocenter motion trends (±0.3 mm/year) translate to uncertainties in Antarctic ice mass change of about 18 gigatons per year (Blazquez et al., 2018). To provide context, a gigaton (Gt) can also be expressed in terms of **Sea Level Equivalent (SLE)**: 1 cubic kilometer of water (or 1 Gt, equivalent to 1 × 10^{12} kg) raises global sea levels by approximately 1/360 mm. According to Blazquez et al. (2018), an uncertainty of 1 mm in each axis of geocenter motion results in uncertainties of 0.5 mm SLE for the X-geocenter, 0.3 mm SLE for the Y-geocenter, and 0.6 mm SLE for the Z-geocenter.

Post-glacial rebound, or GIA, refers to the delayed viscoelastic response of the solid Earth to the removal of ice mass following the last glacial maximum, roughly 13,000 years ago. This process leads to significant vertical uplift, which can exceed 1 cm per year in regions like North America and Fennoscandia, where the ice sheet was thickest. Improving GIA models, which rely on an understanding of Earth's rheology and historical ice coverage, requires precise estimates of uplift rates. Achieving this level of accuracy depends on a more stable and precise reference frame (Métivier et al., 2020).

On shorter timescales, GNSS stations capture Earth's elastic response to surface mass redistribution driven by the **climatic system** (mainly changes in continental water storage, atmosphere variations, and ocean levels). A highly stable and precise reference frame is crucial for interpreting these observations accurately, as they are critical for predicting potential hazards versus identifying errors in measurement techniques.

Accurate determination of **ice mass loss** and **post-glacial rebound** depends on precise measurements of Earth's **CM**. Climate change, particularly **ice sheet melting**, affects CM motion, impacting calculations of water mass redistribution and sea level rise. Uncertainties in CM coordinates translate into mass changes related to **GIA** or **ice mass loss**, equivalent to about 0.5 mm in **Sea Level Equivalent (SLE)**. A stable reference frame is essential to minimize these uncertainties and ensure reliable geodetic data.

3.7 Conclusion

Current limitations in geophysical applications, such as monitoring mean sea level change or ice mass loss, primarily stem from uncertainties in the **CM** or the origin of the TRF, as well as its **scale**.

The accuracy of the TRF is affected by uncertainties in the ties between co-located techniques at ground stations, which currently have a **tie accuracy** at cm level. Additionally, there are **scale errors** and **CM biases** between the reference frames produced by different geodetic techniques, leading to discrepancies at few millimeters level.

Furthermore, the EOP and CRF as well as the TRF are all impacted by **atmospheric interference**, which affects the quality of the data.

4. IMPROVEMENT WITH GENESIS.

An important goal of the scientific community is to enhance the accuracy of scales and CM determinations across all geodesic techniques to improve the ITRF. Achieving this requires a multidisciplinary effort, and the GENESIS mission will act as a catalyst in this process. Studying additional space ties thoroughly will help refine the determination of the TRF. However, it is clear that relying on a single satellite will not meet the precision required by the United Nations (see Section 2). This Section 4 reviews the progress made in this direction.

Geodetic VLBI is unique among geodetic techniques because it provides the complete set of EOP, including polar motion, UT1, and celestial pole offsets. It also contributes to the ITRF scale and exclusively realizes ICRF, unlike satellite-based methods such as SLR, GNSS, and DORIS. Using a VLBI Transmitter (VT) on a satellite offers a compelling opportunity to directly link CRF, TRF, EOP, and satellite orbits within a unified framework, leading to a consistent set of global geodetic products. This is in addition to the advantage of integrating multiple space-geodetic techniques in space.

Furthermore, antenna-related effects, which are significant in GNSS due to factors like multi-path interference, and antenna phase center offsets, are not a concern at VLBI stations, thanks to the use of highly directive well-calibrated parabolic antennas. This makes VLBI an appealing choice for cross-technique orbit validation.

4.1 Combination strategy to build the ITRF

Multi-technique combination at the solution level: The first method for combining spatial geodesy techniques on a single satellite involves creating a solution for each technique separately, and then merging these single-technique solutions into a multi-technique solution. Observations from each technique are initially processed by arc (an individual solution calculated from data collected over a specific time interval). These individual solutions are then accumulated to produce a long-term solution for each technique. Finally, the long-term solutions from each technique are combined to generate a multi-technique long-term solution. The most significant application of this multi-technique combination at the solution level is the determination of the ITRF (Altamimi et al., 2007, 2011, 2016, 2023).

Multi-technique combination at the observation level: An alternative method for combining techniques involves calculating solution parameters simultaneously using the same procedures and methods, known as observation-level combination. In this approach, observation equations from all techniques are created and combined directly, allowing for the simultaneous estimation of all parameters. To my knowledge, this method has never been implemented, despite its potential to **enhance the accuracy of the ITRF**.

Co-location sites provide observation from different space geodesy techniques at the same ground station. A co-location site is defined by the presence of at least two space geodesy instruments at the same location. Highly precise topometric measurements are conducted to determine the vector between the reference points of two instruments (e.g., between a GPS antenna reference point and a DORIS beacon). This vector is called a **local tie** (see Section 3.1). However, the use of local ties has several **drawbacks**, such as low accuracy (many ties have an unknown precision, e.g., Altamimi, 2003), limited co-location between certain techniques, and poor geographical distribution (with few sites hosting more than two technique antennas and no continuous observations). Due to the limited number of local ties, it is difficult to assess their quality, as all must be used in the combination, leaving little room for independent validation. Moreover, inconsistencies frequently arise when comparing local ties with results from individual space geodesy solutions. The most common method for accurately linking the specific frames of each technique is to use highly precise topometric links between stations of different techniques co-located at the same site (local ties). However, the current discrepancies between these local ties and the positions estimated by space geodesy are a major limiting factor in the quality of the ITRF.
Local ties at ground stations currently have an accuracy of only 1 cm. Skeens et al. (2023) tested a new method to enhance local tie accuracy using small-baseline GNSS data co-located with VLBI. They developed a radio interferometer consisting of a GNSS antenna and a Very Long Baseline Interferometry radio telescope. The goal is to apply this interferometer to local tie measurements (see Skeens et al., 2023, and Section 3.1).

Another method to integrate different space geodesy techniques involves using **multi-technique satellites** equipped with instruments from several space geodesy systems. The idea is to establish spatial ties between techniques co-located on satellites. Satellite orbits can serve as common parameters linking techniques on Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and GNSS satellites. Many scientific satellites are observed by multiple techniques, and GNSS satellites are often tracked by SLR (including most GLONASS satellites, some GPS satellites, and the entire GALILEO constellation).
The primary challenge in using satellites as inter-technique **space ties** lies in accurately determining the vectors between the satellite's CM (or another reference point) and the reference points of the various instruments. GENESIS is an example of such a satellite and can function as a "space tie." The question remains whether this "space tie" will be robust enough to unify the four techniques into a common, homogeneous reference frame and geocenter in a multi-technique solution. There is a risk that each technique could remain within its own frame of reference, despite the presence of space ties.

> Improving the ITRF requires **accurate local ties**, **an increased number of co-location sites**, and **better global distribution**. Incorporating **space ties** can also help reduce biases between techniques.

Methodologically, a promising approach for **multi-technique combination** is to work at the **observation level** rather than the solution level.

4.2 Geocenter position and scale improvement

Improving the geocenter position and scale requires distinguishing between what GENESIS can contribute to each individual geodetic technique and what it can offer as "space ties" between these techniques.

For the **GNSS technique**, it is well established that **adding an orbiting receiver** to ground-based GNSS receivers improves the localization of the CM and the scale, provided that the antennas of this receiving satellite are very precisely calibrated (Huang et al., 2022). Männel and Rothacher (2017) demonstrated that combining ground-based GNSS data with GNSS observations from high-quality dual-frequency receivers on **LEO satellites** enhances the realization of the TRF, the estimation of geocenter coordinates, GNSS satellite orbits, and Earth rotation parameters. The inclusion of a single LEO reduces formal errors by about 20%, and solutions with four LEOs show a significant reduction in LEO-specific errors. Männel and Rothacher's comparison of their derived geocenter coordinates with respect to LAGEOS results and with respect to external solutions based on GPS and SLR data showed good agreement in amplitude across all components, though discrepancies were found in the phases of the X- and Z-directions.
As noted by Zhang et al. (2024), LEO satellites offer a distinct advantage in detecting geocenter variations due to their lower orbit altitude. Closer to the Earth's surface, LEO satellites provide unique observational benefits, complementing existing GNSS systems for Earth studies. However, the more complex orbit modeling required for LEOs presents challenges for precise geocenter estimation, despite the wealth of GNSS observations from the increasing number of LEOs. Based on a detailed experiment carried out for Jason-3 for a time span of three years, Kobel (2023) showed, however, that there is still potential to improve LEO POD precision, particularly by modeling non-gravitational forces and single-receiver ambiguity resolution. This may require higher sampling rates than the current 300 seconds for precise LEO orbit solutions or reducing the number of other estimated parameters (e.g., modeling GNSS satellite clocks rather than estimating them, an option available for the high-quality clocks on Galileo satellites). Additionally, rigorous calibration of GNSS transmitter and LEO receiver antennas is crucial for enhancing global network solutions involving LEOs.
Zhang et al. (2024) additionally emphasized that imperfections in *a priori* LEO models can cause significant distortions in derived geocenter coordinates. Addressing these deficiencies through additional scale parameter estimation, which accounts for inaccuracies in atmospheric drag and solar-pressure effects, can reduce orbital artifacts in the geocenter coordinates. Zhang et al. (2024) showed that ambiguity resolution improves the accuracy of geocenter coordinates, reducing formal errors by over 80% for the equatorial component and 28% for the Z component. Multi-LEO combined solutions also improve parameter decorrelation, decreasing the impact of orbit modeling deficiencies.
Further research is needed to investigate how different orbit parametrizations for the LEOs affect the computation of global network solutions. Nevertheless, the results clearly indicate that integrating LEOs into processing leads to further improvement.

GENESIS may not offer the same advantages as a conventional LEO due to its **relatively high altitude**, which raises concerns about its orbit determination via GNSS (Montenbruck et al., 2023), and its planned **quasi-polar inclination**, which may limit its contribution to the determination of the Z component of the geocenter.

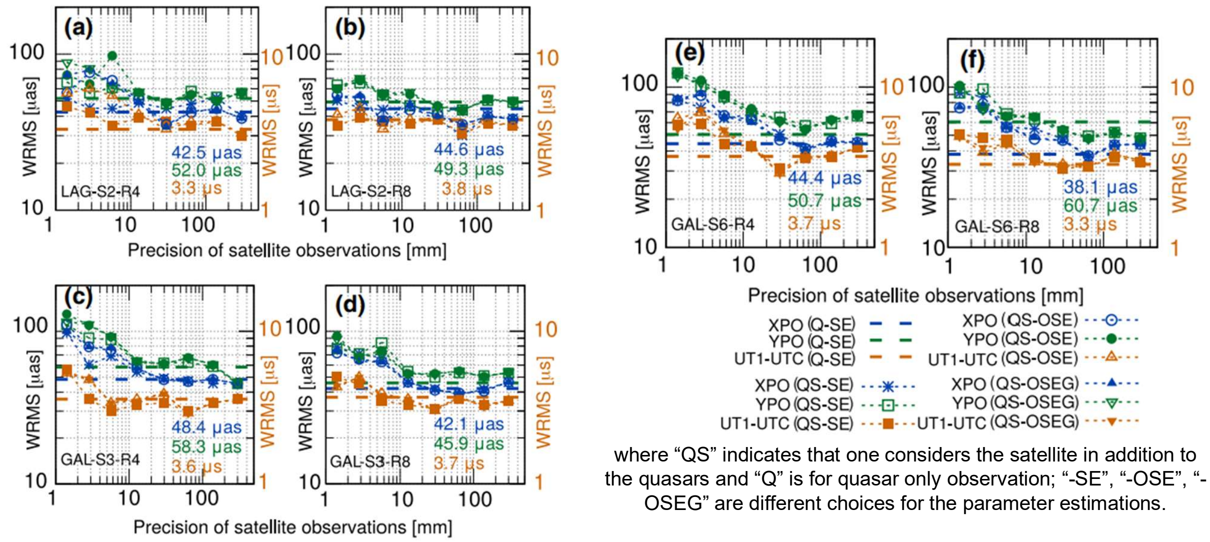
Regarding the **DORIS technique**, a new, well-calibrated satellite could potentially enhance the determination of the terrestrial scale. Nevertheless, GENESIS's high planned orbit for a DORIS satellite could impact its contribution, depending on the exact orbital parameters. As for the geocenter, adding another quasi-polar orbiting satellite may not fundamentally affect DORIS-based geocenter estimation. On the **SLR** side, GENESIS will add another satellite to the existing group, including LAGEOS and Etalon, potentially aiding in geocenter and scale determination. Progress in this area has already been made. Zoulida's PhD thesis in 2016 used the Jason-2 satellite as a "space tie" (see Section 4.8), and similar efforts were made with Sentinel-6 (see Section 4.9).

Regarding **VLBI**, adding an orbiting transmitter to the existing set of extragalactic sources has the potential to increase VLBI's sensitivity to the CM position. Building on a rigorous understanding of the measurement principles and the inherent sensitivities of the techniques, we conclude that **VLBI and SLR provide complementary contributions to estimating the geocenter**. Incorporating VT introduces an additional means of geocenter measurement. However, its overall impact requires further evaluation. An initial assumption might suggest that the geocenter is **more effectively sensed by a ranging technique like SLR**. Nonetheless, a combined approach would undoubtedly make for an interesting case study. Klopotek et al. (2020) demonstrated that geocenter offsets, which were previously beyond the scope of geodetic **VLBI** analysis, are now approaching the detection limit in simulations involving VGOS observations of Galileo satellites, with the potential to further improve the results. However, as their study showed, poor satellite geometry can negatively impact outcomes. In simulations using legacy VLBI observations of LAGEOS-like and selected Galileo satellites, the precision of the obtained geocenter offsets was only at the level of a single centimeter for LAGEOS-like satellites and a few centimeters for Galileo satellites. This precision is insufficient for detecting geocenter motion, which has an annual signal in the range of a few millimeters (see Section 3.2). Furthermore, the Z-component of the geocenter offset could not be reliably derived due to modeling deficiencies related to solar radiation pressure acting on the spacecraft. Nonetheless, the study highlighted that **VGOS**-era satellite observations offer significant improvements for both orbit solutions and geocenter components, nearly **reaching the detection threshold for geocenter motion**. This is attributed to the increased observation density, a more homogeneous station distribution, and quasar observations that are ten times more precise. These factors contribute to better observation geometry for POD and more effective mitigation of major error sources that impact geodetic VLBI observations. In Klopotek et al.'s study, a simplified scheduling strategy was used to incorporate satellite observations into the schedules, restricted only by the common-visibility criterion. This approach is suboptimal, and additional factors, such as baseline length and orientation, should be considered. Therefore, **careful scheduling** of both quasar and satellite observations is essential to fully capitalize on this new observation concept. Nevertheless, with **only one satellite** and a relatively limited number of observations, the **improvement** in geocenter determination is still expected to be **moderate**.

To enhance geocenter position and scale accuracy, the addition of a **space tie** is highly valuable. Integrating **orbiting GNSS receivers on LEO satellites** has already demonstrated **clear benefits**. Similarly, incorporating DORIS and SLR techniques is beneficial. Nevertheless, the effectiveness of these additions **depends on the satellite's orbit** and requires precise calibration onboard the spacecraft. GENESIS's higher altitude and quasi-polar orbit may limit its impact. An orbiting **VLBI transmitter** also shows **promise**, but its effectiveness is constrained by the limited number of observations. Addressing **atmospheric errors** remains crucial for improving scale and CM determinations to meet UN standards.

4.3 Earth rotation

Geodetic VLBI is the only technique that provides the complete set of EOP, including polar motion, UT1/LOD, and celestial pole offsets. It also contributes to the ITRF scale and uniquely realizes the International Celestial Reference System, unlike satellite-based techniques, as mentioned in the introduction of Section 4. As demonstrated by Klopotek et al. (2020), and also discussed by Anderson et al. (2018), the combination of quasar and satellite observations has an impact on EOP estimations. This effect is illustrated in their Figure 7, reproduced here, where Weighted Root Mean Square (WRMS, indicating the accuracy) of the derived polar motion (x_p, y_p) and UT1-UTC are shown based on schedules that include tracking of LAGEOS (LAG) and Galileo (GAL) satellites. Estimation of additional parameters, i.e., zenith wet delays, tropospheric gradients, station clocks, as well as estimation of station positions with No-Net-Translation condition and No-Net-Rotation conditions using VLBI stations as well as VGOS stations for the network, was carried out in all the analysis options. The results are compared with reference solutions that only include quasar observations (indicated with a Q, while QS indicates that quasar and satellite observation are foreseen). The results are presented in the Figure below. These findings suggest that adding satellite observations does not improve EOP estimations, as evidenced by the WRMS of the dashed lines for quasar-only solutions being lower than those for the other solutions. The key takeaway from these simulations is the importance of maintaining the same number of quasar-only observations, as reducing them degrades the solution quality.



WRMS (accuracy) of polar motion (x_p, y_p) and UT1-UTC from a–b LAG-type and c–f GAL-type schedules. For each schedule type, the color-coded (blue, green, orange) values correspond to EOP derived from the related reference solution © Klopotek et al. (2020).

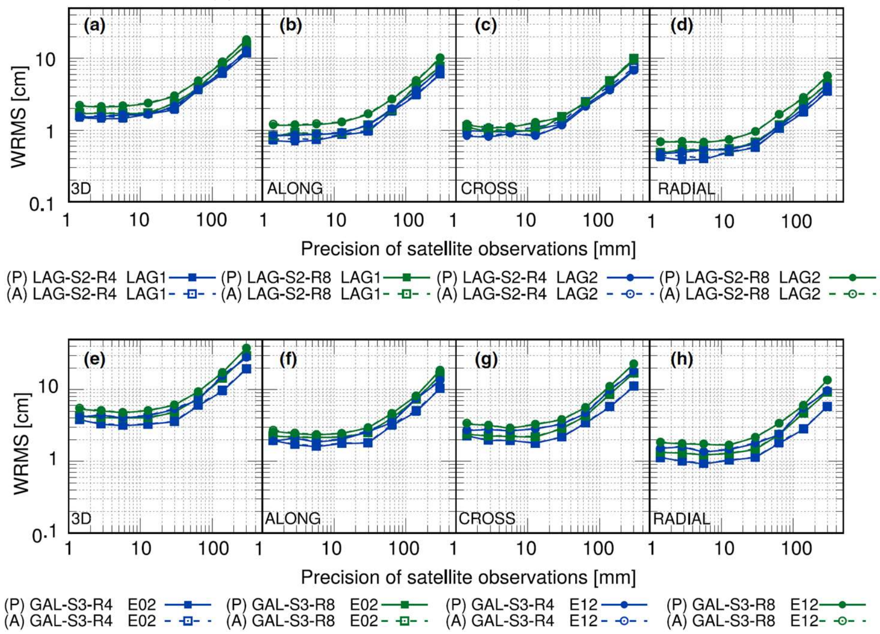
Schunck et al. (2024) conducted extensive simulations for GENESIS, incorporating both current and anticipated modern VGOS antenna networks. They assumed that GENESIS observations would be integrated into regular geodetic experiments. While including GENESIS as an additional source in the scheduling, they ensured **minimal degradation** in geodetic parameter estimates, with station positions and UT1-UTC showing deviations of less than 0.09 mm and 0.06 µs, respectively. The findings recommend **scheduling GENESIS scans at intervals of approximately 5 minutes** (with scan lengths of 30 s, as this is the common practice currently employed in VGOS experiments) to ensure that the reduction in the number of geodetic source observations remains below 5% compared to schedules containing only geodetic radio sources.

Recently, the ROB team (see Sert et al., 2023, see also Section 4.10) demonstrated that the UT1-UTC parameter, which is crucial for precise orbit calculations but is insensitive to satellites, can be transferred using a VLBI transmitter onboard GNSS satellites. They showed that UT1-UTC can be transferred with a precision of approximately 30 µs over a long VLBI baseline. Utilizing VLBI networks, as opposed to a single baseline, can further improve the precision by more than 20%, depending on the choice of baselines.

VLBI remains the only technique capable of providing the full set of EOP (polar motion, UT1, and celestial pole offsets). Introducing an orbiting **VLBI transmitter** does not help the EOP determination accuracy. Simulations emphasize that proper **scheduling** is essential.

4.4 Improvement in orbit determination

Klopotek et al. (2023) calculated the improvement in orbit precision when adding a VT onboard LAGEOS-like and Galileo-like satellites. They assessed the 3D quality of the orbit using location-dependent position scatter (location-dependent WRMS values) of the satellite. For the Galileo satellites, they observed a clear dependence between orbit quality and both the number of observed satellites and the number of satellite observations. The orbit precision in this case ranges from 3.9 to 9.6 cm, with an average of 6.3 cm. For LAGEOS-like satellites, the number of observations and observation density have minimal impact on the precision of the orbit determination (POD), with an orbit precision of 2.0 cm in most cases. Increased observation density and enhanced satellite observation precision lead to improved orbit solutions (both in terms of precision and accuracy), as shown in their Figure 3, reproduced below for convenience.



Precision (P) and accuracy (A) of the determined orbits as a function of the satellite observation precision. The WRMS values were calculated for the along-track (ALONG), cross-track (CROSS), radial components (RADIAL) and as a 3D orbit scatter (3D). The results include schedules with (a–d) LAGEOS-like satellite (LAG) and (e–h) Galileo satellites (GAL). © Klopotek et al. (2020).

Other factors that influence the quality of derived orbits include the network configuration, specifically the distribution of participating stations around the globe. Klopotek et al. (2023) show that regions lacking VLBI stations or with limited mutual visibility between stations and satellites negatively impact average orbit quality. This is particularly evident in the southern hemisphere, where location-dependent WRMS values indicate that orbit solutions are at least twice as poor for both satellite types (LAGEOS-like and Galileo-like) compared to the northern hemisphere.

The addition of a VT onboard LAGEOS-like and Galileo-like satellites enhances orbit determination accuracy, with improvements depending on **observation quantity**, **strategy**, and **network configuration**.

4.5 Gravity field improvement

SLR studies and simulations have shown that adding a single satellite to a solution based on five SLR satellites can significantly improve the determination of the low-degree spherical harmonics of the Earth gravity field (Bloßfeld et al., 2018; Kehm et al., 2018). The **most notable improvements** were observed in the coefficients **C_{10}, C_{20}, and C_{40}**, with standard deviations improving by up to 30%. Further improvements in the POD of such satellites will support this goal.

Including a VT onboard various altimetric missions (e.g., Sentinel-6-second generation) or positioning missions (e.g., Galileo second generation) will certainly help. However, estimating the exact benefit is challenging, as the spacecraft **orbit geometry** and the **ground station network** involved play a crucial role.

Adding a satellite like GENESIS to an existing SLR satellite constellation improves the determination of low-degree spherical harmonics coefficients **C_{10}, C_{20}, and C_{40}**, and including a VT further enhances these improvements, though the **exact benefit** depends on spacecraft **orbit geometry** and the **ground station network**.

4.6 Improvement in altimetry and sea level rise

As explained in Section 3.5, we found that geocenter biases of 5 mm lead to an error of 0.6 mm in mean sea level, and geocenter rate biases of 0.5 mm/year result in a change in mean sea level of about 0.06 mm/year. Assuming a factor of 2 improvement in CM biases for realizing the TRF, applying the same method reduces these values to approximately 0.3 mm and 0.03 mm/year, respectively. However, we also noted that accuracy might be limited by discrepancies with tide gauge measurements, which show a difference of about 1 mm/year. This discrepancy is expected to decrease over time.

Since accuracy in the geocenter position and rate directly impacts global mean sea level accuracy, we can expect a **precision of 0.3 mm and 0.03 mm/year** for mean sea level, though these values are **not yet confirmed by tide gauge measurements**.

4.7 Role of the combination

Each technique provides access to some of the geodetic parameters described above, with varying levels of precision. The main sources of each parameter are listed in the table below. This table is based on Zoulida's PhD thesis (2016), and I have also included estimates of what can be achieved with the VT in the final column.

Parameter type	DORIS	GNSS	SLR	VLBI	VT on satellite

Quasar positions				XXX	If used as calibrator
Precession-Nutation		X	X	XXX	XXX
UT1				XXX	XXX
LOD	XX	XXX	XXX	XX	XX
Polar Motion	X	XXX	XX	XX	XX
Orbits	XXX	XXX	XXX		XXX
Station Positions	XXX	XXX	XXX	XXX	XXX
Geocenter	XX	XX	XXX		XXX
Scale	XX	XX	XXX	XXX	XXX
Troposphere	X	XXX	X	XX	XX
Ionosphere	XX	XXX		XX	XX
Geographic coverage	XX	XXX	X	X	

4.8 Simulations done for Jason-2

In her 2016 thesis, Zoulida presents the results of multi-technique analyses (GPS + SLR + DORIS) on the Jason-2 satellite, using it as a "**space tie**," and compares these results to traditional single-technique analyses. Specifically, she evaluates the impact of resolving GPS phase ambiguities, simultaneously estimating the orbits of the GPS constellation satellites and Jason-2 and determining the positions of ground stations.
As one of the few satellites combining DORIS, GPS, and SLR instruments, Jason-2 can be considered a prototype for GENESIS, albeit without the VT. The precision of the POD for Jason-2 has reached unprecedented levels, achieving 1 cm on the radial component, and its instruments have demonstrated stable performance over the years. Thus, studying Jason-2 as a space tie provides valuable insights into the potential effectiveness of the GENESIS mission for orbit determination and Earth reference frame establishment.

Zoulida (2016) compared GPS-only solutions with GPS+Jason-2 solutions. The network solutions for each technique were compared to corresponding official solutions, with an iterative process used to remove outliers. The level of agreement between each network solution and the official solution was quantified by the WRMS of the station position residuals. Zoulida (2016) found that adding Jason-2 GPS observations resulted in a shift of about 0.5 mm in the East and North components, and 1.3 mm in the vertical component. Observations from other techniques showed no significant additional effect. When comparing the SLR+Jason-2 solution to the SLR-only solution, it was shown that adding Jason-2 observations significantly impacted the SLR network solutions. The **GPS observations of Jason-2** also significantly affected the GPS geocenter coordinates, particularly the TX component, which shifted by approximately 7 mm, bringing it closer to the geocenter TX coordinate estimated by SLR. Furthermore, the time series of GPS geocenter components appeared smoother when Jason-2 observations were included.
One of Zoulida's key findings was that, although the addition of Jason-2 observations significantly improved the geocenter parameters for the GPS network, the multi-technique combination did not notably affect the geocenter or scale of any individual technique. Each technique essentially realized its own benchmark within the combined solution. Notable **biases** remained between the

geocenter and scale parameters of the different techniques, particularly between DORIS and the other two. This suggests that using only the Jason-2 satellite does not provide a sufficiently strong link between the techniques to yield a homogeneous combined solution, at least with the current parameterization.

It is crucial to emphasize that the effective use of space links relies on highly accurate knowledge of Jason-2 (LEO) orbits, achieved through the POD process. Multi-technique satellites are particularly advantageous for precise POD determination. However, the **accuracy of POD-estimated orbits** is sensitive to various error sources, including **inaccuracies** in modeling non-gravitational forces acting on the spacecraft, **errors** in the data reduction process, and observational **biases**. For GPS-estimated orbits, careful attention must be given to the ephemerides and **clocks** used as references, as any errors in these components can also affect orbit calculations. Additionally, it is essential to utilize the specific reference points of the antennas for the different instruments onboard the spacecraft. With these considerations in place, integrating GNSS data from LEO satellites to supplement data from GNSS ground stations could significantly enhance the quality of derived geodetic solutions.

Zoulida's study of the Jason-2 satellite as a space tie demonstrated significant **improvements in geocenter** determination for the GPS network but highlighted the need for **better links between techniques** to achieve a homogeneous solution and emphasized the importance of **precise LEO orbit determination** for successful POD and geodetic applications.

4.9 Simulations done for Sentinel-6

The ESA Sentinel-6 is an altimetry mission that requires highly accurate knowledge of the spacecraft's orbital position, with radial RMS orbit errors of less than 1.5 cm. For precise orbit determination (POD), the spacecraft is equipped with a dual-constellation **GNSS receiver**. Montenbruck et al. (2021) computed POD solutions for the first six months after launch and demonstrated **1-cm consistency** between ambiguity-fixed GPS-only and Galileo-only solutions with the dual-constellation product. A similar performance (1.3 cm 3D RMS) was achieved when comparing kinematic (without modelling of the forces) and reduced dynamic orbits (combining tracking data with models of the forces acting on the satellite). POD also incorporates antenna locations and knowledge of the center of mass location within the spacecraft. Overall, reduced dynamic orbit determination using GPS and Galileo tracking meets the altimetry-related requirements of the Sentinel-6 mission, achieving RMS height errors of less than 1.5 cm.

However, Galileo observations alone cannot provide independent scale information. Using **SLR** data from selected high-performance stations, a **better-than-1 cm RMS** consistency with the GNSS-based orbits was achieved. This improved further to 6 mm RMS when station-specific corrections, including site positions and ranging biases, were applied. For the radial orbit component, the SLR analysis showed a bias of less than 1 mm relative to the mean height of 13 high-performance SLR stations (Montenbruck et al., 2021).

ESA plans to equip the next generation of Sentinel-6 with a VT to further improve POD and enhance future TRF realization.

Montenbruck et al. (2021) demonstrated that Sentinel-6's dual-constellation GNSS receiver and SLR observations achieve **cm-level precision in orbit determination**.

4.10 Simulations with VT

Simulations conducted by the GFZ team (Mammadaliyev et al., 2019) with a VT onboard a LEO satellite at 762 km altitude and 63° inclination were carried out using the VieVS2tie software. The simulations involved two different station networks and ten different scenarios, aiming to assess the potential contribution of VLBI to geocenter determination. The results demonstrated VLBI's **ability to determine the geocenter**, with the station network affecting the geocenter estimation by up to **5 mm**.

For a satellite at 2000 and 6000 km altitude (MEO satellites) and with 105° and 110° inclinations respectively, Plank et al. (2014) performed simulations with various processing options and ground station networks. Their results showed that VLBI allows determination of antenna and **station positions** on Earth with a precision of a **few millimeters to 1–2 cm for weekly solutions**.

Similarly, Klopotek et al. (2020) performed simulations using MEO satellites (LAGEOS-type and Galileo-type) and legacy VLBI stations (extrapolating results for VGOS stations). They showed that geodetic VLBI performs on par with other space-geodetic techniques in terms of POD for satellites. For an assumed satellite observation precision better than 47 ps, they found average 3D orbit precision of 2.0 cm for LAGEOS and 6.3 cm for Galileo satellites (see Section 4.4). The simulations indicated that satellite geometry only marginally improved station position estimates, regardless of observation strategy and station network. The processing of the zenith wet delay was a key factor in these simulations. With simulated legacy VLBI observations of LAGEOS-like satellites and selected Galileo satellites, the precision of geocenter offsets, previously beyond the scope of geodetic VLBI analysis, was limited to the order of a single centimeter to a few centimeters. Unfortunately, this is insufficient to detect geocenter motion, which has an annual signal on the order of a few millimeters (see Section 3.2). **VGOS** provides an average precision improvement of 80% compared to legacy VLBI, with **geocenter offsets reaching the 7 mm level (near the detection limit)** for simulations with VGOS observations of Galileo satellites. This is due to enhanced observation density, homogeneous station distribution, and ten times more precise quasar observations. In principle, combining quasar and satellite observations could allow for simultaneous estimation of Earth rotation parameters (polar motion and UT1-UTC), geocenter offsets, VLBI station positions, and satellite orbits. However, Klopotek et al. (2020) also showed that poor satellite geometry can degrade the estimation of Earth rotation parameters and VLBI legacy station positions compared to quasar-only reference schedules (see Section 4.3). Therefore, careful scheduling of both quasar and satellite observations is necessary to fully benefit from this novel observation concept. **No negative impact on EOP** was observed, however, in the case of satellite observations with the **VGOS-type network**.

More recently, Sert et al. (2023) examined the improvement on UT1-UTC when using a VT onboard GNSS satellites. UT1-UTC is a crucial EOP that can only be determined by VLBI, which observes distant celestial sources to measure Earth's rotation angle. GNSS satellites, tracked from Earth, are insensitive to this angle, and the Orbit Determination and Time Synchronization (ODTS) process for GNSS satellites requires UT1-UTC as an input. Currently, UT1-UTC is provided by the International Earth Rotation and Reference Systems Service (IERS). A VT onboard GNSS satellites would enable the direct transfer of this information as an integrated step in the ODTS process, establishing a space tie between VLBI and GNSS techniques. Sert et al. (2023) investigated the **transfer quality of UT1-UTC** in this concept by considering different VLBI baselines. In their simulations, they assumed observations from a **VT onboard a Galileo satellite**, combined with quasar observations acquired by the same VLBI ground stations during the session, allowing for the direct transfer of UT1-UTC to the GNSS constellation. The geometrical configuration of the Galileo satellite relative to the ground stations was quantified by the UT1-UTC dilution of precision (UDOP). The simulations showed that UT1-UTC could be transferred with a **precision of about 30 µs** for a long VLBI baseline, where the precision estimated from quasar observations is 20 µs. Using VLBI networks instead of a single baseline further improved the transfer precision by more than 20%, depending on baseline selection.

Simulations with a VT onboard satellites, including LEO, MEO, and Galileo orbit configurations, demonstrate the ability to **improve geocenter determination** and Earth rotation parameter estimation, with significant gains in precision when using **VGOS-type networks** and dual (quasar-VT) observation strategies. Such simulations also show the potential **benefits for UT1-UTC transfer in GNSS** applications.

4.11 Simulations done for E-GRASP

Numerical simulations were conducted by the French Groupe de Recherche de Géodésie Spatiale (GRGS) for the E-GRASP proposal, submitted in response to the ESA EE-9 call. There are several limitations affecting the accuracy and stability of the ITRF, with the primary ones being the systematic errors of space geodetic techniques and the local ties. A **space-tie** offers the advantage of orbiting around the Earth, allowing continuous observation by multiple geodetic instruments, which helps strengthen the links between techniques. Pollet et al. (2023) conducted simulations with the goals of (1) evaluating the feasibility of achieving TRF objectives (mm-level accuracy and 0.1 mm/year stability), (2) determining the precision needed for onboard instrument positioning, and (3) identifying the minimum mission duration, with a maximum limit of five years set by ESA for the EE-9 call. They generated **synthetic measurements** for the four techniques, DORIS, GPS, SLR, and VLBI, using a global network of ground stations, applying specific models and noise. These measurements were processed to calculate orbital parameters, station positions, geocenter position, and EOPs, with current model accuracy assessed by comparing different existing models. The E-GRASP satellite was simulated with an **orbit inclined at 63°** and at an **altitude of 10,500 km**. The ground segment included all available DORIS stations, a set of geographically well-distributed IGS core stations to ensure accurate GNSS orbit estimation, the anticipated SLR stations in 2025 as provided by ILRS, and the expected 2025 VLBI stations. Petrachenko et al. (2009) recommended a globally distributed network of at least 16 VGOS antennas for daily EOP determination, while MacMillan (2017) used 27 stations in a decade-long simulation; Pollet et al. (2023) used 25 VGOS stations. The simulations included a quadratic polynomial for DORIS data processing to account for longer observation passes possible with the E-GRASP orbit compared to existing DORIS satellites.

The differences between the **calculated orbit and the reference orbit** varied by strategy, with values ranging from 0 to 0.3 mm, and standard deviations of 3–5 mm (radial), 5–7 mm (along-track), and 3–6 mm (cross-track), with 3D WRMS values of 6–10 mm. Millimeter-level accuracy is expected if an **accelerometer on-board** E-GRASP measures all **non-gravitational forces**. A cubic accelerometer and high-frequency measurements allowed for E-GRASP orbit accuracy at a **few mm**.

Regarding the biases and drifts estimated for the TRF determination, specifically the **geocenter position and the scale**, all drifts were below 0.07 mm/year. Biases included **0.5-0.7 mm** for the **X-component of the origin**, **0.1-1.0 mm** for the **Y-component**, and **0.1-0.6 mm** for the **Z-component**. The **scale** bias is **between 0.4 and 0.6 mm**, with a drift **below 0.03 mm/year**. To achieve this precision, Pollet et al. (2023) applied a geocenter motion model fitting $A + B\,t + C\ \cos\omega t + D\ \sin\omega t + E\ \cos 2\omega t + F\ \sin 2\omega t$ (where ω is 1 cycle/year) to the residual series of each origin component to account for the difference between CM and CE. Their simulations concluded that a satellite like E-GRASP could achieve **close to 1 mm accuracy and better than 0.1 mm/year stability for the TRF after five years**, with a **minimum mission duration of 3.5 years** required to meet these goals. They also stressed the importance of sub-millimeter precision for onboard antenna positioning to meet the requirements.

Key differences from the Jason-2 case include (1) **the presence of an onboard accelerometer**, (2) **better than millimeter-level calibration and positioning of onboard instruments**, (3) GNSS measurements with fixed ambiguity processing, (4) SLR measurement sampling equivalent to LAGEOS, and (5) a **high number of VLBI observations**.

Simulations for the E-GRASP mission demonstrate that a satellite equipped with precise instrumentation, including an accelerometer, can achieve **near-millimeter accuracy and long-term stability for the TRF**, provided the **mission duration** is at least **3.5 years** and onboard instruments are precisely **calibrated**.

4.12 Simulations done for GENESIS

Grounded in a rigorous understanding of the measurement principles and the underlying sensitivities of the techniques, we deduce that **VLBI and SLR offer complementary sensitivities to estimated parameters** such as the geocenter and Earth Orientation Parameters (EOP). While **SLR** excels in **ranging accuracy**, **VLBI** offers superior **angular resolution**. This distinction becomes clear from the construction of their observation equations. For SLR, the ranging observation equation involves to the pointing vector between the station and the satellite. In quasar VLBI, the observed quasar is effectively at an infinite distance, so the source pointing vector remains the same for both stations, depending solely on the quasar's Right Ascension and Declination, emphasizing angular sensitivity. In **satellite VLBI**, the sensitivity arises from the

difference between the pointing vectors from both stations to the satellite. While **angular sensitivity remains dominant**, the satellite's **distance also contributes to the equations**.
For GNSS, sensitivity comes from combining ranging measurements from multiple directions. At any epoch, numerous satellites are visible, providing robust directional sensitivity through diverse and simultaneous ranging observations.

More recently, simulations of the GENESIS mission conducted by CNES (Pollet, personal communication) support these arguments. However, they revealed issues related to the mission's **quasi-polar orbit**. Their results indicate that the current orbit configuration, as chosen by ESA, does not allow for accurate determination of the **Z-component of the geocenter**, even with simulated ideal and extensive laser measurements on the satellite. This **problem disappears when the orbit is tilted away from a purely polar inclination**. Another factor likely to impact data quality is the shared clock between GNSS and DORIS systems. Tests are currently underway within the IDS on Sentinel-6A to assess the influence of this shared clock on DORIS processing. It seems **unlikely** that GENESIS will achieve the E-GRASP mission's **precision level of a few mm**; while the **radial component of the geocenter** might be better than a **centimeter**, other components may remain in the range of a few centimeters.

Ait-Lakbir et al. (2024) presented simulation results at the ESA Science Working Group using the GINS (Géodésie par Intégrations Numériques Simultanées) software (Marty et al., 2011), focusing on the impact of GENESIS's orbit characteristics on reference frame parameters. These simulations incorporated synthetic space geodetic data for DORIS, GNSS, SLR, and VLBI, using GINS, which supports both simulation and processing. Data generation was based on the current network of ground stations, with an *a priori* geocenter motion model (Cheng et al., 2013) integrated into the simulated observations. Ait-Lakbir et al. (2024) suggested that the current GENESIS orbit may not provide additional valuable information for the TRF, particularly due to its polar inclination, which limits the observation of the annual signal in the **Z-coordinate of the TRF origin**. A recommended **inclination of 61°** could improve this aspect.

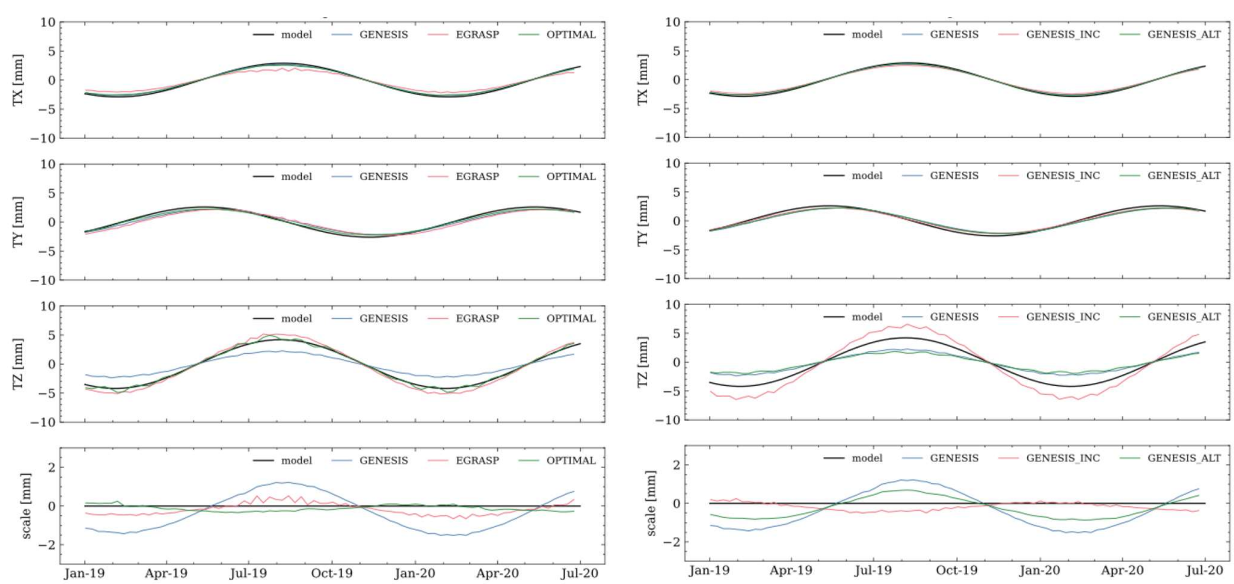
For their analysis, Ait-Lakbir et al. (2024) compared different orbit designs to evaluate their effectiveness in **capturing reference frame parameters**, focusing on the Z-coordinate of the **geocenter**. Because the geocenter motion is currently determined primarily by SLR, they used this technique as reference for sensitivity testing. Various orbital configurations, including E-GRASP (Pollet et al., 2023), GENESIS (Delva et al., 2023), and an optimized orbit designed to maximize visibility for each technique while considering design constraints (e.g., eclipse duration, radiation exposure), were examined. They also tested modified GENESIS orbits, one with an altered inclination (GENESIS-inc) and another with a different altitude (GENESIS-alt). The results showed that inclination was the key factor limiting GENESIS's performance compared to E-GRASP and OPTIMAL orbits. The characteristics of these orbits are summarized in the Table below.

	Semi-major axis/ Altitude [km]	Eccentricity	Inclination [deg]	Draconic period [days]
E-GRASP	10488/4109	0.32	63.42	5.85
GENESIS	12379/6000	0.001	95.5	399.77

OPTIMAL	15628/9250	0.001	61.0	287.36
GENESIS-inc	12371/5992	0.001	61.0	189.09
GENESIS-alt	15628/9250	0.001	95.5	380.34

With the two alternative versions of the GENESIS orbit (GENESIS_inc and GENESIS_alt), they show that the inclination is the reason why the GENESIS orbit cannot achieve the same performance as the E-GRASP and OPTIMAL orbits.

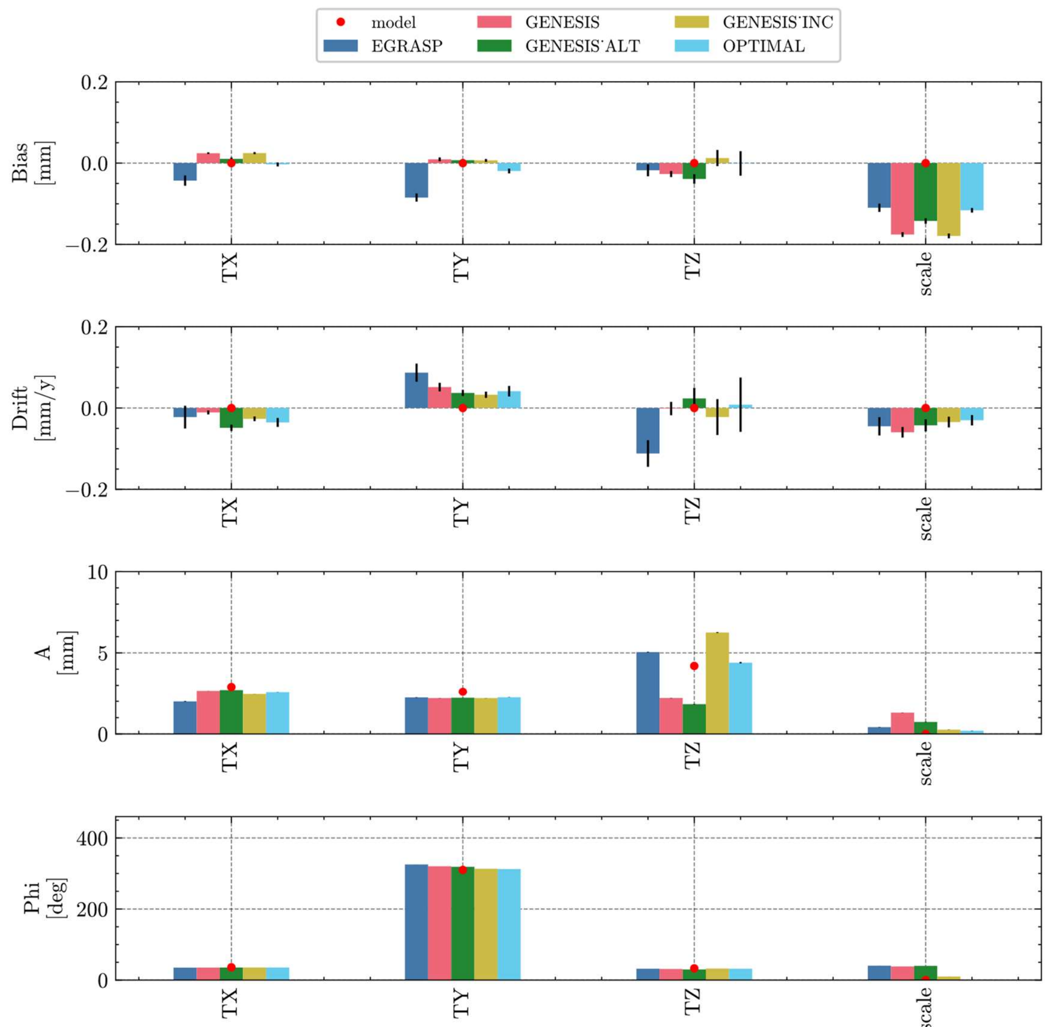
The Figure below provides estimation of the geocenter coordinates (TZ, TY,TZ), representing the translation of the origin, and the scale factor, estimated from the station coordinates with respect to the *a priori* reference frame (ITRF2020) without the geocenter model. Biases in the X and Y coordinates of the geocenter were observed for the E-GRASP orbit, as previously noted by Pollet et al. (2023). These biases were reduced when using the GENESIS or optimal orbit configurations. However, significant biases in the scale factor, ranging from -0.10 mm to -0.17 mm, were consistent across all tested orbits. Although limited by a dataset of only 1.5 years, the GENESIS and optimal orbits demonstrated improved drift accuracy in the Y and Z components of the geocenter compared to E-GRASP. The current GENESIS orbit exhibits a notable annual signal in the scale factor, with an amplitude of 1.30 mm, due to a correlation between the scale factor and the Z-component of geocenter motion. This emphasizes the importance of orbit selection for GENESIS, particularly its impact on the Z-coordinate determination of the geocenter.



Weekly estimates of reference frame the origin (TX,TY,TZ) and scale factor with respect to ITRF2020, for GENESIS, E-GRASP and OPTIMAL orbits on the left, and for GENESIS, GENESIS_inc, and GENESIS_alt on the right.

Changing to an optimal inclination improves the scale factor and better **captures the annual signal in the Z direction**, although it overestimates the amplitude by 48%. Adjusting the altitude, however, had no effect. The Figure below presents the bias, drift and amplitude and phase angle of the annual signal estimated from the time series.

Solar radiation pressure modeling errors are a primary source of orbital inaccuracies, particularly generating spurious signals at draconic frequencies. The **draconic period for GENESIS**'s current orbit closely aligns with the annual frequency, **complicating the separation** of geophysical signals from systematic errors. Similarly, the draconic year for the GENESIS orbit with a modified inclination (GENESIS-inc) is also near the semi-annual frequency. Only the elliptic orbit proposed for E-GRASP or an optimized design that **maximizes the separation between draconic and seasonal frequencies** seems to provide a viable solution.



Biases, drift and annual signals (Amplitude A **and Phase** Phi**) estimated from the origin translation (TX,TY,TZ) and scale factor time series. The red dots represent the geocenter motion model (Cheng et al., 2013) introduced in the reference frame used for simulating the observations. The phase angle reference is January 1st. © Ait-Lakbir et al. (2024)**

In summary, orbit selection also affects the transfer of orbital errors to reference frame parameters, particularly the TZ component. The current GENESIS orbit is not ideal for minimizing errors caused by cross-track dynamical mismodeling, particularly discrepancies in **solar radiation pressure**. An onboard **accelerometer**, if included on GENESIS, could mitigate these **non-gravitational force** modeling errors, as shown by GRACE data (Kuang et al., 2015) and E-GRASP simulations (Pollet et al., 2023). Without accelerometers, **precise knowledge of the satellite's design (optics, mass evolution, attitude control)** or choosing an **orbit that minimizes these effects** becomes critical. Changing GENESIS's inclination to 61° improves the observation of the annual signal in the Z-component of the geocenter and reduces the transfer of orbital errors to this component.

The GRGS group has announced plans for more realistic simulations, focusing on the impact of systematic errors in the next phase of their research.

In POD of MEO satellites, the radial component is typically determined with higher accuracy than the along-track and cross-track components. Schunck et al. (2024) performed simulations of GENESIS POD, accounting for this difference: the along-track and cross-track components of all offset positions were scaled to exceed the offsets in the radial direction. However, Delva et al. (2023) suggest that the GENESIS orbit could achieve accuracies better than 1 cm, as GNSS data typically provide strong contributions to POD for LEO missions due to the nearly continuous tracking of GNSS satellites. Montenbruck et al. (2023) emphasize though that at an altitude of 6000 km, GNSS tracking coverage for a spaceborne receiver is significantly reduced. To adopt a more conservative approach, Schunck et al. (2024) started with noise levels of 1 cm, 2 cm, and 3 cm and calculated the delay differences resulting from offsets between the true and erroneous satellite positions as observed by ground stations. Derived parameters were then estimated from the simulated observations using a least-squares adjustment, which included estimating station positions, tropospheric effects at the ground stations, and UT1-UTC. Geodetic source positions were fixed to *a priori* values, and an optimized VGOS schedule was employed, considering both current and projected VGOS antenna networks. Within this framework, Schunck et al. (2024) demonstrated that, with **proper scheduling**, the **degradation of station position** and **UT1-UTC** repeatabilities could be limited to **less than 0.09 mm and 0.06 μs**, respectively.

Simulations for the GENESIS mission emphasize the critical role of **orbit selection**, highlighting that the current **quasi-polar configuration limits the accuracy** of geocenter determination, particularly for the Z-component. Adjusting the orbital inclination could significantly enhance performance.
Additionally, simulations indicate that incorporating VT observations into geodetic sessions focused on quasar observations may **degrade** the accuracy of station positions or EOP unless **proper scheduling** of **VGOS** stations is implemented.

4.13 In practice

Some tips and tricks we are thinking of (largely based on Zoulida's processing using GINS and from my own experience in orbit determination):
- Use all possible ground stations,
- Use all possible well-determined local ties,
- Measure space ties extremely well,

- Use antenna calibrations,
- EOPs and station coordinates at collocated stations are taken into account as common parameters,
- As *a priori* for orbits and clocks of the constellation satellites, use those of the GNSS satellite network given by IGS,
- As *a priori* for ground displacements and velocities, use those given by the different services,
- As *a priori* on geocenter coordinates and scales, use those given by the different services,
- Use *a priori* values of link between CM and CN given by the different techniques,
- As *a priori* for the EOPs, use those provided by the different techniques or IERS,
- Use integer ambiguity values for GNSS station network as given by IGS, but estimate satellite ambiguities,
- Model sites deformations from tidal effects and atmospheric & oceanic loading,
- Model shifts and post-seismic deformations for sites affected by major earthquakes,
- Use a strategy for the detection of discontinuities in the technique station position time series and correct for them,
- Estimate ground station positions and velocities, satellite orbits, clock parameters, scale and position on geocenter (technique biases), EOPs, troposphere corrections, ionosphere effects (chose these as variables in the equations),
- Estimate annual and semi-annual terms for the stations of all techniques with long enough data spans, as well as for the CN-CM link,
- Possibly, at collocated sites, estimate troposphere as one,
- Possibly estimate errors in the reference coordinates of the satellite tracking stations in POD calculations,
- Possibly estimate common satellite orbits at once,
- Perhaps use dynamic constraints (solar radiation pressure, albedo, drag) in POD and estimate a scale independent of the techniques,
- Possibly estimate phase ambiguities of GNSS data,
- Maybe it will be necessary to estimate corrections for GNSS satellite orbits (and clocks) using GPS ground station observations (this is what Zoulida did when she processed Jason-2)
- If ILRS does not provide official guidance on range biases for SLR data, perhaps biases should be estimated on observations for all SLR stations,
- Put constraints so that the geocenter, scale, EOP, orbit solutions are as close as possible to the *a priori*,
- If we use the normal equations given by the different analysis centers, we must remove the constraints,
- GNSS observation sampling rate could be set to 300 seconds, as a compromise between orbit quality and processing time.

Dynamic constraints in POD involve using "long-arc" calculations (e.g., over a full week or 9 days), where gravitational and non-gravitational forces acting on the satellite are modeled based on current knowledge, with some scale parameters adjusted to fit the data (see Beutler et al., 1994; Haines et al., 2015; and our TN1).

Key parameters to monitor in this process include arc lengths for orbits, discontinuities at midnight between consecutive orbits, scale factors for non-gravitational forces, biases specific to each

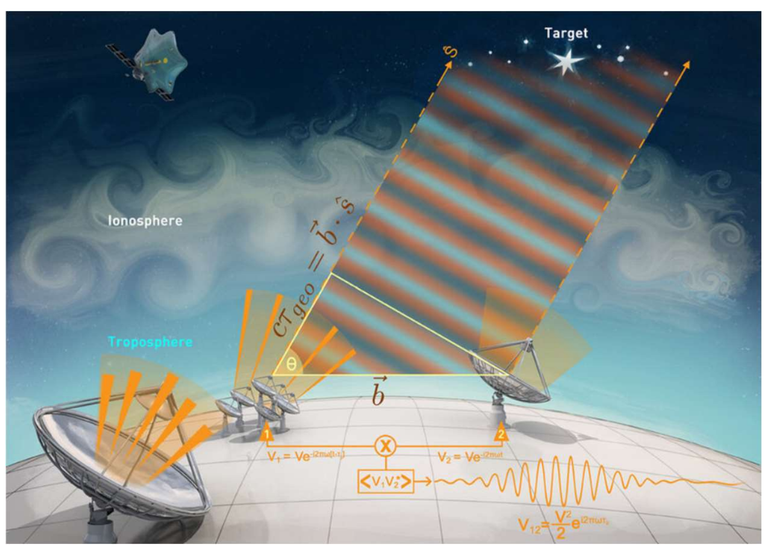
technique, the influence of analysis strategies on the results, and systematic errors inherent to each technique (e.g., antenna calibration at ground stations or onboard the satellite).
Another potential challenge is the draconic signal discussed in Section 3.1. Uncertainties in solar radiation pressure models are the primary sources of orbital errors. These uncertainties often generate spurious signals in the geodetic parameters at draconic frequencies, making this a crucial factor to address.

The GENESIS mission will contribute to the determination of the TRF and its related by-products, enhancing the **identification of biases** and **increasing the robustness** of accuracy assessments. However, GENESIS alone will not fully resolve the existing challenges in scale and CM determination. A larger **constellation of satellites like GENESIS**, along with different orbital **inclinations**, would be required to achieve this goal.

4.14 Annex final note

Based on my experience with Same Beam Interferometry (SBI) to enhance precision in radioscience, I proposed using SBI in VLBI observations, rather than relying solely on traditional VLBI, to increase observational accuracy. Leonid Petrov pointed out that this technique is already applied in astrometry when differential measurements are taken across multiple quasars in the sky, often using a "calibrator" (a more stable source) to improve measurement precision. He specifically mentioned the work of Rioja and Dodson (2020), which is known as multi-view astrometry. This next generation of techniques will enable ultra-precise astrometry across a much broader frequency range, from hundreds of MHz to hundreds of GHz.

One of the key advantages of this methodology is that astrometry will become more suitable for large, unbiased surveys. It allows for the mitigation of atmospheric gradient effects, significantly reducing atmospheric distortions, which are the primary limiting factor in VLBI observations. A forthcoming paper by Ding et al. (with Petrov as a co-author) will address this topic. Leonid Petrov suggested exploring this multi-view approach using a VLBI Transmitter (VT) on satellites.



Schematic from Rioja & Dodson (2020) that shows all the possible approaches for sub-mm astrometric VLBI

Implementing SBI with a VT and quasars would involve using two ground stations, similar to traditional VLBI, while observing a multi-view field beneath the satellite. This would involve using a secondary field of view to successively observe a "calibrator" and additional quasars, with 2 to 8 objects in the field of view. There might be configurations where this is feasible for GENESIS. Leonid Petrov recommends investigating this direction, and if we decide to pursue it, we should seek guidance from the astrometric community, as they already employ this technique. If we proceed, Leonid Petrov is willing to support us. Demonstrating the viability of this approach could prompt the IVS to launch a dedicated campaign on the subject, potentially providing real data in preparation for, or during, the GENESIS mission.

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