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ORIGINAL ARTICLE

Prospects of GENESIS and Galileo joint orbit and clock determination

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Abstract

The European Space Agency (ESA) is preparing a satellite mission called GENESIS to be launched in 2027 as part of the FutureNAV program. GENESIS co-locates, for the first time, all four space geodetic techniques on one satellite platform. The main objectives of the mission are the realization of the International Terrestrial Reference Frames and the mitigation of biases in geodetic measurements; however, GENESIS will remarkably contribute to the determination of the geodetic parameters. The precise GENESIS orbits will be determined through satellite-to-satellite tracking, employing two GNSS antennas to observe GPS and Galileo satellites in both nadir and zenith directions. In this research, we show results from simulations of GENESIS and Galileo-like constellations with joint orbit and clock determination. We assess the orbit quality of GENESIS based on nadir-only, zenith-only, and combined nadir–zenith GNSS observations. The results prove that GENESIS and Galileo joint orbit and clock determination substantially improves Galileo orbits, satellite clocks, and even ground-based clocks of GNSS receivers tracking Galileo satellites. Although zenith and nadir GNSS antennas favor different orbital planes in terms of the number of collected observations, the mean results for each Galileo orbital plane are improved to a similar extent. The 3D orbit error of Galileo is improved from 27 mm (Galileo-only), 23 mm (Galileo + zenith), 16 mm (Galileo + nadir), to 14 mm (Galileo + zenith + nadir GENESIS observations), i.e., almost by a factor of two in the joint GENESIS + Galileo orbit and clock solutions.

Keywords Space geodesy · Co-location in space · Space ties · GENESIS · GNSS · Precise orbit determination

1 Introduction

The forthcoming GENESIS mission constitutes a part of the European Space Agency's (ESA) FutureNAV program planned to be launched in 2027. The mission will integrate, for the very first time, all four techniques of space geodesy (see Fig. 1)—three satellite techniques and one quasar-based interferometric technique. The fundamental advantage of GENESIS is the complementary, highly accurate co-location of Global Navigation Satellite System (GNSS—including American GPS and European Galileo), Very Long Baseline Interferometry (VLBI, Schuh and Böhm 2014), Satellite Laser Ranging (SLR, Pearlman et al. 2019) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS, Moreaux et al. 2023) on the same satellite platform (Delva et al. 2023). Although there are satellite missions aggregating more than one space technique e.g., Sentinel-3A/B (Fletcher 2012) and Sentinel-6A (Donlon et al. 2021), none of those exploits VLBI onboard. The mission is supported by a global geodetic scientific community that actively cooperates within the International Association of Geodesy Services, including worldwide networks, data providers, and analysis centers, as well as ESA's Navigation Science Office. GENESIS introduces a chance to derive global geodetic parameters, as well as to directly compare space geodetic techniques along with improving our comprehension regarding the systematic errors and biases among solutions obtained through different techniques.

GENESIS will considerably improve various Earth-related parameters, particularly in research associated with precise positioning, reference frames, and mass displacements in the Earth system (Delva et al. 2023). Consequently, this mission ensures that Earth science and future politics on Earth-related topics will reap the benefits of improvements in the Terrestrial Reference System (TRS) and its connection to the Celestial Reference System (CRS). Precise realization of

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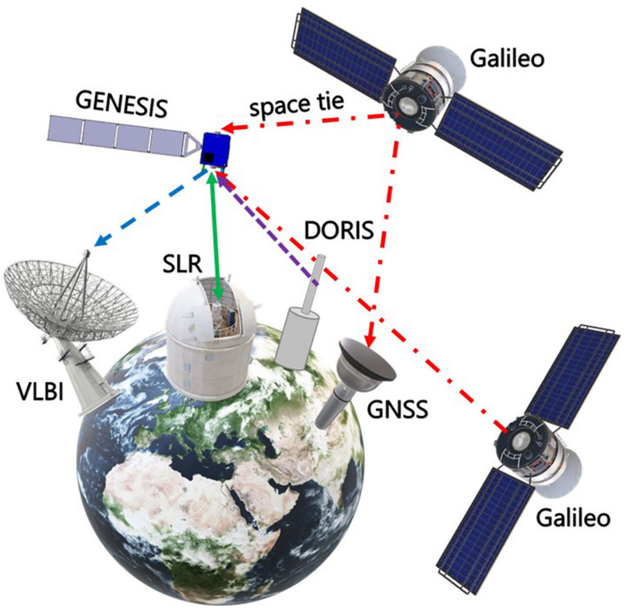

Fig. 1 The idea of space geodesy technique co-location including GENESIS satellite serving as a space tie

the TRS together with awareness of Earth's kinematic parameters are essential for many scientific and social ventures.

Today, space geodetic techniques suffer from systematic errors and biases that emerge from the lack of precise antenna calibrations, delays in detectors and electronic circuits, and imprecise background models of the geodynamic processes or, e.g., signal propagation models through different atmosphere layers (Appleby et al. 2016; Luceri et al. 2019). Consequently, space geodetic techniques provide solutions with high intra-technique consistency (i.e., precision) but low inter-technique agreement (accuracy). The inadequate spatial distribution of co-location sites across the globe and errors in local ties ground measurements in geodetic observatories introduce another source of inconsistencies between different geodetic techniques limiting the current accuracy in geodesy (Thaller et al. 2011; Glaser et al. 2019; Zajdel et al. 2019; Bury et al. 2021).

The primary challenge in establishing a TRS stems from the difficulty in measuring with sufficient accuracy the local ties, i.e., the connections between reference points, e.g., the intersection of axes of large instruments or phase centers of antennas. Also, terrestrial and celestial reference frames (physical realizations of TRS and CRS, respectively) are determined independently—one of them is fixed when computing the other. Both frames are connected with Earth orientation parameters (EOP). The IAG Resolution 2 at the International Union of Geodesy and Geophysics (IUGG) General Assembly in Melbourne in 2011 recommends that the highest consistency between the CRF, the TRF, and the EOP should be a primary goal in all future realizations of the CRS. The adjustment of the celestial and terrestrial reference frames and EOP might be improved from new observations provided by GENESIS. The GENESIS mission is thus dedicated to improving space references to realize TRS in accordance with the Global Geodetic Observing System (GGOS) necessities (Plag and Pearlman 2009). The GGOS accuracy and stability requirements are set to observe the smallest variations in the Earth system. The goals of the GGOS adopt specific requirements for the reference frame accuracy and stability equal to 1 mm and 0.1 mm/y, respectively.

The payload designed to achieve the co-location in space consists of a VLBI transmitter, a GNSS receiver tracking GPS and Galileo with nadir and zenith-pointing antennas, a DORIS receiver, a passive laser retro-reflector (P-LRR) for SLR, and an ultra-stable oscillator (USO) that will interconnect all four techniques (Delva et al. 2023). GENESIS will serve as a calibrated co-location and reference point in space, complementing the ground-based co-location attempts, and should result in the effective connection of ground stations. The satellite will be equipped with accurately calibrated antennas providing high-accuracy reference points. By doing so, it will enable the simultaneous determination of a part of instrumental biases of the observing techniques. The bias determination is crucial to mitigate systematic errors that could lead to erroneous interpretations of differences between the techniques (Collilieux et al. 2009; Appleby et al. 2016; Schmid et al. 2016; Drożdżewski and Sośnica 2021). GENESIS has the potential to establish the TRF via GNSS satellites with millimeter-level accuracy to any location on Earth, thus improving precise positioning and navigation.

The GENESIS mission has a number of key requirements vital for ensuring its success in achieving the main mission objective, namely the co-location of the four geodetic techniques in space (Delva et al. 2023). The development time of the platform should not exceed 4 years. Moreover, the mission's operational lifetime must extend for a minimum of three years. Precision is paramount in the GENESIS mission's design, in particular precisely calibrated onboard ties. The center-of-mass (COM) should be known with 1 mm accuracy in the satellite frame (Delva et al. 2023). The same accuracy is designed for the offset between the payload and the satellite COM which should not surpass 1 mm accuracy during the mission. In this case, adequate thermoelastic materials or extremely accurate on-ground calibration tests are required (Delva et al. 2023).

GENESIS precise orbit should be determined with accuracy better than 1 cm. GENESIS orbit is expected to be computed as dynamic mode or reduced-dynamic mode based on GPS + Galileo observations (Montenbruck et al. 2023). The orbit of GENESIS will be mainly determined in satellite-to-satellite tracking with the use of two GNSS antennas observing GPS and Galileo satellites in nadir and zenith directions (Delva et al. 2023). A dual antenna system will overcome the navigation satellites' visibility limitations and offer better tracking capabilities (Montenbruck et al. 2023). Using GNSS measurements will ensure one of the most reliable precise orbit determination (POD) contributions thanks to the tracking of all-in-view navigation satellites. However, the quality of GNSS-based orbits heavily depends on the ability to accurately model systematic errors, e.g., variations of the phase center of the receiver and transmitter antennas. It is expected that improved calibrations of the receiver antennas mounted on the GENESIS platform will also enhance POD capabilities (Montenbruck et al. 2023; Delva et al. 2023). When measurements are collected at low elevation angles from the perspective of a low-orbiting satellite, the role of calibration becomes crucial (Schmid et al. 2016). Two factors will be vital—a high success rate of integer ambiguity resolution together with an accurate radiation pressure model of the GENESIS spacecraft. Achieving the highest precision requires an in-depth understanding of the optical and thermal properties of materials used in assembling the platform, including factors such as material absorption and reflection. Additionally, all onboard instruments have to be synchronized to a common time reference, i.e., all geodetic instruments shall be referenced and synchronized to each other. Finally, the orbit-related products from global tracking networks of the geodetic space techniques should be approachable to provide the link with current TRF realizations.

Our work follows the idea of considering GENESIS in the Medium Earth Orbit (MEO) together with the existing Galileo constellation for precise orbit and clock determination as an intermediate step before implementing high-advanced solutions, such as the inter-satellite links (ISL) terminals or optical clocks in the proposed new generation of navigational MEO-LEO constellations (Giorgi et al. 2019; Michalak et al. 2021). Please note that the GENESIS altitude is equal to about 6000 km, which is considered as MEO, but lower than GNSS constellations. GENESIS serves as a platform for establishing a connection between Galileo satellites. Such an approach can be compared to the indirect ISL when the satellites in the constellation are linked via connecting points but without the impact of atmosphere- and ground station-related errors. A similar concept is apparent in the future GNSS constellation "Kepler" proposed by the German Aerospace Center (DLR) consisting of 24 MEO satellites on three orbital planes (analogous to the Galileo constellation) and 6 low Earth orbit (LEO) satellites on two near-polar orbital planes (Glaser et al. 2020; Michalak et al. 2021). The Kepler constellation is internally connected with two-way optical inter-satellite links and optical frequency references—LEO satellites carry ultra-stable optical clocks and serve as a very stable time reference for Kepler (Giorgi et al. 2019). Such design allows for deriving an offset value between the system time and the ground time scale. The ISL is established between MEO satellites in one orbital plane, and the LEO and MEO satellites are connected according to the ISL scheduler (Glaser et al. 2020).

GENESIS will be a unique mission because, for the very first time, a MEO satellite mission will be equipped with two GNSS antennas. Two GNSS antennas pointing in different directions were installed onboard LEO missions; however, the zenith antenna was typically used for POD, whereas the side antenna was typically employed for radio-occultation studies of the atmosphere or nadir pointing antenna for GNSS reflectometry. A configuration similar to GENESIS with a spacecraft at an altitude of about 6000 km and two GNSS antennas has not been exploited so far.

In this research, we position GENESIS in the role of platform for the link between Galileo satellites; thus, the orbits and clocks of Galileo and GENESIS can be jointly determined. Section 2 provides a brief overview of simulation methodology. Section 3 describes the impact of the observation geometry and its impact on the orbit parameters. In Sect. 4, we show a detailed evaluation of the joint GENESIS and Galileo-like orbit and clock determination with a preliminary assessment of other possible observation geometries, i.e., Sentinel-like satellite instead of GENESIS and with additional exploitation of the ISL; then, Sect. 5 provides concluding remarks.

2 Simulation methodology

2.1 Simulation setup

The analysis of GENESIS and Galileo-like joint processing is conducted in the General Simulation Tool for Earth-Orbiting Objects (GSTE) software written in MATLAB (https://www.mathworks.com/—accessed 27.11.2023), initially prepared for simulating various options for the Galileo system of the second generation, such as onboard accelerometers, ISL, and solar radiation pressure modeling, and the quality of geodetic parameters derived from the enhanced navigation system. The software consists of several modules; the key parts are the orbit propagator, a configurable simulator of the GNSS and the ISL observations, and a parameter estimator based on weighted least squares (WLS) (Kur and Kalarus 2021; Kur and Liwosz 2022).

Simulations are performed for the Galileo-like constellation and the GENESIS satellite with properties described in Table 1. Reference satellite orbits were propagated by exploiting a set of gravitational and non-gravitational force models (Table 1). In the simulations, 30 evenly distributed GNSS ground stations are used. The satellite clock errors are co-estimated with other parameters. GNSS observations from Galileo to GENESIS account for eclipsing seasons. In

Table 1 Simulation characteristics—(a) satellite models, (b) properties of orbit propagation, (c) setup of simulated GNSS observations, and (d) estimated parameters

Simulation characteristics	
(a) Satellite models	
Galileo-like constellation	Galileo FOC box-wing model
Walker definition	56°: 24/3/1 Orbital plane A: SVN = 1–8 Orbital plane B: SVN = 9–16 Orbital plane C: SVN = 17–24
Orbit radius	29 600 km
Numerical integrator	Runge–Kutta 4th order
GENESIS	Galileo FOC box-wing model
Inclination	95.5°
Orbit radius	12 378 km
Numerical integrator	Runge–Kutta 4th order
(b) Force models used in orbit propagator	
Earth gravity field	EGM2008 16 × 16 (Pavlis et al. 2012)
Gravitational perturbation	Sun, Moon, and planets
Relativistic perturbations	Schwarzschild Term, Lense-Thirring Precession, Geodetic Precession (Petit and Luzum 2010)
Solar flux	Constant
Earth's albedo	Analytical
Satellite surface properties	Box-wing model based on GSA metadata https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata
(c) Simulation of GNSS observations	
Data time span	21 days with 1-day arcs
30 ground stations (evenly distributed)	
GNSS (Galileo) observations for ground stations	
Sampling interval	30 s
Observation noise	1 cm
Zenith wet delays	Harmonic function with horizontal variations
Observation weighting	Observation weight $P_{GNSS} = \frac{cos^2(z)}{\sigma_{GNSS}^2}$, where z is the satellite zenith angle and σ_{GNSS} is GNSS observation noise
Station clock errors—observation noise	1 ns
Satellite clock errors—observation noise	0.1 ns
GNSS (Galileo) observations for GENESIS	
Sampling interval	30 s
Observation noise	0.5 cm + antenna error up to 0.4 cm
Observation weight	$P_{ISL} = \frac{1}{\sigma^2}$, where σ is observation noise
Satellite clock errors—observation noise	0.1 ns
(d) Estimated parameters	
Satellites' positions and velocities in Cartesian coordinates*	
ECOM2*—9 parameters (constants D_0, Y_0, B_0, and periodic terms $D_{2,C}$, $D_{2,S}$, $D_{4,C}$, $D_{4,S}$, $B_{1,C}$, $B_{1,S}$ (Arnold et al. 2015)	
Epoch-wise satellite clocks*	
Epoch-wise station clocks (one station clock is as a reference)	
Zenith wet delays—piecewise linear model (only for ground stations, 13 parameters)	
*Estimated for Galileo and GENESIS	

addition, we reject all observations passing up to 1000 km above the Earth, which are not included in the processing to avoid signal bending and occultation in the upper atmosphere. The optical properties of the GENESIS satellite bus and solar panels for constructing the box-wing model are not yet defined. In the analysis, we assume twin box-wing models for the Galileo and GENESIS satellites with surface properties the same as for Galileo Full Operational Capability (FOC) satellites in yaw steering mode. The simulated phase measurements are equivalent to a dual-frequency ionosphere-free combination of phases. GNSS phase observations collected by ground stations are simulated as white noise with a standard deviation equal to 1 cm, which assumes that mismodeled atmospheric propagation errors—troposphere and ionosphere—are included in the overall observation error budget. GNSS measurements to GENESIS are burdened with white noise with a standard deviation of 0.5 cm plus additional error associated with the zenith/nadir angle of the GENESIS GNSS antennas due to the current limits of antenna calibrations. Each simulation scenario shown at the end of the section is propagated for 21 days with randomly generated measurement errors. The applied errors and mismodeling effects were carefully chosen to obtain orbit error for a Galileo-like case similar to the precise orbit accuracy of GPS as reported on the International GNSS Service webpage at the level of about 2.5–3 cm.

Orbital parameters of GENESIS, i.e., the semimajor axis of 12 378 km and the inclination angle of 95.5°, were selected as a trade-off for different space geodetic techniques (Delva et al. 2023). VLBI prefers high-orbiting targets because at least two stations must observe the same object at the same time, which is easier for high targets, and some large VLBI telescopes have limits in their rotational motion to follow low-orbiting fast-moving objects. Contrary, SLR and DORIS prefer low-orbiting targets because the number of reflected photons decreases with the fourth power of the station-satellite distance for two-way laser ranging, and only low-orbiting satellites provide large relative station-satellite velocity differences to employ high-accuracy Doppler positioning techniques. The selected GENESIS orbital parameters shall satisfy the requirements of all geodetic techniques to the possible extent; therefore, the rather untypical parameters for satellite missions were chosen with a satellite height of almost 6000 km and near-polar orbit.

In the figures illustrating orbit and clock estimation errors in Sect. 4, we show the mean RMS error values derived from the simulation period along with their corresponding standard deviations. RMS is computed from differences between the simulated reference orbit and clock parameters and estimated parameters reconstructed on the basis of simulated data with pre-defined measurement errors. It is also important to emphasize that the estimated corrections obtained from real-world data are affected by numerous environmental and electronic factors, including tidal motion, biases, antenna phase center variations, and satellite attitude, which are not addressed in this study.

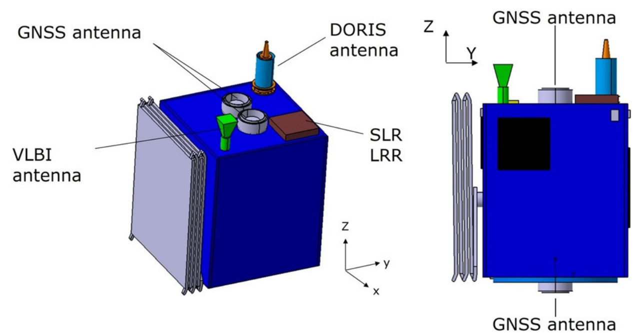

Fig. 2 Overview of GENESIS instruments, including GNSS nadir and zenith antennas (source: Delva et al., (2023) with own modifications)

2.2 GNSS antennas on GENESIS

GENESIS satellite will be equipped with two GNSS antennas—zenith and nadir pointing (Fig. 2). Nadir antenna, i.e., pointing to the geocenter, will allow observing Galileo satellites on the other side of the Earth. Some of the potential GNSS measurements from the nadir antenna will not be available due to the obstruction of satellite signals by the Earth. Additionally, a number of measurements pass through the atmosphere, which are apparent for the nadir antenna only. These observations are typically valuable for ionospheric and tropospheric studies using the GNSS radio-occultation techniques, however, the bent signals introduce additional challenges in employing them in POD. Table 2 displays the number of observations passing below the selected height of the atmosphere compared with the sum of measurements obtained for the GENESIS nadir antenna for one day of simulation. Table 2 demonstrates that about 10% of all possible GNSS measurements pass the atmosphere and would require ionospheric and tropospheric corrections. In this research, the minimum nadir angle for GNSS observations collected by GENESIS is slightly above 36.6° as observations passing through the atmosphere are not included in the POD. In general, the minimum nadir angle equal to 31.1° is observed which agrees with Montenbruck et al. (2023) where the value of 31.2° is proposed for GENESIS data processing to exclude observations obscured by the Earth. In Sect. 3, we provide a comprehensive analysis of observational geometry from both GENESIS antennas.

In the simulations, we apply an error pattern dependent on the zenith/nadir angle of the observations for both GENESIS antennas which is defined as

$$\sigma_{\mathrm{A}} = \left\lfloor \frac{\angle A}{10^\circ} \right\rfloor \cdot 0.5 \ \ \mathrm{mm}, \tag{1}$$

Table 2 Number of Galileo observations collected by GENESIS nadir antenna passing through the chosen height of the atmosphere for GNSS radio-occultation studies

Atmosphere height [km]	Number of observations (% of all measurements passing higher than 1000 km above the Earth)	Nadir angle range [degrees]
< 40	160 (~ 0.5%)	31.1–31.3
< 100	355 (~ 1.0%)	31.1–31.6
< 200	703 (~ 2.0%)	31.1–32.1
< 300	1040 (~ 3.0%)	31.1–32.7
< 400	1376 (~ 3.9%)	31.1–33.2
< 500	1739 (~ 5.0%)	31.1–33.8
< 600	2087 (~ 6.0%)	31.1–34.4
< 700	2436 (~ 7.0%)	31.1–34.9
< 800	2801 (~ 8.0%)	31.1–35.5
< 900	3170 (~ 8.1%)	31.1–36.0
< 1000	3539 (~ 10.2%)	31.1–36.6
> 1000	34,857	36.6–90.0

Table 3 Physical and orbital characteristics of GENESIS

Diameter (m)	0.8 × 0.8 × 1.0
Mass (kg)	375.0 (wet) 310.0 (dry)
Area-to-mass (m^2/kg)	ca. $2.0 \cdot 10^{-3}$—$2.6 \cdot 10^{-3}$
Semimajor axis a (km)	12,378
Altitude (km)	6000
Eccentricity	≤ 0.02
Inclination (°)	95.5
Drift of ascending node (days)	3789
Drift of perigee (days)	771
Draconitic year (days)	404
Orbital period (hh:mm)	3:49

where σ_A means antenna error and $\angle A$ is the zenith/nadir angle for the respective antenna given in degrees and measured in the GENESIS satellite frame. The antennas assume error values in the range from 0 mm (applicable only for the zenith-pointing observations) up to 4 mm for the highest observation angles.

We analyze the following simulation scenarios for the purpose of the orbit and clock determination which diverge in GNSS observations exploited:

1. Galileo-like—only GNSS observations collected by ground stations observing Galileo satellites are considered.
2. Galileo-like + GENESIS (zenith)—GNSS observations collected by ground stations observing Galileo satellites and GNSS observations collected by GENESIS zenith antenna from Galileo satellites are considered.
3. Galileo-like + GENESIS (nadir)—GNSS observations collected by ground stations observing Galileo satellites and GNSS observations collected by GENESIS nadir antenna observing Galileo satellites are considered.
4. Galileo-like + GENESIS (both)—GNSS observations collected by ground stations observing Galileo satellites and GNSS observations collected by GENESIS zenith and nadir antennas observing Galileo satellites are considered.

3 Geometry of GNSS observations

In this section, we focus on the impact of observation geometry collected by GENESIS antennas and their potential impact on measurement errors. The planned physical and orbital characteristics of GENESIS are demonstrated in Table 3 based on the information provided by Delva et al. (2023). In general, the observation geometry between Galileo satellites distributed among three orbital planes and GENESIS will change slowly. The drift of GENESIS ascending node in near-polar orbit due to Earth's oblateness is equal to 34.5 degrees/year. The repeatability period between GENESIS and Galileo orbital planes is about 3000 days (8.2 years), while the draconitic year for GENESIS is equal to 404 days. The nominal lifetime GENESIS mission is estimated for two years, and it should allow for preliminary improvements in orbit modeling associated with solar radiation pressure parameters. However, the mission length does not allow for the full revolution of the GENESIS orbits with respect to the Galileo constellation.

The number of possible GNSS observations collected by GENESIS nadir and zenith antennas and their error characteristics will depend on the orbital plane due to geometric properties in the multi-constellation. For the adopted simulation settings, the zenith antenna observes satellites from orbital plane A to the greatest extent, while the nadir antenna observes mostly satellites from orbital planes B and C (Table 4). Figure 3 shows the number of observations for satellites representing different orbital planes. In general, the GENESIS zenith antenna will observe much fewer satellites than the nadir antenna, but at the same time, most observations will have better accuracy due to lower zenith angles. Also, each Galileo orbital plane will be characterized by an observation pattern similar to all satellites from the same plane. For the nadir antenna, none of the observations will

Table 4 Number of GNSS observations collected per day by GENESIS GNSS antennas from different Galileo orbital planes

	Plane A (SVN 1—8)		Plane B (SVN 9—16)		Plane C (SVN 17—24)	
	Total	Mean per day/satellite (standard deviation)	Total	Mean per day/satellite (standard deviation)	Total	Mean per day/satellite (standard deviation)
Zenith antenna	165,788	987 (76)	137,900	821 (35)	144,555	860 (26)
Nadir antenna	199,066	1,185 (34)	272,259	1,621 (53)	262,453	1,562 (52)
Both	364,854	2,172 (61)	410,159	2,442 (39)	407,008	2,422 (43)

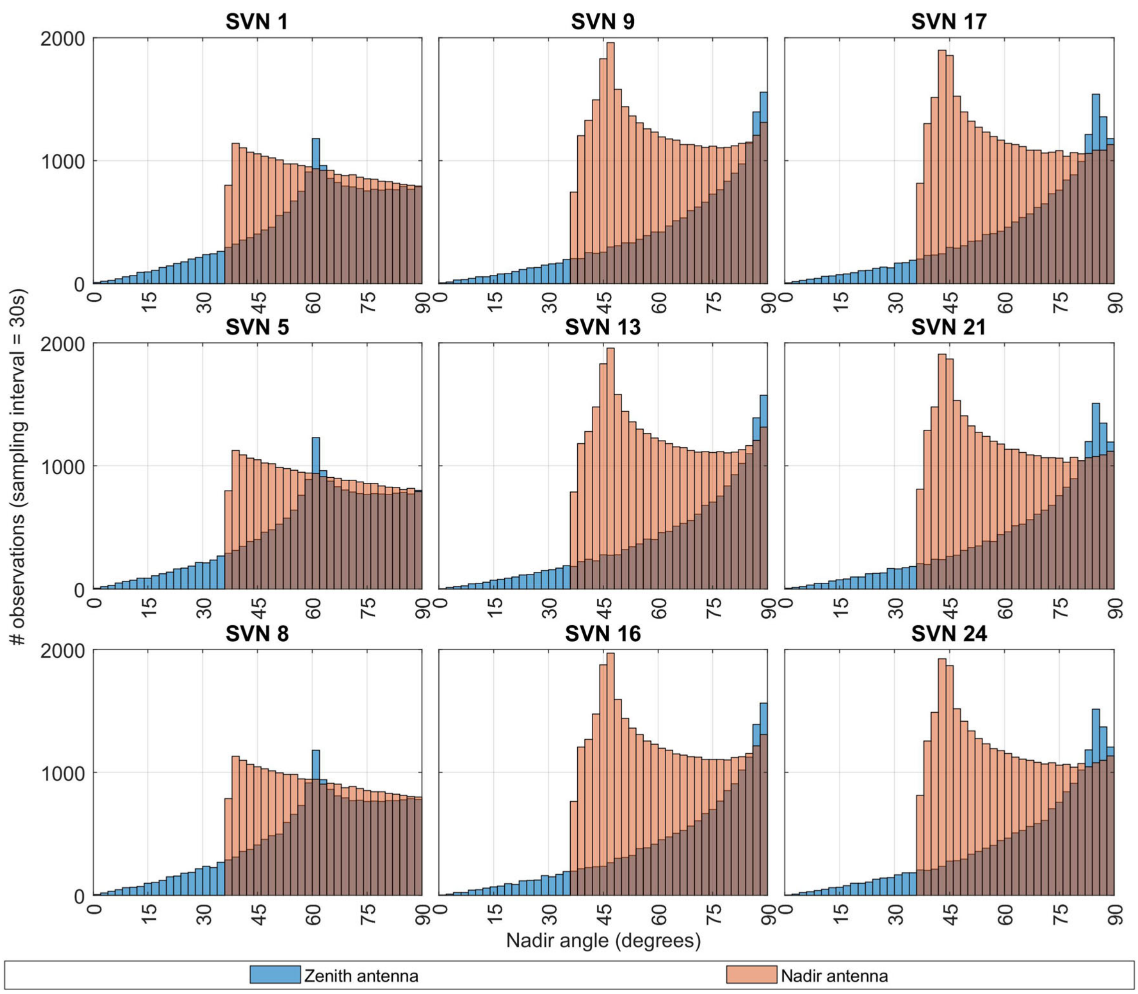

Fig. 3 Histograms of nadir and zenith angles between GENESIS antennas and selected Galileo satellites. Each column represents satellites from a single orbital plane

be collected below 35° due to the signal occultation caused by the Earth.

For the zenith antenna and the Galileo orbital plane A, the peak in the number of observations is at an angle of about 60°, while for nadir direction, it is about 38° with the maximum difference up to 300 measurements between different angle values (see Fig. 3). For B and C orbital planes, the pattern represented by the number of observations is comparable; for the nadir antenna, the peak is between 40° and 50°, and for the zenith antenna, it is above 85°. These values show that observations from the nadir antenna might substantially improve the estimation because of the high number of observations with good quality (i.e., antenna error between 1 and 2 mm) for all three orbital planes. In contrast, a zenith antenna can provide a limited number of very accurate measurements (antenna errors below 1 mm) with many observations with maximum antenna error, especially for orbital planes B and C. Figure 4 displays the number of observations including their zenith/nadir angles and antenna error values. The figure clearly shows the inconsistency in observation distribution between both GENESIS antennas. The observations above the nadir angle of 75° will be difficult to track because of the inferior signal-to-noise ratio, especially for L1/E1 frequencies (Montenbruck et al. 2023). At the same time, in this range of angles, a considerable number of GNSS measurements are available. In such a case, extremely accurate on-ground calibrations of both antennas will be one of the most important requirements to provide high-quality observations that can be used to improve GENESIS but also Galileo's orbits and clocks. Figure 5 depicts traces of Galileo satellites as observed by GENESIS zenith and nadir GNSS antennas during one revolution of Galileo satellites and GENESIS, i.e., 14 h 21 min (Fig. 5a and b) and 3 h 49 min (Fig. 5c and d), respectively. For the nadir antenna, we can observe that for the angles below about 37 degrees, there are no observations because they would have to pass through the atmosphere or the Earth.

4 Results of orbit and clock determination

4.1 Orbit and clock determination

Joint orbit and clock determination for Galileo-like and GENESIS is a noteworthy idea allowing for considering all parameters' correlations properly and for employing the full observation geometry. Figure 6 illustrates boxplots of RMS orbit errors for four simulation scenarios in the radial (Fig. 6a), along-track (Fig. 6b), and cross-track (Fig. 6c) components along with total 3D error (Fig. 6d). In all directions, the mean value of orbit error decreases together with their spread, i.e., the standard deviations and IQR. For all position components, the improvement reaches about 50% when observations from nadir and zenith antennas are used. The outcomes also demonstrate that mostly the nadir antenna is responsible for orbit estimation accuracy improvement. For 3D error, the difference between nadir and nadir + zenith case is equal to 2 mm, while for only zenith and nadir + zenith case, the discrepancy reaches almost 9 mm, which is more than twice the difference between Galileo-like and Galileo-like + GENESIS (zenith) case.

The discrepancies between each plane within the selected simulation scenario are negligible when comparing RMS errors for single orbital planes in the Galileo constellation. However, the percentage improvements between Galileo-like and Galileo-like with GENESIS observations differ from less than 1% for the radial direction and up to 10% in the case of the cross-track component within a single simulation case (see Fig. 7). The highest values of improvement at the level of 42–54% are noticed when zenith + nadir antennas are used; moreover, when only the zenith antenna case is considered, the changes are at the level from 12 to 24%. The relation between each position component and the use of specific antenna type mostly remains unchanged, i.e., using nadir or zenith + nadir antenna gives almost the same value of improvement for planes B and C because these orbital planes provide the largest number of GNSS measurements in the simulations as shown in Table 4. However, that rule cannot be applied to plane A which has more observations for the zenith antenna compared to planes C and B. The cross-track component of orbits in plane A improves mostly thanks to observations from the nadir antenna. In the case of the GENESIS zenith antenna and from the point of view of the results' improvement, plane A is similar to plane C in the radial component and to plane B in the along-track component (Fig. 7). The GENESIS-based results are also sensitive to the choice of the antenna observing GNSS satellites. Both antennas perform equivalently for the radial component, while for the along-track and cross-track, the zenith antenna results in smaller estimation errors. When observations from both antennas are included, the radial component is the most amended.

The Galileo orbit errors obtained in joint orbit determination with the additional use of GENESIS show improvement up to a noteworthy 48% when nadir and zenith antennas are used. The scenario with the zenith antenna only provides a minor improvement; however, using only the nadir antenna leads to comparable results to the case when both GNSS antennas are used. Returning to the analysis from the previous section, the geometry of the observation is an important factor in the proposed approach to joint orbit determination.

Figure 8a illustrates a decrease in clock estimation errors for satellite and station clocks, parallel to orbit improvement when exploiting GENESIS. The values of the improvement rate of satellite clock mean error for the case with GENESIS zenith antenna are higher than the percentage

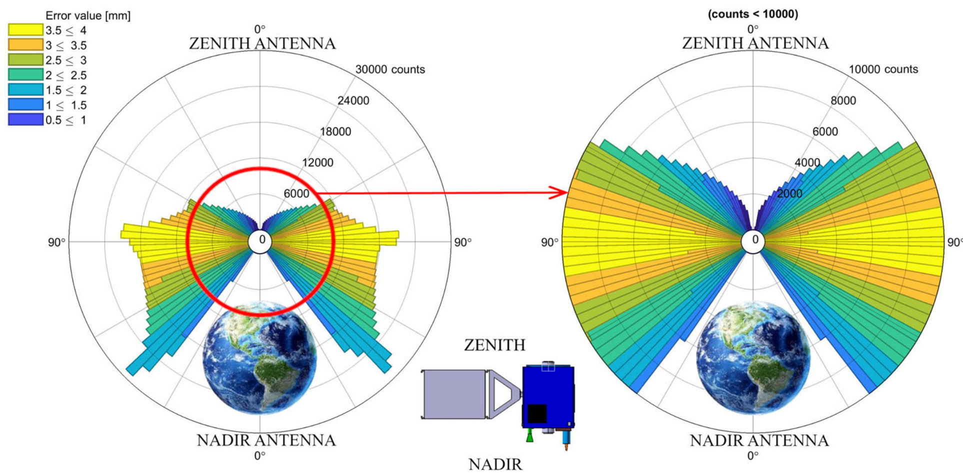

Fig. 4 Distribution of observations and their errors from both antennas: the upper half is for the zenith antenna; the lower half is for the nadir antenna as GENESIS orientation indicates. The center of the figure depicts the orientation of GENESIS

changes observed in the case of orbit determination. For nadir or zenith + nadir instance, the change is at the level of 41–47% with reference to the scenario without GENESIS. Noteworthy is that the station clock errors are lower by 15–32% compared to Galileo-like solution when using GENESIS despite that no direct observations between ground stations and GENESIS are provided. The only connection between ground GNSS stations and GENESIS is provided via common Galileo observations collected by ground-based GNSS receivers and GENESIS-based GNSS receivers. The improved Galileo orbits and more accurate satellite clock estimates in the joint orbit and clock determination process lead to an improvement of all estimated parameters. Without adding any observations to ground stations, the reconstruction of the station clock values with respect to the a priori values is improved through better Galileo orbit and clock estimates when adding GENESIS.

Figure 8b displays satellite clock error with distinction to orbital planes and GENESIS onboard clock. The mutual differences between planes for chosen simulation scenarios range from 2–4%. Using observation from the nadir antenna allows for improving clock error by about 15% compared to the zenith antenna while using zenith + nadir allows for a further improvement of 5–6%. GENESIS clock error decreases by almost 0.01 ns when switching from zenith to nadir-only antenna and the difference between nadir-only and zenith + nadir is less than 0.005 ns.

4.2 Signal in space ranging error and orbit geometry

The improvements in orbit and clocks also affect Signal in Space Ranging Errors (SISRE) for the Galileo constellation. SISRE reflects the influence of satellite orbit on user range measurements and constitutes one of the fundamental parameters characterizing the quality of GNSS products. Figure 9 depicts the orbital $\mathrm{SISRE_{orb}}$ and the total SISRE defined as follows:

$$\mathrm{SISRE_{orb}} = \sqrt{w_\mathrm{R}^2 \cdot R^2 + w_\mathrm{A,C}^2 \cdot (A^2 + C^2)}, \tag{2}$$

$$\mathrm{SISRE} = \sqrt{[\mathrm{rms}(w_\mathrm{R} \cdot R - \Delta cdt)]^2 + w_\mathrm{A,C}^2 \cdot (A^2 + C^2)}, \tag{3}$$

where R, A, C mean the rms error in the radial, along-track, and cross-track, respectively with weight factors $w_\mathrm{R} = 0.984$ and $w_\mathrm{A,C} = 0.124$ for Galileo, including Δcdt as the error of the clock offset (Montenbruck et al. 2015, 2021). These results show potential improvement in user ranging when Galileo orbit determination is supported with GNSS measurements collected by GENESIS. The orbital $SISRE_{orb}$ and the total $SISRE$ are computed only for Galileo-like satellites. The outcomes replicate patterns seen in the previous analysis, i.e., the zenith + nadir antennas have the highest impact on Galileo orbit and clock improvement, but the largest contribution comes from the nadir antenna on GENESIS. The total SISRE is reduced from 26 to 14 mm between Galileo-only and Galileo + GENESIS zenith and nadir observations, i.e., by almost a factor of two.

The uneven distribution of observations slightly affects the geometry of Galileo orbits by altering their orbital elements. Table 5 demonstrates median and interquartile range (IQR) values of the semimajor axis and inclination differences between the reference propagated orbit and the determined orbit in each simulation scenario and Fig. 10 depicts summary statistics for the semimajor axis. The inclusion of GENESIS enhances precision, which is evident in terms of smaller IQR values for Galileo. Generally, Galileo orbital plane B exhibits the lowest median and IQR values for the semimajor axis, along with the lowest median value for inclination. However, IQR for inclination for this plane is the highest among all simulation scenarios. Concerning the GENESIS semimajor axis, its IQR values indicate high precision, but

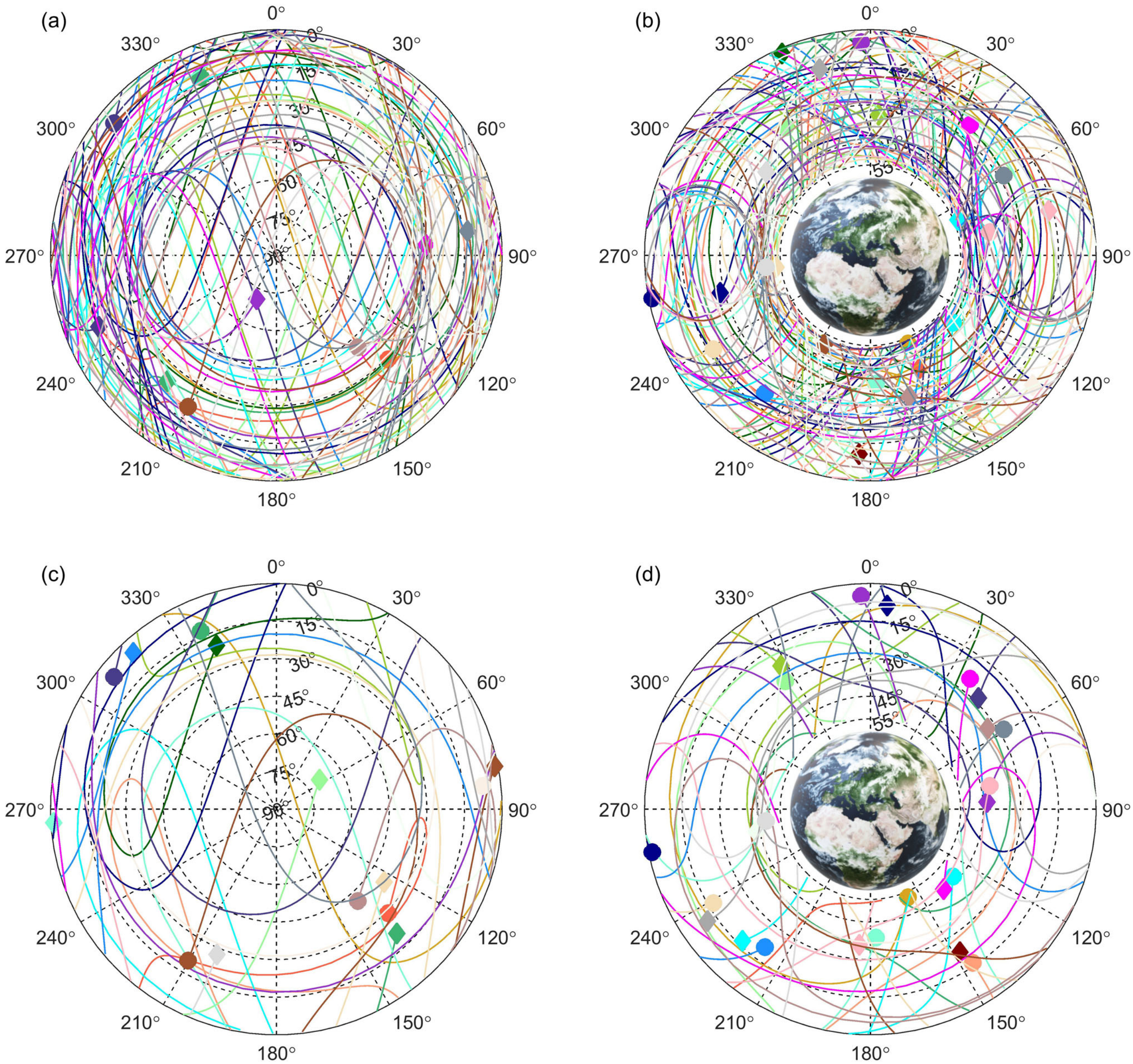

Fig. 5 Galileo traces as seen from facet containing: **a** GENESIS zenith GNSS antenna, and **b** GENESIS nadir GNSS antenna during one Galileo revolution (14 h and 21 min) and **c** GENESIS zenith GNSS antenna, and **d** GENESIS nadir GNSS antenna during one GENESIS revolution (3 h and 49 min). Circles represent the initial satellite positions and diamonds the final position. No GENESIS maneuvers were applied in the simulations

the median values show a bias when only a single antenna is utilized. Nonetheless, incorporating both zenith and nadir GENESIS observations significantly reduces IQR values of errors by a factor of two compared to the Galileo-only solution. Analyzing the results for a single Galileo orbital plane, noticeable improvement is observed only for planes A and B across all three tested scenarios, with an enhancement of up to 50% when a single GENESIS antenna is employed. For plane C, an improvement of 0.1 cm is observed when only the GENESIS nadir antenna is utilized. When observations from the zenith antenna are included, the median offset error equals 5 mm, while in the zenith + nadir case, the median error reaches 8 mm. Plane C exhibits a 50% change when comparing zenith + nadir to the nadir-only case, experiencing the highest variability in the interquartile range (IQR) among Galileo planes. The median value of the semimajor axis of GENESIS is more sensitive to GNSS antenna selection than Galileo, with values of − 1.3 cm, 1.0 cm, and − 0.1 cm for

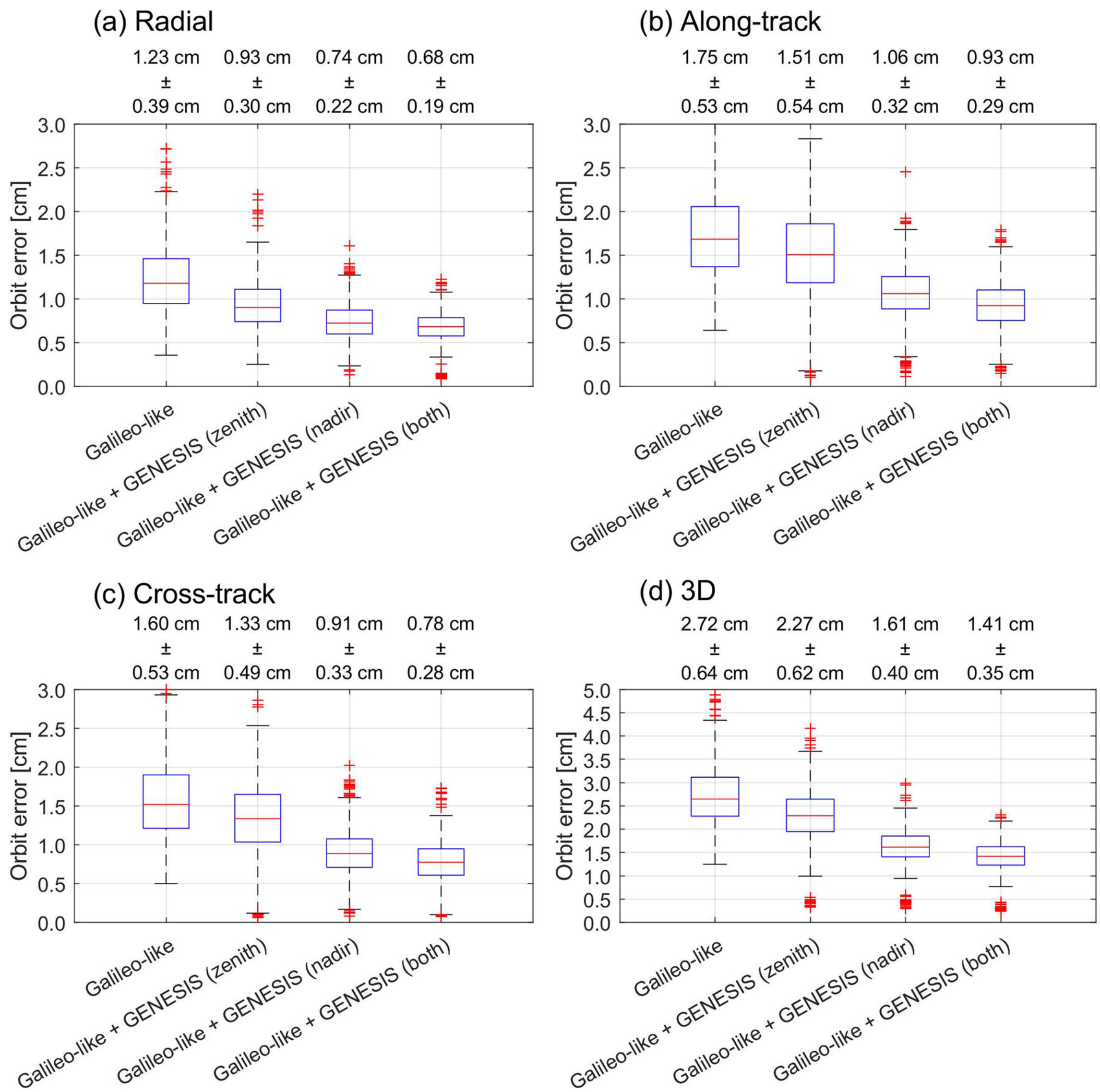

Fig. 6 Orbit errors for **a** radial, **b** along-track, **c** cross-track, and **d** 3D position components as a difference between the reference orbit and the reconstructed orbit based on simulated Galileo and GENESIS observations. Mean orbit errors for each simulation scenario with their standard deviations are provided above the subplots

the zenith, nadir, and zenith + nadir antennas, respectively. In this case, the number of GNSS observations for GENESIS is not essential; their spatial distribution appears to impact the GENESIS semimajor axis more significantly, with the mean value biased at least 50% more than in the Galileo constellation.

4.3 A preliminary trade-off between GENESIS, Sentinel-like, and the inter-satellite links

The use of MEO or LEO satellites for joint navigation satellite orbit and clock determination might be an intermediate step before introducing ISL to the GNSS constellations or even before the full constellation has such operability. Currently, we may employ LEO satellites, such as Sentinel-6 that tracks GPS and Galileo for improving GNSS orbits and clocks. In this section, we compare Galileo-like, Galileo-like + Sentinel-like, and Galileo-like + GENESIS with both antennas, as well as Galileo-like + ISL + GENESIS cases (see Fig. 11). We check only the impact of diverse observation geometry on Galileo orbit determination results to independently evaluate the prospects of joint Galileo and GENESIS orbit determination.

For the second simulation scenario, Sentinel-like is simulated with an altitude equal to 1336 km and 66.0° inclination which corresponds to orbital characteristics of Sentinel-6.

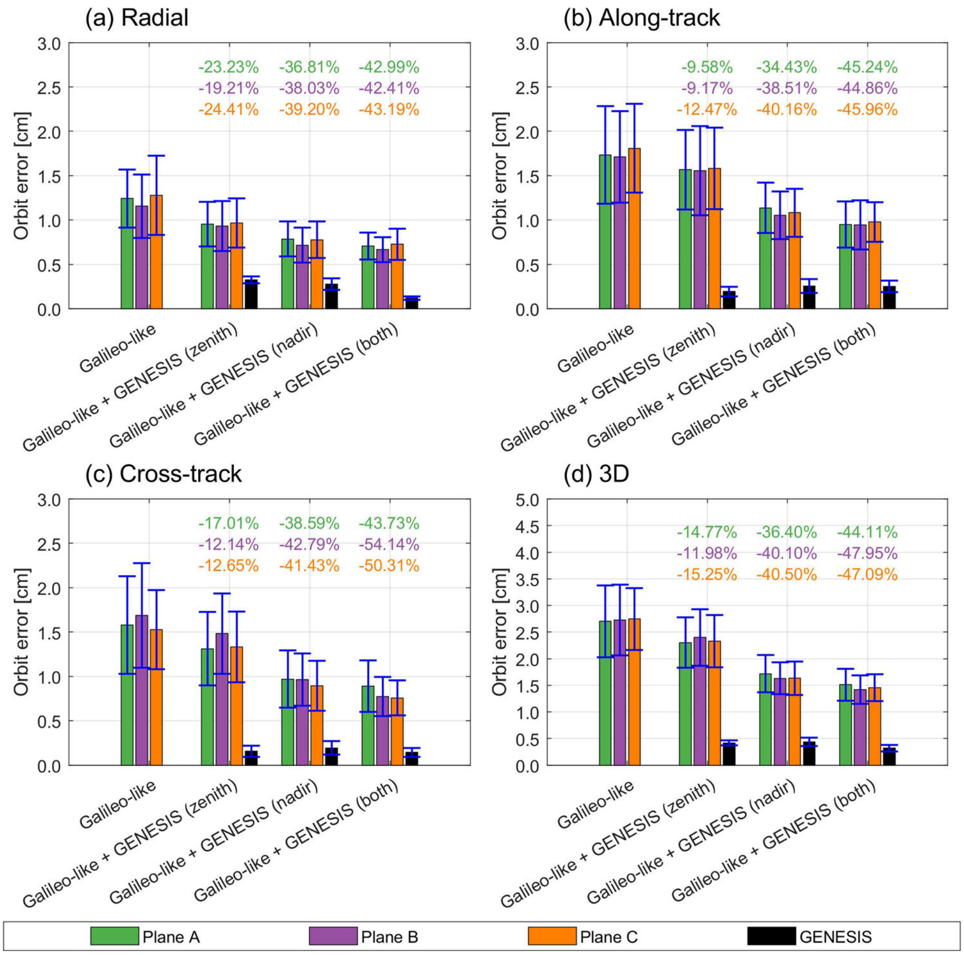

Fig. 7 Orbit errors change for **a** radial, **b** along-track, **c** cross-track, and **d** 3D position components with distinction for Galileo orbital planes and GENESIS. Percentage values represent the improvement for each orbital plane in comparison to the Galileo-like simulation scenario when GENESIS is included in the orbit determination

GNSS observations are collected only by the zenith antenna of Sentinel; however, the number of collected observations is greater than for GENESIS zenith antenna due to the lower latitude of Sentinel-6. During the 21-day simulation period, it collected 197,886; 180,151; and 164,132 measurements from satellites on Planes A, B, and C, respectively. Comparing the daily mean number of observations per Galileo satellite on selected orbital plane collected by the zenith antenna of Sentinel-like and GENESIS, it is as follows: 1178 to 987 for Plane A, 1072 to 821 for Plane B, and 976 to 860 for Plane C. We can notice that the low orbit ensures more observations collected by the zenith antenna of Sentinel-like. However, the nadir antenna of GENESIS contributes better to the Galileo orbit determination than the zenith antenna.

The sequential scenario is used for ISL, which is one of the most beneficial for clock and orbit estimation along with a similar distribution of links between the planes (Fernández 2011; Kur and Kalarus 2021). ISLs are simulated with the same observation rate as GNSS observations, i.e., 30 s and measurement noise equal 0.5 cm, i.e., the same as nominal for GNSS measurement collected by GENESIS. The total number of ISL is almost 43% lower than GNSS observation to GENESIS (32,000–56,300 on average, respectively). ISL and GNSS observations collected by GENESIS or Sentinel-like have similar characteristics, i.e., are not burdened with atmosphere refraction as well as ground station clocks do not directly impact the measurements. ISLs do not consider antenna error relation to observation angles; thus, ISLs are up to 2 times more accurate compared to the worst GENESIS observation scenario.

Figure 12 illustrates orbit determination results together with results improvement with reference to the Galileo-like scenario. Between the simulation of GENESIS with zenith and nadir antennas and Sentinel-like with only zenith antenna, the smallest difference is noticed for the radial component with mean improvement of Galileo positions at the level of 43% and 37%, respectively. Results in the along-track (Fig. 12b) and cross-track (Fig. 12c) components are more variable, also for each orbital plane. With Sentinel-like aided orbit determination, the percentage of the improvement is equal from 13.8 to 20.4% in the along-track component and from 10.0 to 20.8% in the cross-track component. When GENESIS is exploited, the improvement values are equal to about 45% in the along-track and from 43.7 to 54.1% in

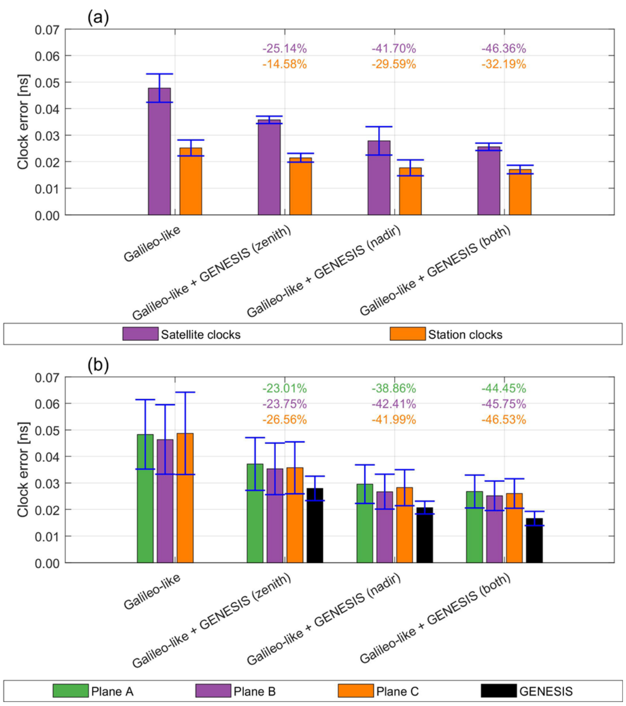

Fig. 8 **a** Satellite and station mean clock errors, **b** Galileo and GENESIS mean satellite clock errors for each orbital plane. Values represent percentage improvement compared to the Galileo-like simulation scenario

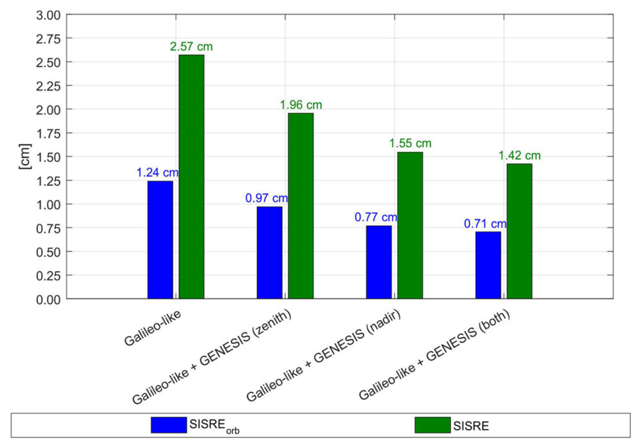

Fig. 9 SISRE$_{\mathrm{orb}}$ and SISRE mean values for simulation scenarios (computed only for Galileo-like)

the cross-track component. It means that GENESIS corrects Galileo orbit in these two components above 2–2.5 times more than Sentinel. ISL + GENESIS aided orbit determination allows for further improvement compared to other tested scenarios with a mean of 64% in the 3D position (Fig. 12d). Simulation scenario with ISL and GENESIS has the best distribution of two kinds of observation and thus, might effectively further improve Galileo orbits.

5 Discussion and conclusions

The GENESIS mission planned under the auspices of ESA will be a breakthrough in the study of the co-location of space geodetic techniques and a unique opportunity to analyze space ties for space geodesy. It will strengthen future realizations of ITRF as well as potentially improve geodetic products, e.g., geocenter coordinates or Earth rotation parameters. But in parallel, the mission will face a challenge also in terms of platform and payload design. Three out of four techniques require radio connection on different frequencies. Considering the relatively small size of GENESIS, interferences between the hardware will appear to some extent and wise placement of the receivers and transmitters will be needed. Another issue relates to the semimajor axis of GENESIS orbit. In Delva et al. (2023) and based on ESA Concurrent Design Facility study output the satellite altitude equal to 6000 km is planned. At this height, the impact of the inner Van Allen radiation belt on payload performance and mission lifetime should be considered and possibly prevented by careful choice of satellite surface materials. Proper radiation shields should be installed to avoid the effects of radiation on geodetic units, clocks, or electronic hardware, i.e., power supply units or onboard computers.

A precise satellite model description will be required for proper accounting of perturbing forces, mostly solar radiation pressure impact. Also, metadata including satellite thermal and optical properties or satellite attitude model will be essential from the perspective of this research. What should be underlined is that a dual antenna system will be mounted for the first time to enhance the orbit determination of the satellite. As demonstrated, GENESIS might also participate as a part of a multi-constellation together with GNSS satellites and possibly with other LEO satellites. In this research, we show the initial concept of joint Galileo and GENESIS orbit and clock determination based on simulations. Due to the mission design stage, many models or properties are still not provided; nonetheless, the paper provides the first insight to this matter.

The results of the analysis show that GENESIS and Galileo joint orbit and clock determination potentially improve Galileo orbits and satellite clocks. The radial orbit error of Galileo is improved from 13 mm (Galileo-only), 9 mm (Galileo + GENESIS zenith antenna), 8 mm (Galileo + GENESIS nadir antenna), to 7 mm (Galileo + zenith + nadir GENESIS) while the 3D error is almost halved between Galileo-like and Galileo + zenith + nadir GENESIS (from 27 to 14 mm, respectively). For adopted simulation parameters, the nadir GNSS antenna of GENESIS has a higher impact on the solution than the zenith antenna, despite providing data of lower quality. Data from the nadir antenna improve especially along- and cross-track. Although zenith and nadir

GNSS antennas favor different orbital planes (plane A and plane C, respectively), it does not substantially impact the mean results for each orbital plane. Additionally, GENESIS improves the ground GNSS clocks despite no direct observations. The contribution of GENESIS in medium orbits to the precise orbit determination of Galileo is greater than the contribution from current low Earth orbiters despite that the expected quality of observations is lower due to the large number of observations collected at low elevation angles. This research also demonstrates the utility of potentially equipping LEO satellites with a nadir GNSS antenna. The accuracy of orbit determination is worse than in GENESIS case due to lower orbit which implicates distinct geometry. We can notice improvement in the 3D orbit error of about 20% with Sentinel like compared to improvement of about 47% achieved with GENESIS.

The study has demonstrated the utility of the GENESIS mission for an alternative, secondary purpose not directly participating in the space technique co-location. It might be a potential enhancement of GNSS constellations without implementing ISL or as an intermediate step in the ISL implementation for Galileo that does not require any further devices onboard GNSS satellites. Our research shows the advantages of GENESIS and GNSS satellites joint orbit and

Table 5 Median and IQR values of differences between reference propagated orbit and determined in each simulation scenario of semimajor axis and inclination

	Median				IQR			
	Plane A	Plane B	Plane C	GENESIS	Plane A	Plane B	Plane C	GENESIS
Semimajor axis [cm]								
Galileo-like	0.7	0.2	0.5	X	5.0	4.1	6.1	X
Galileo-like + GENESIS (zenith)	0.4	0.0	0.5	− 1.3	4.0	3.3	5.1	0.3
Galileo-like + GENESIS (nadir)	0.4	0.1	0.4	1.0	3.5	2.6	4.0	0.3
Galileo-like + GENESIS (both)	0.5	0.2	0.8	− 0.1	3.1	2.3	3.5	0.2
Inclination [1e-8 degrees]								
Galileo-like	0.4	0.1	− 0.3	X	4.3	5.0	4.9	X
Galileo-like + GENESIS (zenith)	0.1	0.1	0.2	− 0.2	3.0	4.8	3.8	1.2
Galileo-like + GENESIS (nadir)	0.4	0.0	− 0.1	− 0.4	2.5	3.3	2.9	1.1
Galileo-like + GENESIS (both)	0.2	0.1	0.1	0.2	2.3	2.8	2.5	1.0

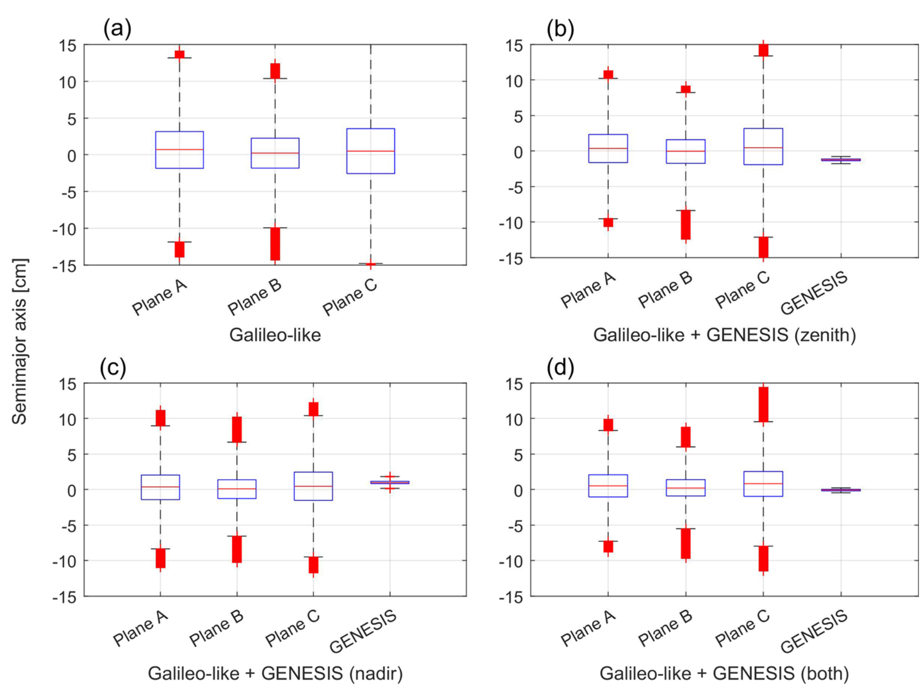

Fig. 10 Semimajor axis differences between simulated and estimated orbits for **a** Galileo-like, **b** Galileo-like and GENESIS zenith antenna, **c** Galileo-like and GENESIS nadir antenna, and **d** Galileo-like and GENESIS both antennas

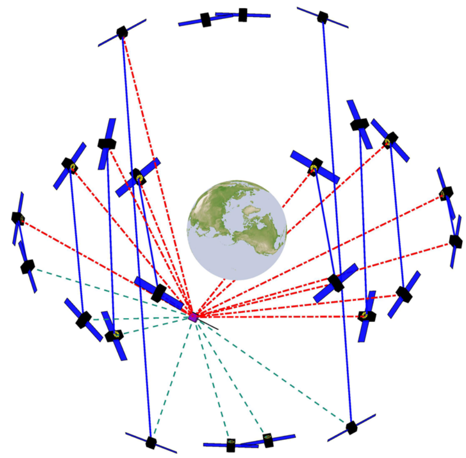

Fig. 11 Visualization of Galileo constellation aided with GENESIS and ISLs for one observation epoch—green dashed lines are GNSS observations collected by GENESIS zenith antenna, red dotted-dashed lines are GNSS observations collected by GENESIS nadir antenna, and solid blue lines are ISLs

clock determination which might be considered as secondary purposes of the GENESIS mission.

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Author contributions KS and TK designed and performed research. TK and MK developed scripts for simulations and analysis. TK analyzed data and did the visualizations. TK prepared the original draft. All authors contributed to the manuscript review and editing.

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Data availability GENESIS initial parameters are taken from: https://doi.org/10.1186/s40623-022-01752-w. Galileo Satellite Metadata are published on the website of the European GNSS Service Centre: https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata (last accessed 22.11.2023). The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

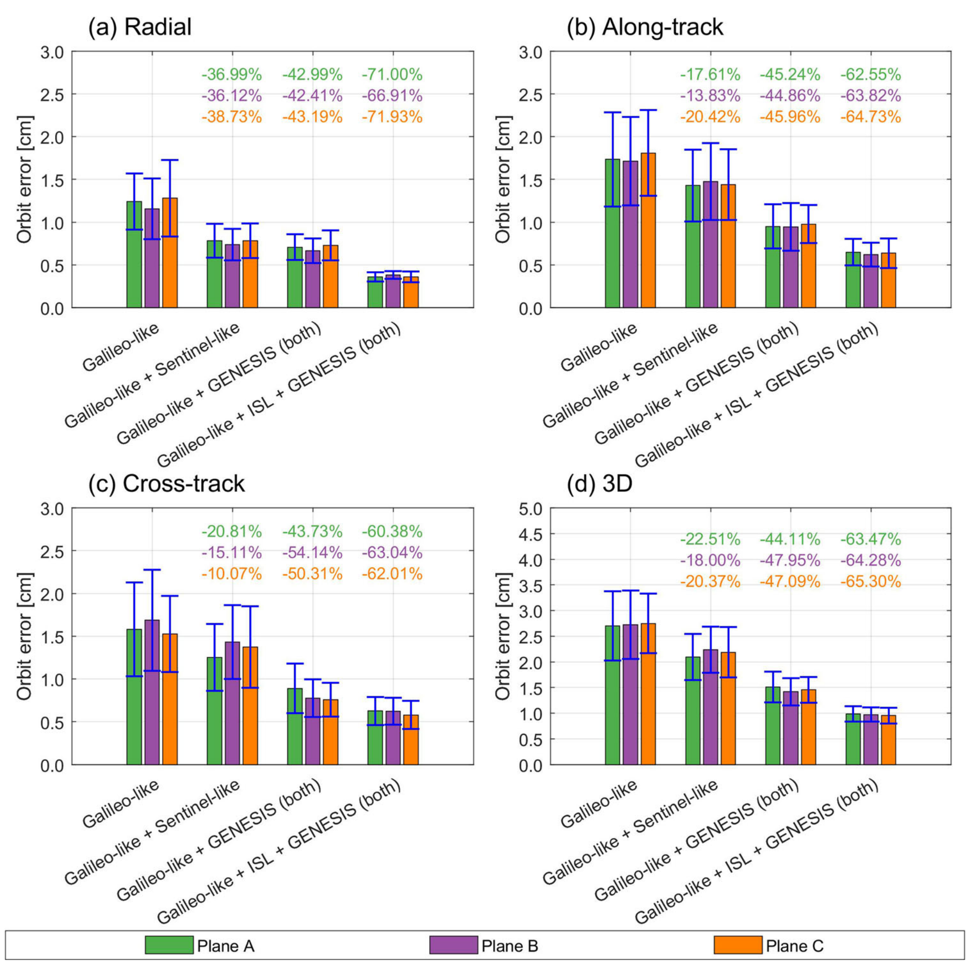

Fig. 12 Galileo orbit errors for **a** radial, **b** along-track, **c** cross-track, and **d** 3D components for Galileo-like, Galileo-like + Sentinel-like, Galileo-like + GENESIS (both), and Galileo-like + ISL + GENESIS (both) simulations scenario

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