Simulation of GNSS observations for GENESIS

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Introduction

A global Terrestrial Reference Frame (TRF) is realized today by four space geodetic techniques, i.e., Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

The current realization of the TRF is based on independent solutions for each of the four contributing space geodetic techniques that are connected on the ground via local ties and common Earth Rotation Parameters. The planned GENESIS mission comprises the new opportunity to co-locate sensors related to GNSS, SLR, DORIS, and VLBI onboard one satellite (Fig. 1).

In this study, we present preliminary results for orbit reconstruction using simulated GNSS observations for the GENESIS satellite. We use the Bernese GNSS Software to simulate GNSS observations to GENESIS for different orbital altitudes, including the currently planned altitude of 6000 km. We assess the quality of the orbit reconstruction using simulated GNSS data from observations of the zenith-, nadir-, and both zenith- and nadir-looking antennas.

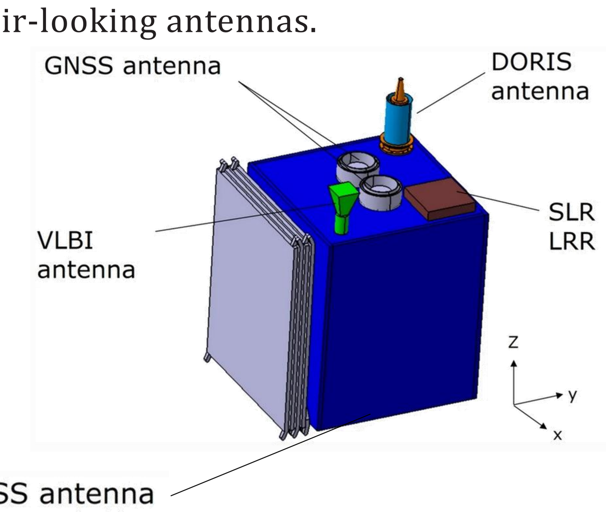

Fig. 1. Graphical visualization of GENESIS nadir-pointing instruments (Delva et al. 2023)

Simulations of GNSS observations

In this study, we assess the impact of the GNSS observations geometry under different noise conditions and orbit altitudes of the GENESIS satellite. We simulate GPS and Galileo observations of both for the zenith- and nadir-pointing antennas of GENESIS. The simulations were conducted for the first two days of 2023. The GENESIS initial orbit is based on the state vector in accordance to the initial assumptions provided by Delva et al. (2023), i.e., a=12 371 km (h=6 000 km), e=0.001, i=95.5°, RAAN: 49.4°, and argument of latitude: 343.4°. As for the GENESIS altitude, we run additional tests with a=11 371 km (h=5 000 km) and a=13 371 km (h=7 000 km) keeping the other Keplerian elements the same.

The GNSS observations to GENESIS are simulated in two scenarios considering different values of the constant noise for the phase observations at the level of 1 mm and 10 mm, whereas for the code observations in both cases we apply the noise at the level of 0.5 m.

The GNSS observations were simulated w.r.t the multi-GNSS (MGEX) orbit products of the Center for Orbit Determination in Europe (CODE). We assume that there is no simultaneous tracking of the identical GNSS satellites by both zenith and nadir antennas.

GNSS antenna calibration

The design of GNSS transmitter antennas aims at covering the Earth's surface and the low Earth orbit (LEO) region with the navigation main lobe signal. The maximum altitudes of GPS and Galileo satellites are 25 780 km and 29 100 km, respectively. Therefore, the boresight angle in the nadir direction accessible for GNSS signals collected at terrestrial GNSS stations reaches up to 14° and 12.7° for GPS and Galileo, respectively. The higher the values of the nadir angle, the weaker the antenna gain, however, the signal is still strong enough to be tracked by other satellites, e.g., at GENESIS altitudes. For GPS, the ground PCV calibration for the nadir angles above 14° were obtained based on the GPS observations to LEO and reach up to 17°. For the Galileo satellites, the PCVs are available thanks to disclosed metadata (GSA, 2016) up to nadir angles of 20°.

GNSS tracking

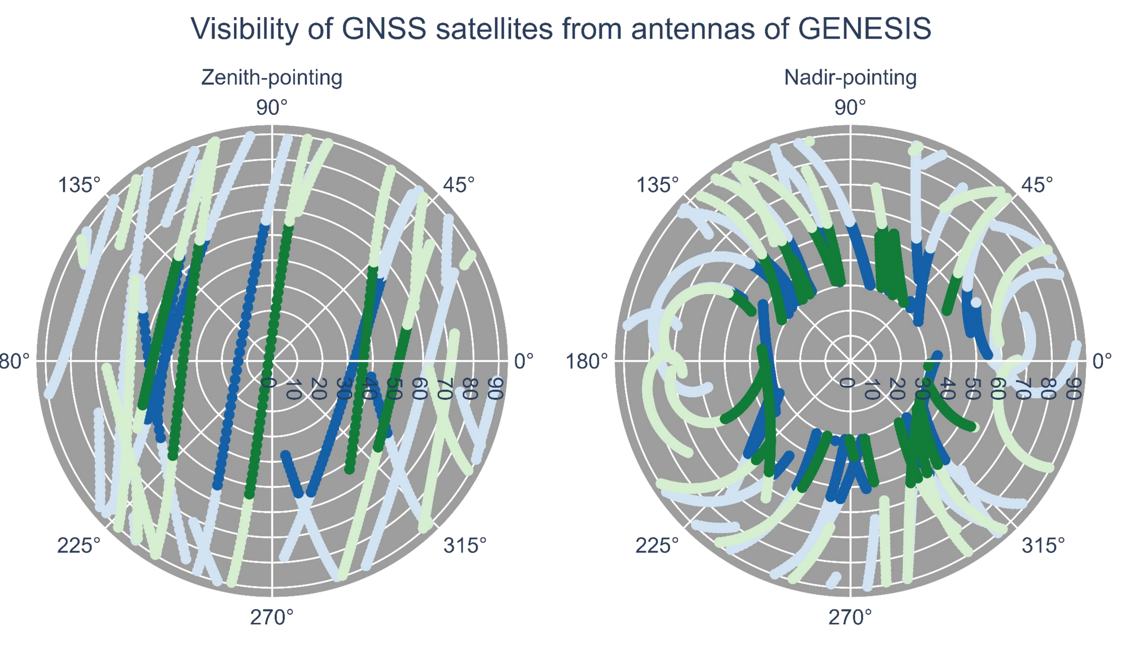

Fig. 2. Visibility of GPS (blue) and Galileo (green) satellites from zenith- and nadir-pointing antennas of GENESIS at altitude ca. 6 000 km for 90 minutes. Dark points illustrate observations limited to the nadir angle resulting from PCV calibrations and light colors denote the extended range of boresight antenna angle.

Table 1. Maximum nadir angle up to which observations are simulated

Max nadir angle[°] (Solution)	PCV (P)	Extended (E)
GPS	**17.0**	**27.8**
Galileo	**20.0**	**24.5**

Figure 2 presents the visibility of GNSS satellites as a function of the zenith distance as seen from the zenith-pointing antenna (Fig. 2 - left) and nadir distance as seen from the nadir-antenna of GENESIS (Fig. 2 - right). We investigated the visibility of the GPS and Galileo satellites tracked by both zenith- and nadir-pointing antennas of GENESIS. We tested two maximum ranges of the antenna boresight angle (Solution *P*) resulting from the official PCV correction, i.e., 17° and 20° for GPS and Galileo, respectively (Fig. 2 - dark dots), and (Solution *E*) the extended case, i.e., 28° and 25° for GPS and Galileo, respectively (Fig. 2 - bright dots). The extended values are the theoretical nadir angle range which can be reached based on the altitude of 6000 km. However, one has to keep in mind that for the extended range of nadir angles, we will be confronted with a significant drop in the antenna gain and the signal will stem for the antenna side lobes (Maqsood et al. 2017).

For the 90-minute window considered in Fig. 2, the number of tracked GNSS (passes) increases more than three times for the zenith antenna and by 72% (78%) for GPS and 39% (38%) for Galileo for the nadir-pointing antenna (Table 2). The duration of GNSS tracking is higher as well. The mean duration of a GPS pass increased by 280% and 345%, and for Galileo by 126% and 205% for zenith and nadir antennas, respectively. The impact for Galileo is less pronounced, as the nadir angle range is increased only by 4° whereas for GPS the angle range was increased by 11°.

Table 2. Number of passes and tracked GNSS satellites, and average length of satellite pass for the 90-minutes window

		Zenith		Nadir	
		GPS	Galileo	GPS	Galileo
E	No. of passes (sat)	21 (21)	17 (17)	41 (31)	33 (25)
	Average pass [min]	38.2	39.1	49.4	50.5
P	No. of passes (sat)	7 (7)	5 (5)	23 (18)	24 (18)
	Average pass [min]	13.6	30.8	14.3	24.6

Figure 3 depicts the number of tracked GPS (blue) and Galileo (green) satellites as a function of time. For solution *P* it is possible to only observe simultaneously at maximum 3 (GPS) and 5 (Galileo), and 7 (GPS) and 9 (Galileo) satellites for zenith-, and nadir-pointing antenna, respectively. When observations from the extended range of nadir angles will be possible (solution *E*), the maximum number of tracked satellites increases to 11 (GPS and Galileo), and 23 (GPS) and 17 (Galileo) for zenith- and nadir-pointing antennas, respectively. providing a significantly improved observation geometry.

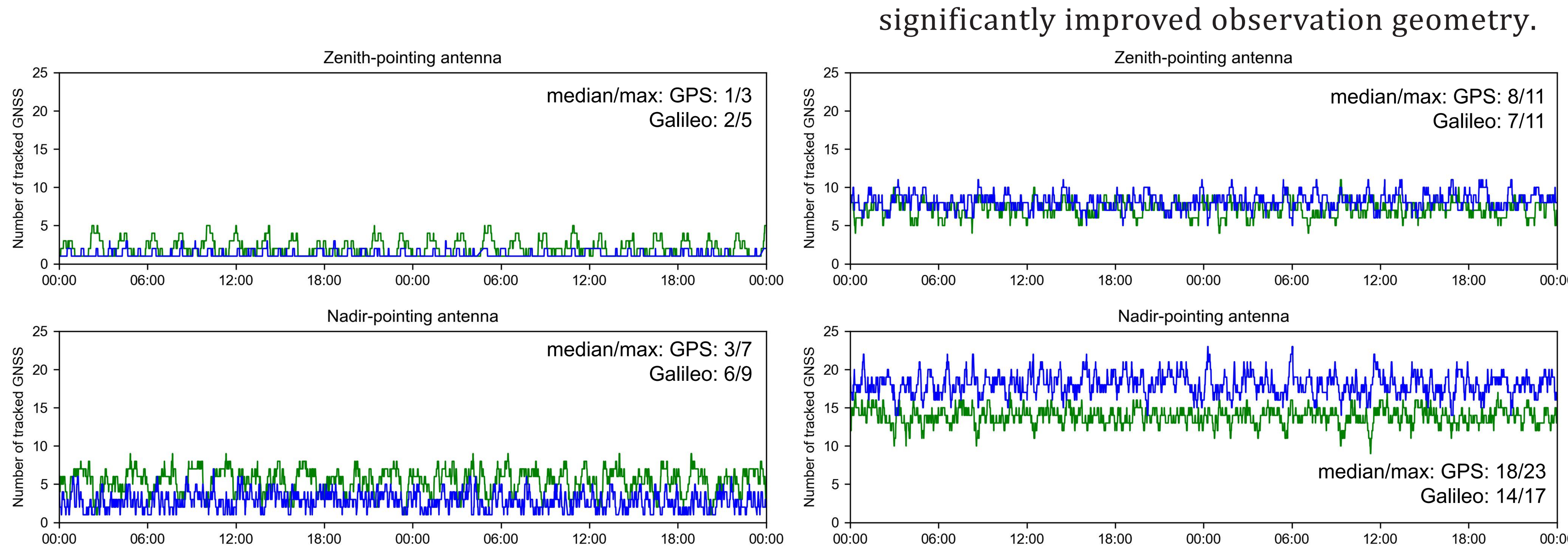

Fig. 3. Number of GPS (blue) and Galileo (green) satellites observed by the zenith- and nadir-pointing antennas of GENESIS for two days of the simulations. Nadir angle limit for GPS/Galileo: 17°/20° (left) and 28°/25° (right)

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Testing different altitudes of GENESIS

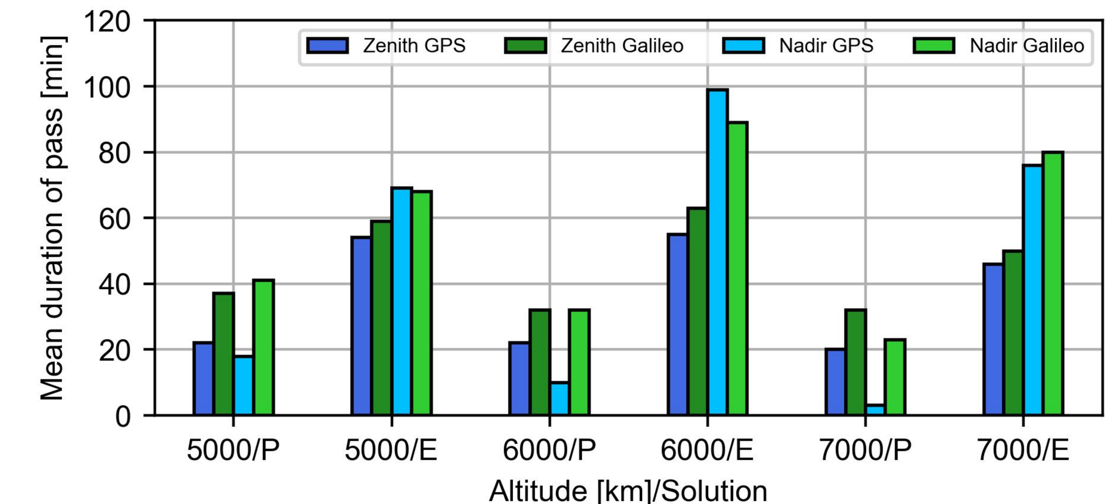

Fig. 4. Median value of the mean duration of the GPS and Galileo satellite passes registered witihn 2 days by the zenith- and nadir-pointing antennas of GENESIS for different orbital altitudes, i.e., around 5000 km, 6000 km, and 7000 km, and for different maximum nadir angle ranges

We test the observation geometry for different orbit heights of 5000, 6000, and 7000 km (Figure 4). When the extended range of the nadir angle will be possible (solution E), the most promising tracking of GENESIS by GNSS is the proposed altitude of 6000 km which is in agreement with Delva et al. (2023). The best results are recorded for both the zenith and nadir-pointing antennas, even though the higher the orbital altitude will be, the more difficult to track GNSS satellite with the zenith antenna. For the altitude of 6000 km, the mean duration for the GPS (Galileo) passes tracked by the zenith and nadir antenna reaches 55 (63) and 99 (89) minutes, respectively. The narrow range of nadir angles in solution *P* is insufficient regardless of the GENESIS altitude. In the best case, the mean duration of a simulated Galileo pass is 41 minutes.

Quality of the GENESIS orbit recovery

Finally, we assess the quality of the GENESIS orbit recovery. Based on the simulated GNSS observations we estimate a 1-day GNESIS orbital arc. The estimated parameters consist of a set of Keplerian elements and 9 empirical parameters, i.e., constant and periodical sine/cosine terms in the radial, along-track, and cross-track directions. In both solution there are no systematic errors like PCV mismodelings, force model mismodelings or attitude errors, as they are not taken into account. Therefore, the results presented within this analysis consider observation geometry under extremely favorable noise conditions. Figure 5 illustrates satellite position differences decomposed into radial, along-track, and cross-track directions.

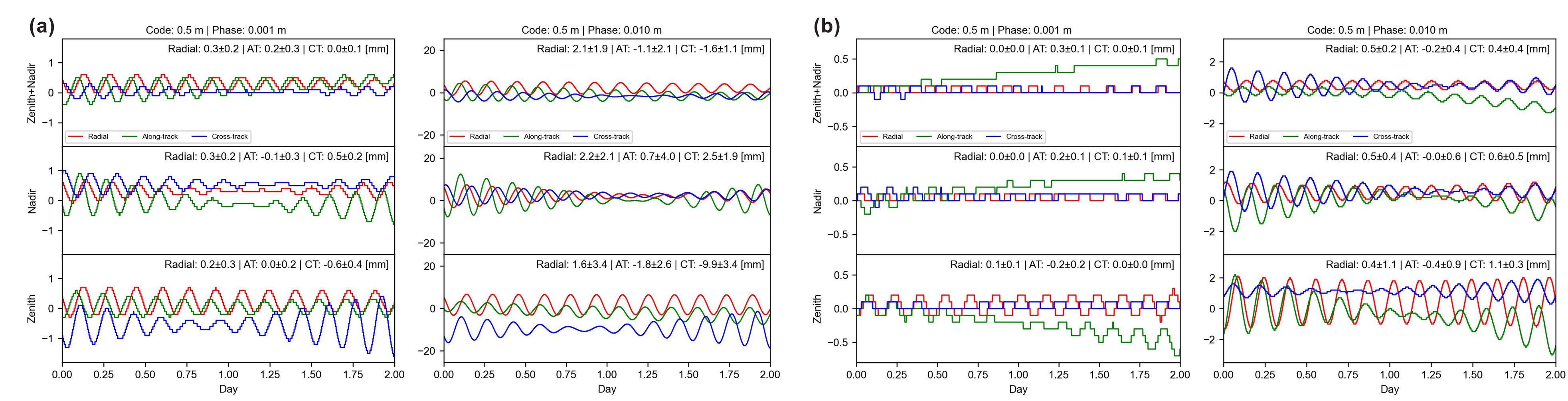

Fig. 5. GENESIS position differences between the a priori orbit for the orbital altitude at the level of 6000 km and the estimated orbit based on solution P (a) and solution E (b). The observations are simulated with the noise at the level of 10 mm (left - a and b) and 1 mm (right - a and b). Note the scale change between the plots. All results are expressed in millimeters

The 3D position difference w.r.t the a priori orbit is at the level of 2.8 mm for the solution *P* (Fig. 5 - a). The extension of the nadir angle range in solution *E* significantly improves the quality of the orbit recovery, especially for the solution with noise at the level of 10 mm. The 3D position difference w.r.t the a priori orbit for a solution *E* (Fig. 5 - b) is at the level of 0.7 mm for a solution with 10 mm noise, whereas for a solution with 1 mm noise the 3D satellite position difference is at the level of 0.3 mm, both for the solution based on the GNSS observations collected by both zenith and nadir antennas.

As for the individual solutions, higher discrepancies between the a priori and estimated position of GENESIS are visible for the solutions calculated based on the observations from the zenith antenna only. This results from a lower number of observed GNSS satellites, and the length of registered passes when compared to the nadir antenna. This is especially visible for the solution with 10 mm noise, for which the offset in the satellite position (cross-track) determined based on the observations collected by the zenith is mitigated by a factor of two when compared to the solution determined based on the observations delivered by the nadir antenna. The most consistent satellite position is obtained when the GENESIS orbit is delivered based on the combined GNSS observations delivered by the zenith- and nadir-pointing antennas.

Conclusions

- We simulated GNSS observations of both zenith- and nadir-pointing antennas of GENESIS in a very simplified environment.
- For the extended range of nadir angles (28°/25° for GPS/Galileo) the number of registered passes increased by 78% and 38% for GPS and Galileo, respectively for the nadir-pointing antennas.
- The number of tracked GNSS increases from 7 to 23 for the extended nadir angles (GPS tracked by the nadir-pointing antenna)
- The altitude of 6 000 km for GENESIS provides the longest duration of simulated passes within the analysis period (on average up to 99 minutes for GPS) when compared to the altitudes of 5 000 km (69 minutes for GPS) and 7 000 km (80 minutes for Galileo).
- The errors of the orbit recovery which results for observation noise of even 10 mm do not exceed 3 mm.
- For future studies, more realistic simulations will be needed to address the impact of all the simplifications, such as neglecting the estimation of time(-variable) biases.

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