Absolute orientation of Galileo orbits from simulated VLBI and GNSS observations

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Abstract The possibility of observing Galileo satellites with Very Long Baseline Interferometry (VLBI) telescopes may become possible in future as there are plans to put VLBI transmitters on these satellites. This would not only bring improvements for products, such as the International Terrestrial Reference Frame (ITRF), but would also allow to determine the absolute orientation of the satellite orbit with respect to the celestial frame. In this study, we investigate the determination of the right ascension of the ascending node Ω of a Galileo satellite orbit using simulated VLBI observations to quasars and a Galileo satellite. Therefore, a schedule including VLBI observations to a satellite covering an ultra short orbit arc of 40 minutes of the satellite surrounded by quasar observations is created, simulated and analysed. There are two different analysis options examined, first estimating Ω in a shorter interval of ten minutes and secondly estimating only one value for the whole 40 minute satellite period. The repeatability of Ω by estimating it in a ten minute interval is between 0.3 and 0.5 mas which corresponds to 4.5 cm and 7.5 cm at the altitude of the orbit. If there is only one value estimated the repeatability is below 0.2 mas which corresponds to approximately 3 cm at the altitude of the orbit.

Keywords Galileo, satellite orbits, VieVS, absolute orientationlo

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1 Introduction

The mounting of a Very Long Baseline Interferometry (VLBI) transmitter (VT) on one or more Galileo satellites enables to observe both, satellites and quasars, with VLBI antennas. Observing a satellite with more than one space geodetic technique permits to determine and use so called space ties. This allows high precision tying of the space geodetic techniques if the tie vectors on the satellite are known with high accuracy. Wolf and Böhm (2023) showed that having VT on Galileo satellites will contribute to an improvement of the International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2023), which is a product of combining all four space geodetic techniques, namely VLBI, Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS). Currently, the ITRF's accuracy is still limited due to errors in local ties on ground (Altamimi et al., 2016).

Further, VLBI observations to satellites and quasars allow Precise Orbit Determination (POD) of the satellites (Klopotek et al., 2020). This can be realized by estimating the position of the satellite in the orbit fixed satellite system (NTW-frame). For that, three so-called Dilution of Precision (DOP) factors representing the sensitivity of a VLBI observation towards the individual components of the satellite position are introduced (Wolf et al., 2022).

However, as VLBI is observing distant celestial objects and therefore realizing the celestial reference system, VLBI observations to satellites permit connecting the satellite orbit with this frame. This allows the determination of the absolute orientation of the satellite constellation with respect to the International Celestial Reference Frame (ICRF) (Charlot et al., 2020).

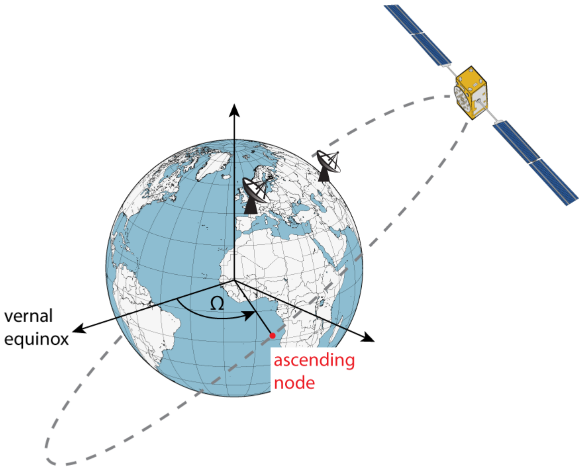

Fig. 1 Illustration of VLBI radio telescopes observing a satellite in its orbit.

Currently, satellites are routinely observed with GNSS, SLR and DORIS but VLBI observations are still missing in satellite geodesy. Anyway, there are plans to mount a VLBI transmitter on board of Galileo satellites which would enable to carry out VLBI observations to these satellites. Moreover, the European Space Agency (ESA) plans the launch of a co-location satellite called Genesis for 2027/2028. This satellite will combine all four space geodetic techniques orbiting the Earth in a polar orbit with 6000 km altitude (Delva et al., 2023).

This study investigates the estimation of the orbital parameter right ascension of ascending node Ω which is related with the absolute orientation of the satellite around the polar axis. This is done using simulated VLBI observations and partial derivatives of the state vector with respect to Ω obtained from the Bernese GNSS Software (Dach et al., 2015). These partial derivatives are introduced in the VLBI analysis and used for estimating the right ascension of the ascending node in the least squares adjustment. In section 2 we describe the network and settings of the scheduling, simulation and analysis of the VLBI observations and the determination of the partial derivatives. Section 3 shows the results and section 4 provides the summary, discussion and outlook.

2 Method

The study is based on a network of nine VLBI Global Observing System (VGOS) (Petrachenko et al., 2012) type stations (Fig. 2) and considers one satellite of the European Global Navigation Satellite System Galileo GSAT0101 (E11). The session starts on January 1, 2021 00:00:00 UTC with a 24 hour duration. We investigate the scenario of covering an ultra short orbit arc with VLBI observations by applying two different analysis options.

2.1 Scheduling

The creation of the schedules is done using the software VieSched++ (Schartner and Böhm, 2019). This software has been equipped with a satellite scheduling module which allows to schedule quasar observations together with satellite observations in an either manual or automatic fashion (Wolf, 2021). In this study the generation of the schedule including satellite observations covering the ultra short orbit arc is done manually. Therefore, during a 40 minute period, from 10:20 UTC to 11:00 UTC, for all five stations for which the satellite is visible satellite scans are scheduled every 90 seconds. For all the stations for which the satellite is not visible during that time quasar scans are scheduled and also the remaining part of the schedule is filled with quasar scans. As the network consists only of VGOS type stations the scan length of satellite and quasar scans is set to 10 seconds in order to meet the VGOS approach of a large number of short scans well distributed over the sky at the individual stations.

2.2 Simulation

The schedules are simulated 1000 times using the Vienna VLBI and Satellite Software (VieVS) (Böhm et al., 2018). These simulations are carried out by using three main error sources, which are tropospheric turbulence, clock errors, and the thermal noise (Pany et al., 2011). The tropospheric refractive index structure constant C_n of all stations is set to 1.8×10^{-7} m $^{-1/3}$ with a scale height of 2000 m (Nilsson et

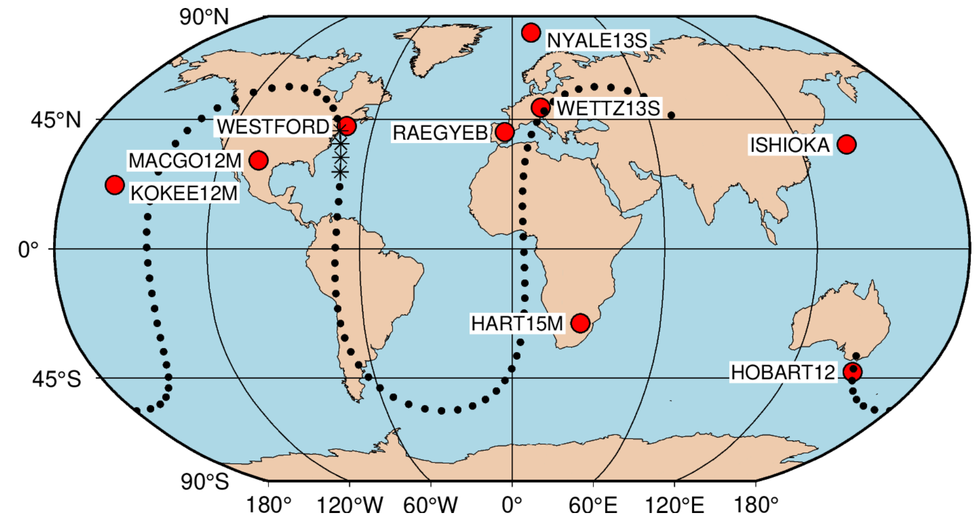

Fig. 2 VGOS station network considered in this study and ground track of the satellite GSAT0101 (E11) during 24 hours starting on January 1, 2021 at 0 UT. The dots represent the ground track of the satellite at a fifteen-minute interval. The asterisks represent the position of the satellite during the observation period.

Fig. 3 Illustration of the scheduling approach. The schedule consists of a 40 minute period of satellite scans surrounded by quasar scans.

al., 2007). The stochastic error of the station clock is simulated as the sum of a random walk and an integrated random walk assuming an Allan Standard Deviation of 1×10^{-14} after 50 minutes (Herring et al., 1990). Additionally, white noise of 10 ps for quasar and satellite observations is added.

2.3 Partial Derivatives

The determination of the partial derivatives of the observable τ with respect to Ω is shown in Figure 4. Therefore, files obtained from the Bernese GNSS Software (FSO and FRP files) are loaded in VieVS. These files include the orbits of the satellites as state vectors and the derivatives of the state vectors with respect to the orbital parameters among other parameters. Within VieVS the partial derivative of the observable τ with respect to the position vector of the satellite is determined. Further, it is used to form the dot product with the partial derivative of the position vector with respect to Ω in order to retrieve the partial derivative of the observable τ with respect to Ω, see Eq. 1.

$$\frac{\partial \tau}{\partial r(t)} \cdot \frac{\partial r(t)}{\partial \Omega} = \frac{\partial \tau}{\partial \Omega} \tag{1}$$

This parameter is introduced in the least squares adjustment and used to estimate piecewise linear offsets (PWLOs) of the Right Ascension of Ascending Node from the a-priori orbit.

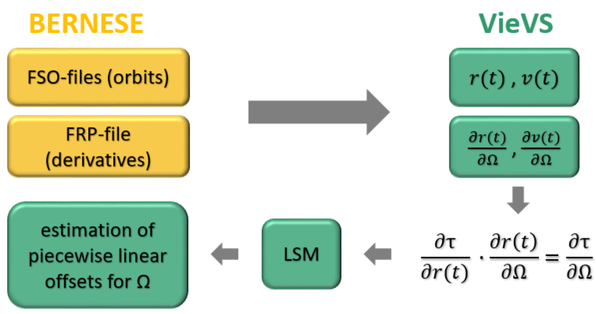

Fig. 4 Flowchart of the concept determining the partial derivatives of the observable τ with respect to Ω in VieVS using data from Bernese and estimating piecewise linear offsets from the a-priori orbit.

2.4 Analysis

The simulated observations are analysed using VieVS by estimating Ω as PWLOs from the a-priori orbit. The a-priori orbit is introduced by using SP3 files. During the analysis the station and source coordinates are fixed to their a priori values and all five Earth orientation parameters are estimated as constant parameters per session. The precision of the estimated right ascension of ascending node of the orbit arc is assessed and evaluated in terms of the repeatability and the mean formal error. Ω is estimated either in shorter, e.g. ten minute intervals, or one value for the whole satellite observation period which has a duration of 40 minutes.

3 Results

Figure 5 shows the repeatability and the mean formal error of the estimated piecewise linear offsets for Ω from the a-priori orbit. If it is estimated within a ten minute interval the repeatability and the mean formal error are higher than if there is only one value estimated for the whole 40 minute period.

This is due to the smaller amount of observations used for the estimation applying a shorter estimation interval rather than using all observations as it is done if only one offset is estimated.

For the shorter estimation interval both, repeatability and mean formal error, have a peak in the middle of the interval. This is related to the worse estimation of the troposphere parameters (zenith delays and gradients) coming from the worse sky coverage at the individual stations as these only observe the satellite during that time period.

However, when estimating Ω in a ten minute interval the repeatability is below 0.5 mas which corresponds to approximately 7.5 cm at the altitude of the orbit. The repeatability for estimating one value for the whole period is below 0.2 mas which corresponds to approximately 3 cm at the altitude of the orbit.

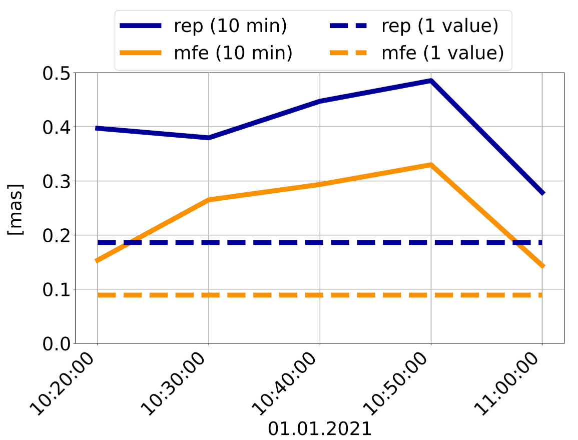

Fig. 5 Repeatabilities (blue) and mean formal errors (yellow) of the estimated PWLO of Ω by either estimating it in a ten minute interval (solid lines) or only one value for the whole observation period (dashed lines).

4 Summary and Discussion

In this study, the absolute orientation of a Galileo satellite orbit is estimated using simulated VLBI observations to one satellite and quasars. This is possible as VLBI enables the connection between the satellite orbit and the celestial frame. Therefore, a schedule including VLBI observations to the Galileo satellite GSAT0101 (E11) covering an ultra short orbit arc using a nine station VGOS network is created and simulated. Further, in the analysis partial derivatives of the observable τ with respect to Ω are retrieved using data obtained from the Bernese GNSS Software. These parameters are introduced in the least squares adjustment for estimating piecewise linear offsets from the a-priori orbit for Ω. The analysis is done by using two different estimation intervals, on the one hand a shorter interval with ten minutes and on the other hand estimating only one value for the whole 40 minute satellite observation period.

The estimates are assessed based on the repeatability and the mean formal error. The results clearly indicate that the repeatability is higher, between 0.3 and 0.5 mas, if the parameter is estimated in a shorter interval than only once for the whole time period, when it is between 0.15 and 0.35 mas. This is linked with the amount of observations used for the estimation as there is only a part of the observations used for the individual estimates if the interval is shorter and all observations are used in case only one value is estimated for the overall time period.

This study also indicates that quasar scans are important for the determination of the troposphere as the repeatability and the mean formal error become higher in the middle of the interval. This is related to the missing quasar scans as the stations only observe one satellite and the therefore worse sky coverage during that time.

In future, the results from VieVS and Bernese could be combined based on the normal equation level by using the ADDNEQ2 module from Bernese. This would allow to retrieve fully consistent results based on VLBI and GNSS observations.

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