Adjustment of Galileo Satellite Orbits with VLBI Observations: A Simulation Study

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Abstract Observing Earth-orbiting satellites and quasars in parallel with Very Long Baseline Interferometry (VLBI) telescopes provides new capabilities such as precise orbit determination (POD) from VLBI observations. As the sensitivity of a satellite observation towards the individual components of the satellite position is dependent on the geometry of the observing stations and the satellite, not all possible satellite observations are equally suitable for orbit determination. We evaluate possible satellite observations in terms of their potential for determining the satellite orbits using Dilution of Precision (DOP) factors, which are indicators for the sensitivities of a satellite observation. We compare the performance of satellite observations having different sensitivities to the satellite position and the precision of the adjusted orbit arc resulting from Monte Carlo simulations of these observations. This study shows that the results of the precision of the adjusted orbit arcs and the values of the DOP factors concur, and therefore possible satellite observations can be evaluated in advance in the scheduling process using DOP factors.

Keywords Galileo, Dilution of Precision factors, satellite orbits, VieSched++, VieVS

1 Introduction

The installation of a Very Long Baseline Interferometry (VLBI) transmitter on one or more Galileo satellites allows the observation of satellites besides natural extra-galactic radio sources with VLBI telescopes. Combining observations to satellites and quasars brings a variety of new possibilities and allows the expansion of the research activities of this highly accurate technique as it enables the connection of the satellite position with the celestial reference frame. This permits the determination of the absolute orientation of the satellite constellation with respect to the International Celestial Reference Frame (ICRF) [3]. Furthermore, it is possible to compare the position of the satellite from VLBI observations with positions obtained from other space geodetic techniques, allowing high precision tying of the different space geodetic techniques. The connection of the different space geodetic techniques via space ties leads to an improvement of the International Terrestrial Reference Frame (ITRF) [1] if the tie vectors on the satellite are known with high accuracy. Moreover, the combination of VLBI observations to quasars and satellites enables Precise Orbit Determination (POD) of these Earth-orbiting satellites [6]. Dilution of Precision (DOP) factors [11] can be used to depict the sensitivity of a satellite observation with VLBI telescopes towards different parameters. In order to reveal the sensitivity of a satellite observation towards the individual components of the satellite position, three intended DOP factors were introduced [12]. These DOP factors can be used to evaluate possible VLBI observations of satellites with respect to their suitability for determining the satellite orbit.

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2 Evaluation of Satellite Observations for Orbit Arc Adjustment

In this study, possible satellite observations from a VGOS network are evaluated in terms of their performance for determining the adjustment of satellite orbits. This is done based on two approaches. The first is based on DOP factors, and the second is based on the analysis of simulations. The two different approaches are described in the following subsections.

2.1 Sensitivity Study using DOP Factors

As a first step, satellite observations are investigated in a sensitivity study using DOP factors. These factors are indicators for the change of the observable by a change of a specific parameter and therefore represent the sensitivity of an observation towards this parameter. We use DOP factors for the sensitivity towards the satellite position in the local orbital NTW-frame (see Figure 1), i.e., the normal DOP (NDOP), tangential DOP (TDOP) and cross-track DOP (WDOP). These DOP factors represent the orbital error in the respective component per VLBI measurement error, both in unit of lengths, and are therefore dimensionless. High sensitivities occur due to more suitable geometric configurations of the satellite position and the observing VLBI stations for determining a component of the satellite position, resulting in small values for the respective DOP factor. Therefore, the smaller the values of the DOP factors the higher the sensitivities towards the respective component.

2.2 Simulation Study

In another step, a simulation study is carried out based on schedules including both satellite and quasar observations. These schedules are created with the scheduling software VieSched++ [10] and contain satellite observations for a specific time period of the entire session (e.g., 50 minutes) to one Galileo satellite from all stations from which the satellite is visible during that time period. The remaining part of the schedule is filled with quasar observations. These schedules are simulated 1,000 times using the Vienna VLBI and Satellite Software (VieVS) [2]. The simulations include tropospheric turbulences, station clocks, and white noise [8]. The troposphere is simulated using a tropospheric turbulence parameter C_n with a value of $1.8 \times 10^{-7}\,\mathrm{m}^{-1/3}$ and a tropospheric scale height of 2,000 m [7]. The stochastic error of the station clocks is simulated using random walk and integrated random walk corresponding to 10^{-14} at 50 minutes [4]. In addition, white noise of 20 ps for quasar observations and 50 ps for satellite observations is added.

These simulations are analyzed using VieVS by estimating offsets for the individual components of the satellite position as continuous piecewise linear offsets in a ten-minute interval using relative constraints of 10 cm for each component. The precision of the adjusted arc is studied and assessed in terms of repeatability of the individual components of the satellite position.

3 Results

Our study is based on an arbitrary 24-hour session starting on April 6, 2022 00:00:00 UTC using a network of nine VLBI Global Observing System (VGOS) [9] stations that are currently operational (Figure 2). For the specified network and observing time, two schedules are created including observations of the Galileo satellite GSAT0206 during 50-minute time periods but at different times. In one schedule the satellite scans are scheduled from 00:50:00 to 01:40:00 UTC and in the second schedule from 12:10:00 to 13:00:00 UTC, which are denoted as observation periods A and B, respectively. In the scheduling process,

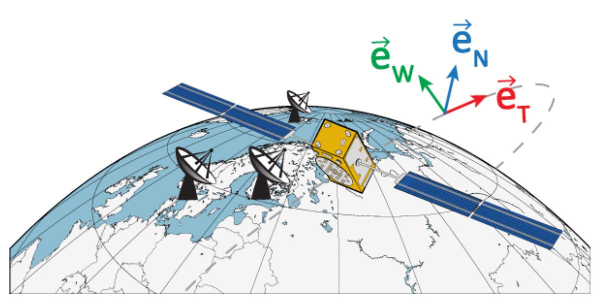

Fig. 1: Local orbital NTW-frame with orthogonal axes, where the N-axis lies in the orbital plane, the T-axis is tangential to the orbit, and the W-axis is orthogonal to the orbital plane.

satellite scans with five seconds of on-source time and 30 seconds in between for calibration and slewing of the antennas are scheduled during these 50 minutes. In the next step, the remaining part of the schedule is filled with quasar observations. It should be noted that quasar observations are also scheduled for stations for which the satellite is not visible during the 50 minutes of satellite scans. During both observation periods, the satellite is visible from a different set of five stations, which are listed in Table 1.

Table 1: Stations where the satellite is visible during the different observation periods.

obs. period A (00:50:00 - 01:40:00)	obs. period B (12:10:00 - 13:00:00)
ISHIOKA	MACGO12M
KOKEE12M	NYALE13S
MACGO12M	RAEGYEB
NYALE13S	WESTFORD
WESTFORD	WETTZ13S

3.1 Results of Sensitivity Study

The results of the sensitivity study, as described in Section 2.1, are shown in Table 2. It is evident that the average value of the NDOP is twenty to thirty times higher compared to the average values of the TDOP and WDOP. This is expected as the sensitivity for the distance is only given by the parallax. Due to the different geometrical configurations of the observing stations and the satellite positions, the values of the DOP factors vary during the two observation periods. The comparison of the DOP values of the different observation periods shows that the average NDOP value is smaller during observation period B but the average TDOP and WDOP values are slightly smaller during the observation period A. This means that the satellite observations during the observation period A are less sensitive to the normal component but more sensitive to the tangential and cross-track components compared to the satellite observations during the observation period B.

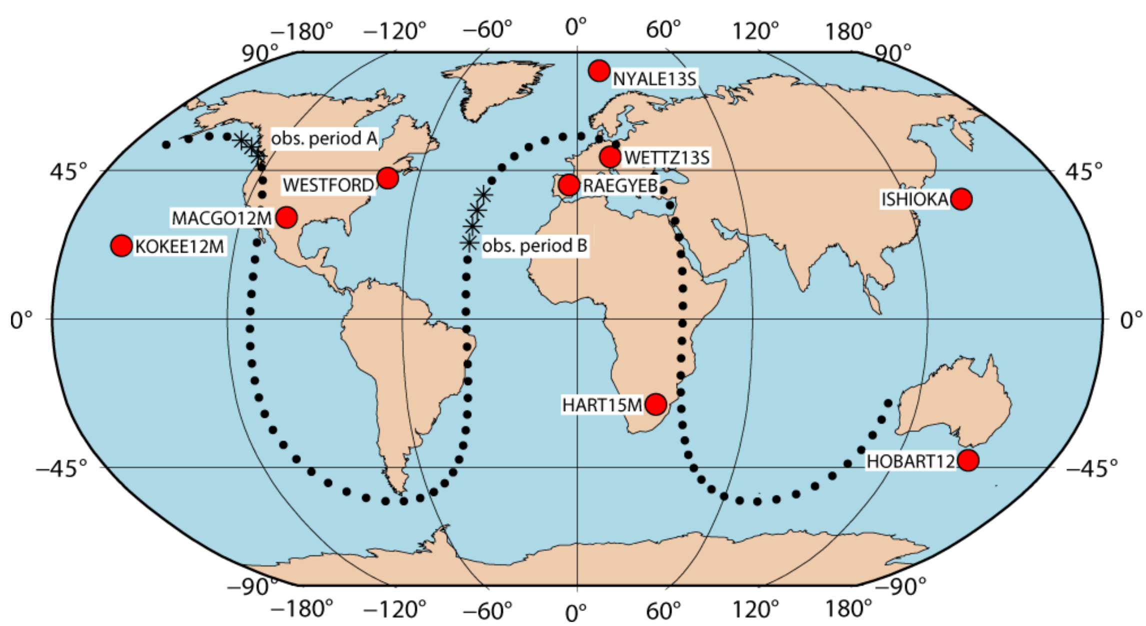

Fig. 2: VGOS station network considered in this study and ground track of the satellite GSAT0206 (E30) during 24 hours starting on April 6, 2022, at 00:00:00 UTC. The dots represent the ground track of the satellite at a 15-minute interval. The asterisks mark the positions of the satellite during the observation periods A and B when satellite scans are scheduled.

Table 2: Average values of the DOP factors (normal N, tangential T, and cross-track W) during the different observation periods.

	#stations	NDOP	TDOP	WDOP
obs. period A (00:50:00 - 01:40:00)	5	46.5	1.6	1.8
obs period B (12:10:00 - 13:00:00)	5	40.7	2.0	2.3

3.2 Results of Simulation Study

As described in Section 2.2, the satellite positions are determined as continuous piecewise linear offsets in each component with ten-minute intervals applying relative constraints of 10 cm. Figure 3 shows the repeatabilities of the estimated offsets from the a-priori orbit (SP3-orbit) for the individual components for each estimation epoch. Comparing the repeatabilities of the normal component during the observation time periods A and B, it is obvious that the accuracy is worse during the observation time period A compared to period B. This concurs with the comparison of the values of the DOP factors, as the NDOP during observation period A is higher and the observations are therefore less sensitive towards the normal component than the observations during time period B. The repeatabilities of the estimated offsets for the tangential and cross-track components are smaller during observation period A than during period B, which again is consistent with the results of the sensitivity study of the corresponding DOP factors as described in Section 3.1.

4 Summary and Discussion

In this study, possible satellite observations from a VGOS network of nine stations to the Galileo satellite GSAT0206 are investigated, first in terms of their sensitivities towards the satellite position and thereafter with regard to the precision of the adjusted orbit arc based on Monte Carlo simulations. The sensitivity analysis of the satellite observations is based on Dilution of Precision factors as indicators for the sensitivity of these observations towards the individual components of the satellite position, namely normal DOP, tangential DOP,

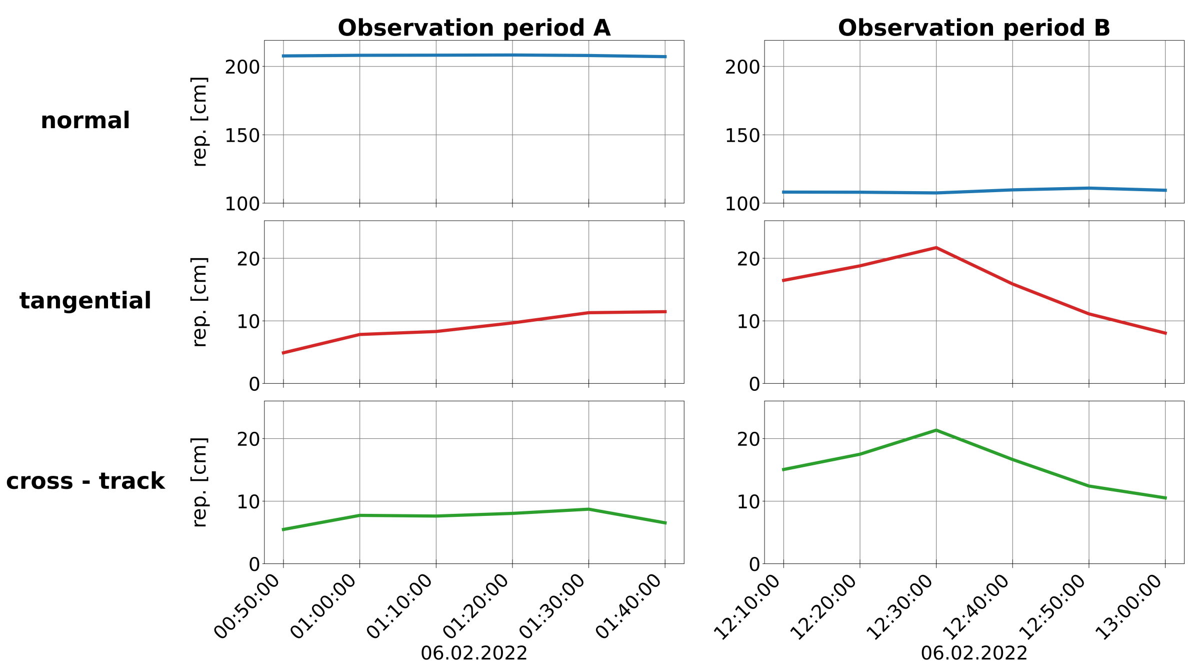

Fig. 3: Repeatability of the estimated offsets of the 1,000 simulations for the individual components (normal, tangential, and cross-track) during the observation periods A and B.

and cross-track DOP. The investigation of the results reveals that satellite observations with high sensitivity towards one of the components of the satellite position exhibit a better repeatability of the estimated offset of the respective component. Therefore, this component can be determined more precisely.

With this study, we further highlight that DOP factors properly represent the precision of satellite observations using VLBI. Therefore, they can be used as an optimization criterion during the scheduling process in order to select satellite scans with high sensitivities to the individual components of the satellite position. In the future, further DOP factors can be introduced, such as a factor for characterizing the quality of the whole schedule for determining the absolute orientation of the satellite constellation.

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