Observing GPS Satellite Signals in L-Band with a Realistic Global VLBI Network: A Simulation Study

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Abstract In the latest realization of the International Terrestrial Reference Frame 2014 (ITRF2014), significant differences are found between tie vectors computed from global-scale space geodesy estimates and terrestrial local ties. As these discrepancies represent one of the most relevant limitations on the quality of the ITRF, the frame ties need to be improved. A promising concept is the establishment of ties via co-location satellites, so-called space ties. However, no dedicated satellite missions are currently in operation. In this paper, we perform a simulation study using geodetic L-band antennas to perform observations of GPS satellites with the Very Long Baseline Interferometry (VLBI) technique. The aim is to investigate the usefulness of utilizing the currently available geodetic infrastructure to tie the VLBI and satellite frames. We achieve station position repeatabilities of about 9 mm to 13 mm with n experiment length of 24 hours. When increasing the experiment length to 48 hours the average repeatability goes down to 6.7 mm. The results indicate that these observations provide results that are not precise enough to tie together the VLBI and satellite frames.

Keywords VLBI, Satellites, Frame Tie

1 Introduction

In ITRF2014, the tie vectors computed from global-scale space geodesy estimates show significant differences to terrestrial local ties (Altamimi et al., 2016). It is believed that most of these discrepancies are related to technique systematic errors rather than local ties. The current ITRF realization is well outside the required accuracy, and as such it is a major error source for observations which are referenced to it. For further improvements of the ITRF, the consistency between local ties and space geodesy estimates needs to be improved as they represent one of the most relevant limitations on the quality of the ITRF (Boucher et al., 2015). A promising and well accepted concept is the additional establishment of ties via co-location satellites, so-called space ties (Rothacher et al., 2009). These ties would be independent of local ties and, therefore, allow the detection of technique-specific biases (Plag, H.-P. and Pearlman, M., 2009). However, no comparable satellite mission is currently in operation. By observing signals emitted by GPS satellites with VLBI, one can make use of the currently available geodetic infrastructure. This approach would build the frame tie between the VLBI and satellite systems. Although first test observations of satellites have successfully been performed, they have not been performed with a global network aiming towards tying the two frames together.

The aim of this paper is to investigate the usefulness of utilizing the current geodetic infrastructure to tie the VLBI and satellite frames by performing VLBI observations of the GPS satellites with a global network of L-band antennas. We present a study simulating and analyzing these observations. In Section 2, the simulation study is described. The results are shown in Section 3. The findings are summarized and discussed in Section 4.

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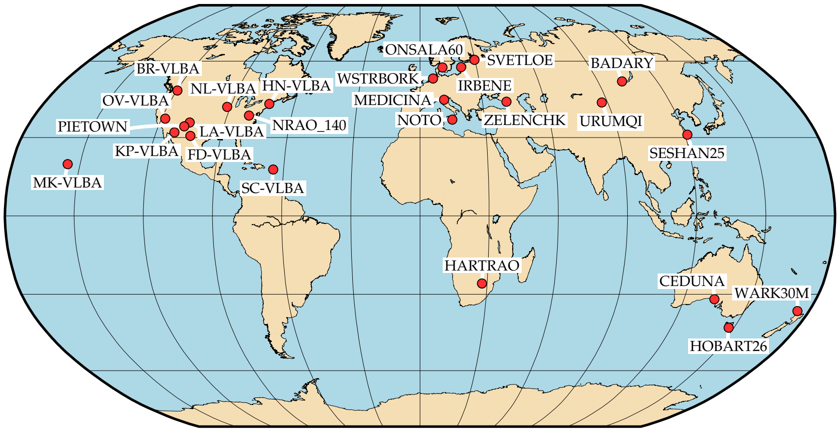

Fig. 1 Global network consisting of 25 stations utilized in the simulation study.

2 Simulation Study

A more detailed description of the network and used GPS satellites is given in Section 2.1 and Section 2.2, respectively. Firstly, as described in Section 2.3, we created an observation schedule. The length of the schedule was chosen to be 24 hours. Based on the schedule the VLBI observations were simulated using the main observation errors and the standard procedure. The simulations are described in Section 2.4. In Section 2.5, the desired parameters are estimated in a least squares adjustment drawing upon the simulations. Section 2.6 presents how the results of the estimation are evaluated.

2.1 Global Station Network

The requirement for a station to be part of the global network is that it be equipped with an adequate L-band receiver to collect signals of GPS satellites. As shown in Figure 1, we found 25 stations that are utilized in this simulation study. Some of these stations have proven to be capable of tracking and recording GNSS satellites in a VLBI experiment (Tornatore et al., 2014; Plank et al., 2017). For the remaining stations we will assume that they have the ability to do so, even though they might run into issues when actually observing GPS satellites in L-band. With only four stations in the Southern hemisphere, the network exhibits an undesired inhomogeneity in the distribution of the stations.

2.2 Satellites

The satellites that serve as sources in the simulation comprise the currently available constellation of Global Positioning Service (GPS) satellites. As of April 12, 2022, there were a total of 30 operational satellites. Throughout the simulation experiment the number of visible satellites for all stations varies between 7 and 14 when considering an elevation mask of 5°.

2.3 Scheduling

The scheduling is performed using the VLBI scheduling software VieSched++ (Schartner and Böhm, 2019). The length of the experiment is chosen to be 24 hours. In comparison to quasars, the signals of GPS satellites are extremely strong. Therefore, a scan time of ten seconds produces a sufficient signal-to-noise ratio to perform fringe-fitting. For the scheduling, fill-in mode and subnetting is used, and only GPS satellites serve as sources. In the following the experiment is referred to as `S24GR`. For the experiment the number of scans was scheduled to be 3,574 with a number of 28.3 scans per station per hour. The number of observations is 56,868 with a sky coverage of 0.45. The sky coverage score is a value between 0 and 1, describing how well the sources are distributed above the sky of a station, where 1 represents a perfect distribution.

Table 1 Parameters used to simulate observations, following the method described in Pany et al. (2011)

Clock	
Allan standard deviation	1×10^{-14}@50 min
Tropospheric turbulence	
Initial zenith wet delay	150 mm
Structure constant C_n	1.8×10^{-7} $\mathrm{m}^{1/3}$
Effective height of the troposphere	2 km
Wind speed in eastern direction	8 m/s
Wind speed in northern direction	0 m/s
Height increment for integration	200 m
Correlation interval	2 h
Measurement error	
White noise	50 ps

2.4 Simulated Observations

The Vienna VLBI and Satellite Software (VieVS) has been used to perform the simulations (Böhm et al., 2018). The three main stochastic error sources applied in this study are wet tropospheric delay, station clock inaccuracies, and measurement noise. We perform 300 repetitions of the simulation to be able to run subsequent statistical evaluations of the results in terms of mean values and variance. Table 1 gives the characteristic numbers for the models.

2.5 Parameter Estimation

In the least squares adjustment, the Earth orientation parameters were not estimated in the adjustment. Zenith wet delays were estimated as piecewise linear (pwl) offsets every 15 min for each station with 1.5 cm relative constraints. Troposphere gradients to address azimuthal asymmetry were estimated in 15 min intervals with 0.05 cm relative constraints and 0.1 cm absolute constraints. The clocks were set up as 30 min pwl offsets and one rate as well as one quadratic term per clock. The clock estimates are also constrained with 1.3 cm. For estimating station coordinates, a datum has to be defined. The datum is set by the GPS satellites. A no-net-rotation (NNR), no-net-translation (NNT) or no-net-scale (NNS) condition is not applied.

Because the station positions and network configuration of the antennas is known relatively precisely in the VLBI frame, we are introducing additional observations. 21 of the stations in our network have coordinates and standard deviations in the IVS contribution to the ITRF2014. The relative distance d between two stations $s1$ and $s2$ is incorporated as an additional observation for the least squares adjustment, using

$$d = \sqrt{(x_{s2} - x_{s1})^2 + (y_{s2} - y_{s1})^2 + (z_{s2} - z_{s1})^2}. \quad (1)$$

Based on the number of possible combinations $n(n-1)/2$, where n is the number of stations, the relative distances between the 21 stations lead to an additional 210 observations, in the following referred to as soft constraints. The weights of these additional observations are derived by the propagation of the variance for the relative distance from the standard deviations of the coordinates, using

$$\sigma_d^2 = \left(\frac{\partial d}{\partial x_{s1}}\right)^2 \cdot \sigma_{x,s1}^2 + \cdots + \left(\frac{\partial d}{\partial z_{s2}}\right)^2 \cdot \sigma_{z,s2}^2. \quad (2)$$

CEDUNA, IRBENE, WARK30, and WSTRBORK are the four stations not being represented in the IVS input to the ITRF2014 and, therefore, also not included as additional observations due to a lack of stochastic information.

2.6 Evaluation

The parameter that is used to assess the simulation results is the repeatability of antenna coordinates with respect to the true, a priori antenna coordinates. For a better geometrical interpretation the repeatabilities in the dx, dy, and dz components are converted to local east (de), north (dn), and up (du) components. The standard deviation σ of these estimates gives a measure of the expected accuracy of derived antenna coordinates. The standard deviation σ_{du} for n samples with the mean value du_m is calculated as

$$\sigma_{du} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(du_i - du_m)^2}. \quad (3)$$

Furthermore, the repeatability of the 3D antenna position is assessed. The root mean square error is defined as

$$\mathrm{e}_{3D} = \sqrt{\sigma_{dx}^2 + \sigma_{dy}^2 + \sigma_{dz}^2} = \sqrt{\sigma_{de}^2 + \sigma_{dn}^2 + \sigma_{du}^2}. \quad (4)$$

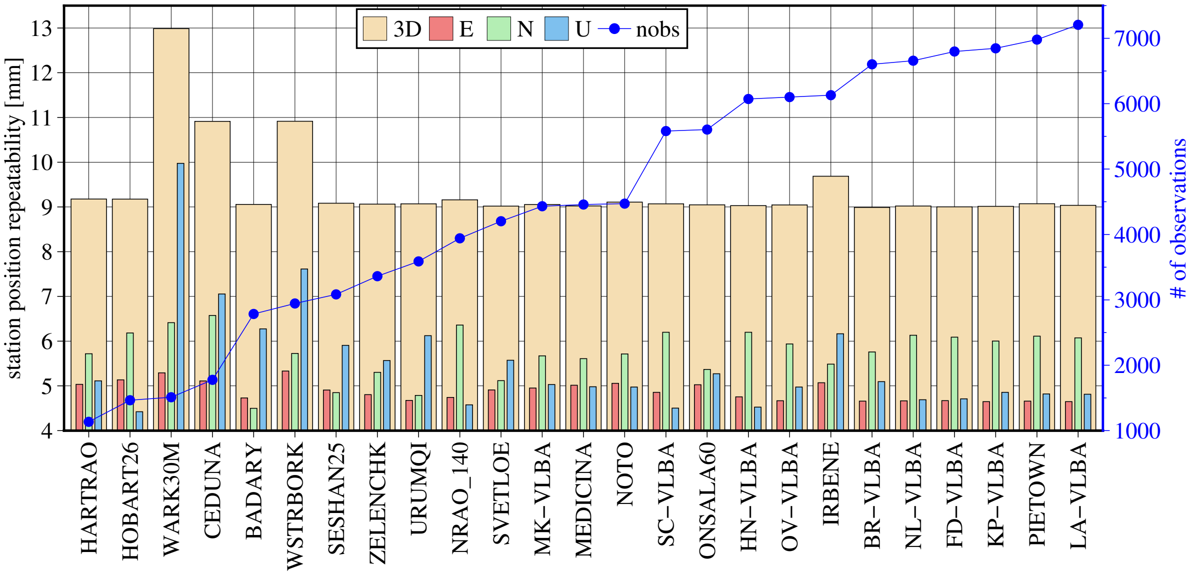

Fig. 2 Station position repeatabilities for the `S24GR` simulation in terms of 3D position rms (*orange*), as well as in the east (*red*), north (*green*) and up (*blue*) components. The *blue* line with the scale on the right gives the number of observations for each station.

3 Results

In Figure 2, the station position repeatabilities are shown when observing a constellation of 30 GPS satellites with a global network of L-band antennas for 24 hours. The results are given as 3D position rms (orange) as well as in the east (red), north (green), and up (blue) components. In addition, the number of observations per station is illustrated. The average and maximum 3D station position repeatabilities are 9.4 mm and about 13 mm, respectively. Overall, they are distributed homogeneously over the stations. This is due to the additionally introduced 210 observations of relative distances between the stations.

The four stations not being included in the soft constraints show a large repeatability in the up component. Large errors in the height are due to the high correlation between the estimated troposphere zenith wet delays and the station height. For the remaining stations the east, north, and up components are relatively similar in magnitude. Introducing the soft constraints makes the station network like a cage with little room for deformation. Stations with a lot of observations being part of a dense regional network (e.g. LA-VLBA) support isolated stations with few observations (e.g. HARTRAO). That leads to the effect that stations with more observations are not significantly more precisely determined than stations with fewer observations.

Most of the antennas are rather large and have a slow slewing speed compared to the new generation VGOS antennas. The determination of the up component of a station coordinate can be increased by increasing the number of observations and distributing them across the sky. This helps in the least squares adjustment to distinguish between the height and troposphere parameters. However, the slow slewing speeds only allow this distinction up to a certain degree. In order to understand how fast slewing antennas would improve the results, we performed an additional simulation `S24GV`, assuming the antennas to be as fast as the new generation VGOS antennas (slew rate 1: 720 degrees per minute, slew rate 2: 360 degrees per minute). Also, another simulation is performed using the original slewing speeds, but the schedule length is increased to 48 hours in `S48GR`.

Assuming antenna slew speeds comparable to the new generation VGOS antennas decreases the average 3D repeatability significantly from 9.4 mm to 5.9 mm. Increasing the length of the schedule from 24 hours to 48 hours also leads to a substantial improvement to 6.7 mm. Furthermore, the impact of the noise is investigated. When neglecting the measurement noise of 50 ps, the average 3D station repeatability goes down from 9.4 mm to 8.7 mm for the 24-hour experiment and from 6.7 mm to 6.0 mm for the 48-hour experiment.

4 Conclusions

The simulation study has shown that observations of GPS satellites enable the derivation of antenna positions in the satellite system with a precision of 9 mm up to 13 mm for a schedule of 24-hour length. Increasing the schedule length to 48 hours improves the precision to 6.7 mm. The slew speed of the antennas is one of the limiting factors. Assuming a slew speed for all antennas comparable to the new generation VGOS antennas improves the average 3D station repeatability to 5.9 mm for a 24-hour schedule. The results show that observations of the GPS satellite constellation with a current infrastructure of L-band antennas in a global network are not precise enough to create the frame tie between the VLBI and GPS systems. The station position repeatabilities are significantly larger as demanded.

A potential problem limiting the results is the sky coverage. The bounded inclination of the GPS constellation of about 55 degrees leads to poor sky coverages for stations that are several tens of degrees away from the equator. A possible solution is to implement the sandwich method with sequences of observations of radio-source–satellite–radio-source. Although not connecting the VLBI and GPS systems, it could improve the troposphere and, hence, the height component estimation. Possible additional error sources such as, e.g., the influence of deficient orbit determination of the target satellites or special characteristics of the transmitter were not included in the investigations above.

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