Direct VLBI Observations of Global Navigation Satellite System Signals

V. Tornatore, R. Haas, S. Casey, D. Duev, S. Pogrebenko, and G. Molera Calvés

Abstract

We describe an experiment carried out to observe signals emitted by GLONASS (GLObal NAvigation Satellite System) satellites using the Very Long Baseline Interferometry (VLBI) technique. This test was performed on a single baseline and had as its primary goal to evaluate the capability of the VLBI system to observe GNSS (Global Navigation Satellite System) signals in terms of scheduling, tracking, acquisition, recording, correlation and processing of data. The general aim of such observations is to contribute to the connection of the reference frames for GNSS and VLBI by so-called co-location in space, or *space-ties*, as a complement to the existing so-called *local-ties* on the Earth's surface.

In our experiment we found an interferometric response from both signals emitted by GLONASS satellites and a natural radio source that was observed as a calibrator, using the same VLBI equipment. The derived fringe phase scatters were 80 ps (2.5 cm) and 1.3 ns (39 cm) in 1 s for the GLONASS satellite and the calibrator signals, respectively. This indicates that the accuracy is not limited by GLONASS signals, but by the calibrator.

Our results show that VLBI observations of GNSS signals are possible and have the potential to derive the satellite positions on a centimetre level for observing times of just a few minutes. Future experiments should include several baselines and a larger number of calibrators in close angular distance to the satellite tracks to allow frequent switching between calibrator and satellite signals.

Keywords

GNSS • *Local-ties* • Reference frames • *Space-ties* • VLBI

1 Introduction and Motivation

Global Earth science applications depend on an accurate Global Terrestrial Reference System (ITRS). Monitoring of parameters describing Earth phenomena and their evolution in time requires space–time reference systems (Kovalevsky et al. 1989; Nothnagel et al. 2010). The latter are realized

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by successive updates of the International Terrestrial Reference Frame (ITRF). This reference frame is a combination and integration of results of the four space geodetic techniques: Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS). The most recent version of the ITRF, called ITRF2008, is described in detail by Altamimi et al. (2011). The requirements of the science community, as set by the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) are to achieve the ITRF with 1 mm accuracy and 0.1 mm/year stability (Plag and Pearlman 2009). This order of magnitude was also endorsed by the NRC (National Research Council) committee on precise geodetic infrastructure (NRC 2007, 2010).

The ITRF combination makes use of so-called fiducial sites that have co-located equipment for two or more space geodetic techniques. At these fiducial sites the three-dimensional vectors that connect the reference points of two geodetic space techniques like, e.g., the reference point of a radio telescope for VLBI and the reference point of a GNSS antenna, have to be known with high accuracy. These vectors are usually called *local-ties* and the most common way to determine *local-ties* is to perform classical geodetic surveys using total stations (Sarti et al. 2004) and levelling instruments. The uncertainty of the *local-ties* between co-located techniques is a major error source for the current ITRF2008. As they represent a key element of the spatial technique combination, they should be more accurate than they are, or at least as accurate as the individual space geodesy solutions incorporated in the ITRF2008 combination. The level of agreement between *local-ties* and estimates of the same vector, obtained by space geodetic techniques after ITRF2008 computation was presented by Altamimi et al. (2011). Only very few of the co-location stations showed an agreement at the level of accuracy of the survey techniques. The best cases were on a level of less than 6 mm, but the majority was above that number, showing clearly that there are problems. The reasons for large discrepancies are difficult to be addressed because these discrepancies could be due to errors in *local-ties*, in space geodesy estimates, or in both.

The scientific community is strongly interested in finding alternative methods to *local-ties*, or at least to have different independent measurements and validation of the *local-tie* surveys, that could help discriminating between tie errors and systematic errors in the techniques themselves. Among the work in progress we can name for example direct SLR observations of GNSS satellites (Thaller et al. 2011) or the GRASP (Geodetic Reference Antenna in Space) project aiming to build a geodetic multi-technique satellite to improve the Terrestrial Reference Frame (TRF) (Bar-Sever et al. 2011).

Another approach to link the observational techniques, and thus the involved frames, is co-location in space by observation of GNSS satellites with VLBI radio telescopes. This is the approach followed in this work. The VLBI technique has been used fruitfully and extensively for tracking of a number of deep-space missions since the second half of the 1980s (Preston et al. 1986). Today, several space agencies increased their interest in VLBI space applications for highly accurate determination of spacecraft state-vector as a function of time. The most recent achievements are for example NASA's Mars Exploration Rover B spacecraft (Lanyi et al. 2007), Very Long Baseline Array (VLBA) tracking of the Cassini spacecraft (Jones et al. 2011) and ESA's spacecraft Venus Express (Duev et al. 2012). Several of the algorithms developed for deep-space navigation (Wagner et al. 2009–2010) have been, in this work, adapted to Earth orbiting satellites, like the GNSS ones. The VLBI observations of GNSS radio signals and of natural radio sources used as calibrators, primarily concern frame ties between the dynamic reference frame of the satellites and the kinematically defined International Celestial Reference Frame (ICRF).

In this paper we will describe in Sect. 2 the measurement principle of observation of GNSS signals by the VLBI technique, followed by Sect. 3 with the description of the observation setup, the data processing pipeline, and the software used. Preliminary results and requirements to improve the link between the GNSS and VLBI frames will be presented in Sect. 4.
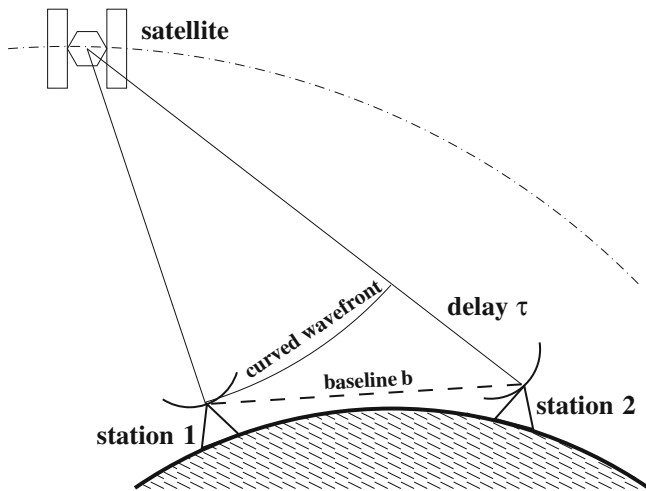
2 Measurement Principle

To achieve the best link between the VLBI and GNSS frames it is important to observe and process GNSS signals using the same optics, electronics and processing pipeline as for natural radio sources observed with the VLBI technique to insure the cross-calibration of the two frames. A variety of interferometric techniques that may be used for measuring the angular location of a spacecraft with respect to natural celestial radio sources have been described in Lanyi et al. (2007).

In our experiments we have considered the orbiting satellite as an *artificial* radio source observed with the VLBI technique, we used the simplest VLBI configuration with two radio telescopes pointing at the same GNSS satellite.

One of the main problems to be considered in such observations is that, unlike in "standard" VLBI observations of *natural* radio sources, the distance to a GNSS satellite cannot be assumed infinite and the "near-field" effects need to be taken into account (Fig. 1). Indeed, a source of radio emission is considered to be in the near field if the so-called Fresnel number $F = b^2/(r \cdot \lambda)$ is greater or similar to 1 (see e.g. Born and Wolf 2002) where b is the characteristic size

Fig. 1 Schematic of VLBI-observations of GNSS-signals. The satellite is not at infinity (plane wave fronts) but is a *near-field* source. Thus the wave fronts are curved

Table 1 Observation plan for the experiment on August 16, 2010

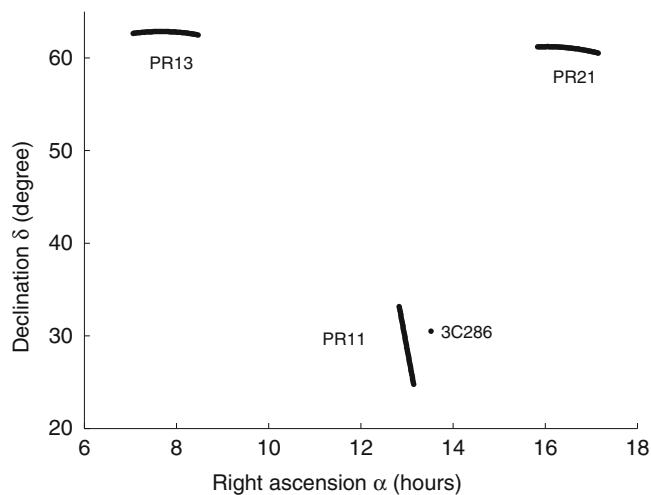| N° scan	Target	Start of scan (UT)	Duration (min)	Sky Freq (MHz)	SNR for the whole scan
1	3C286	11:40	5	1,602.00	100
2	PR11	12:00	15	1,602.00	2×10^4
3	PR21	12:45	15	1,604.25	2×10^4
4	PR13	13:30	15	1,600.25	2×10^4
5	3C286	14:00	5	1,602.00	100

advanced ionosphere and troposphere delay corrections were rigorously tested using VLBI observations of the ESA Venus Express and Mars Express spacecraft and corresponding analysis at the Joint Institute for VLBI in Europe (JIVE) (Duev et al. 2012).

3   Observations and Test Setup

Several tests to observe GNSS satellites using the VLBI technique were carried out in 2010. The main problems that had to be faced in order to observe GNSS signals in VLBI mode were the preparation of observing schedules, the tracking of fast moving objects, the recording of artificial radio signals and the development of algorithms for data correlation and processing. The difference in the observation of artificial radio signals with respect to natural radio astronomical signals stands in the small bandwidth of the satellite signals and in the very high signal strengths, that require attenuation of the VLBI equipment.

In particular we report here on the experiment performed on 2010, August 16 (see also Tornatore et al. 2011). The radio telescopes at Medicina (Italy) and Onsala (Sweden), both equipped with L-band receivers, were used to observe 3 GLONASS satellites, each for about 15 min. We chose GLONASS satellites instead of GPS satellites, since the L-band systems of the Italian station Medicina can not observe at the GPS frequencies. The telescopes were repointed every 20 s in order to follow the satellites. A natural radio source (3C286) was observed as a calibrator for 5 min at the beginning and at the end of the whole satellite observation session. We note that the spectral power density of the satellite signals is several orders of magnitude higher than that of the natural radio source. Therefore additional attenuation was necessary at the stations to avoid damage of the receiving systems when observing satellite signals. Table 1 gives an overview of the characteristics of the observations.

During the experiment signals in four intermediate frequency (IF) bands were simultaneously recorded. Two of the bands were permanently tuned to 1,610 MHz, one of these recorded RHCP (Right Hand Circular Polarization), and the other LHCP (Left Hand Circular Polarization).

of the aperture, λ is the wavelength and r is the distance from the aperture to the source. For VLBI observations at L-band ($\lambda \sim$20 cm) with an array of radio telescopes with a synthesized aperture $b \sim$1,000 km this is true for $r < 30$ AU (Astronomical Unit). Therefore, the GNSS case, where the satellite is at a distance from the Earth of about 20,000 km, can be thought of as "ultra" near field with the source being "inside" the synthesized aperture.

For the scheduling of standard VLBI observations the position of a radio source is considered to be constant in a celestial reference frame during the observing run for all participating telescopes. Usually, the radio source's equatorial coordinates in the International Celestial Reference Frame (ICRF) at epoch J2000.0 are used as input for the scheduling and delay computation software.

For near-field VLBI observations of a spacecraft, the target can move rapidly across the primary beam of a telescope. Therefore, the position of a spacecraft is calculated at different epochs and it is then used for pointing the antenna at the spacecraft during those particular epochs. In the "ultra" near-field case, i.e. when the target is within (or very close to) the synthesised aperture of a VLBI array, so-called cross-eyed scheduling is necessary. This means that the equatorial coordinates of such a spacecraft are different in the schedules for different VLBI stations (Duev et al. 2012).

The near-field VLBI delay model is formulated in the Barycentric Celestial Reference System (BCRS) in order to be consistent with the "standard" VLBI model. The a priori orbit of a GNSS satellite, retrieved in our case from the International GNSS Service (IGS), was transformed from ITRF to BCRS following the IERS Conventions 2010 (Petit and Luzum 2010). The current implementation of the near field delay model and

Fig. 2 Observation situation at Onsala for the experiment on August 16, 2010. Shown are the right ascension and declination of the calibrator radio source 3C286 and of the three GLONASS satellites. The calibrator was observed for 5 min at the beginning and the end of the observation session. The satellites were observed each for 15 min with telescope positioning updates every 20 s

The other two IFs, which again recorded RHCP and LHCP, were set to one of the three frequencies corresponding to the satellite being observed and therefore changed during the experiment. A bandwidth of 16 MHz was observed in a way that each one of the emitted frequencies was in the center of the bandwidth. Additional attenuation for both RHCP and LHCP channels was applied in order to avoid saturation of the receiving systems by the strong satellite signals. For the calibrator 3C286 two IFs were at 1,592.88 MHz and two at 1,610 MHz, both RHPC and LHCP. The radio source 3C286 was observed at the start of the satellite session for 5 min beginning 11:40:00 UT and for 5 min at the end of the satellite session beginning at 14:00 UT. We allocated 30 min time between satellite scans in order to move the telescopes and to adjust the attenuation level.

The GLONASS satellites had to be simultaneously visible at the two sites, they were chosen with a not too low elevation, to mitigate troposphere effects and also with a not too high elevation to avoid pointing problems with VLBI antennas. An example the observation situation at Onsala is shown in Fig. 2. The position of the calibrator radio source and the three satellites are represented in a right ascension and declination plot.

The calibrator was near to the PR11 satellite, but was several degrees apart from PR13 and PR21. This scheme is far to being optimal, a nodding cycle of about 5 min (2 min on calibrator, slewing, 2 min on satellite) would have been more preferable, as well as the use of multiple calibrators. But, this was not a goal of this test run, that as stated, was principally oriented to find proper ways to perform non
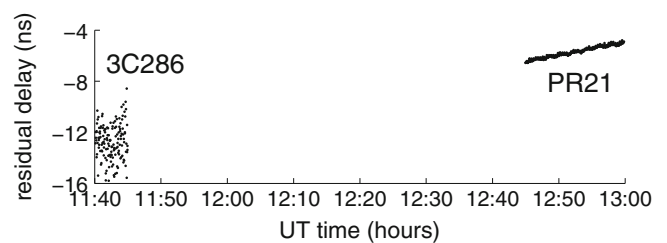

Fig. 3 Residual delays (after model applied) for the calibrator source 3C286 (first 5 min) and GLONASS satellite PR21 (last 15 min). The integration time per point is 2 s

standard VLBI observations of GNSS signals. We will try a setup with faster and shorter alternating scans between satellite and calibrators in future tests.

4   Processing, First Results and Requirements for Further Tests

Signals for all the three GLONASS satellites and of the calibrator were recorded using the standard Mark4 VLBI data acquisition rack and Mark5A disk-based recorders. The correlation was performed using the EVN (European VLBI Network) software correlator at JIVE (Joint Institute for VLBI in Europe) SFXC (Software FX Correlator, Keimpema et al. 2011). We found an interferometric response for the satellite PR21 and for the calibrator. The reason why we found no correlation results on other scans is not yet clear. Perhaps some problems occurred due to manual switching of attenuation and of observing frequencies between scans, or because of imprecise tracking.

To demonstrate the success in correlation of data for GLONASS satellite PR21 and calibrator source 3C286, we show in Fig. 3 the residual delays after applying the near field model delay for the satellite and standard model delay for the calibrator. The a priori orbit of the GLONASS satellite and vertical Total Electron Content (vTEC) maps on a daily basis with a 2 h temporal resolution on a global grid were used, both provided by IGS. For the tropospheric effect on the signal propagation delay, the ray-tracing algorithm from Hobiger et al. (2008), with some changes developed by Duev et al. (2011), was adopted. The meteorological data from the European Centre for medium-range weather forecasts (ECMWF) were used for ray-tracing. Additionally, contributions to the delay due to the antenna axis offsets and smaller size effects due to thermal deformations of telescopes (Nothnagel 2009) are also taken into account in our delay model, signal path variations due to gravity (Sarti et al. 2009; Clark and Thomsen 1988) have been considered only for the Medicina antenna whose gravitational deformation model is available.
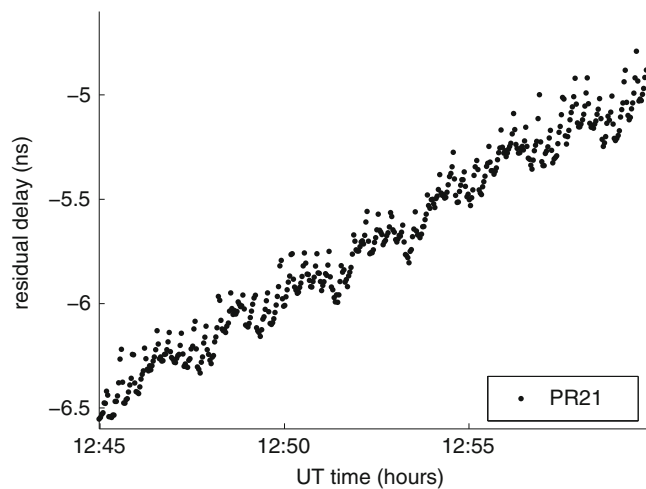
Fig. 4 Residual delays for the GLONASS satellite PR21. The integration time per point is 2 s

We determined clock offsets between stations, but these were not very useful because it was just one calibrator observed. To discriminate between clock offsets and propagation effects more calibrators are needed, but the goal of this observation run was principally to gauge whether observations and correlation of GNSS signals were achievable or not. Systematic biases are visible for both the calibrator and the GLONASS satellite. These biases are probably caused by instrumental errors (e.g., station clock biases) and deficiencies in the delay model, but cannot be eliminated from observations on just one baseline and one calibrator. The stochastic delay measurement noise (after removal of a linear trend) is at a level of 1.3 ns in 1 s and 115 ps in 5 min for calibrator source 3C286, and 80 ps in 1 s and 4 ps in 15 min for the GLONASS satellite PR21.

The stochastic error for the GLONASS signals is lower than for the calibrator due to much higher SNR, even though the effective bandwidth of GLONASS signals is less than 16 MHz. The behaviour of the residual delays for GLONASS satellite PR21 is depicted in Fig. 4, which is a zoom-in to in Fig. 3.

We clearly detect a kind of instrumental jitter caused by the rough re-pointing scheme used in the observations, since the telescopes were re-positioned every 20 s to follow the satellite. Furthermore, a trend in the GLONASS delay is clearly seen and it is probably related to undetermined clock offsets and clock rates at the stations. This trend could also be caused for example by imperfections in the delay model mainly due to the troposphere, ionosphere, etc.

The attempt of an array calibration by observations of natural radio sources seems also to be a limiting factor due to a narrow bandwidth. The use of digital base band convertors

(BBC) could allow increasing the bandwidth, thus reducing the stochastic error for the calibrators. Longer observations with more baselines could be helpful to discriminate between them.

Our next goal is to extend the VLBI network to a number of at least three or four stations tracking the same GNSS satellite to mitigate present bias and determine coordinate of a certain number of satellites. Then we want to test the method of phase referencing between GNSS satellites and background extragalactic sources, using more calibrators at small angular distances from each satellite and contemporary visible at all the stations. To reach this goal several problems still need to be solved. One major requirement is that a large enough number of stations with L-band receivers is available. It is necessary to observe on both frequencies for each GNSS constellation in order to be able to solve for ionospheric effects without using external data. Other major improvements concern the automation of the scheduling and the determination of signal attenuations, and the satellite tracking capabilities inside the FS (Field System) itself. It is also necessary to improve the import of the correlation results into analysis software packages like AIPS (Astronomical Image Processing System) (Greisen 1998), and Calc/Solve (Ma et al. 1990), where also the "near field" delay model needs to be implemented.

5   Conclusions and Outlook

We have found interferometric response from observations of signals of a GLONASS satellite and a background extragalactic radio sources in the same VLBI experiment using the same receivers and the same VLBI setup. This proves that direct VLBI observations of GNSS satellite signals are possible and have the potential to contribute to an improved connection between VLBI and GNSS frames. The scatter of the residual delays for the GLONASS satellites is 15 ps and for the radio source 260 ps over 1 min. Future work will focus on an improvement of the delay models and observations with larger VLBI networks and fast switching between natural radio sources and GNSS satellites to help to improve the link between the frames.

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