Single baseline GLONASS observations with VLBI: data processing and first results

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Abstract The VLBI technique, in geodetic mode, was used to observe signals emitted by three GLONASS (GLObal NAvigation Satellite System) satellites. The baseline observing simultaneously satellites had at its ends the Medicina (32 m) and Onsala85 (25 m) radio telescopes, both equipped with L-band receivers. Several preparatory tests were necessary for obtaining good data that could be processed.
In this paper we report on the observations performed on August 16, 2010 data processing and results of the experiment. The natural radio source 3c286 was observed also as a calibrator before and after satellite observing sessions. A narrow band approach using software primarily developed for astronomical and space applications, was applied to extract the narrow band carrier.
Differential frequency on the baseline Medicina-Onsala was also evaluated to compute differential phase which was then adopted to determine satellite coordinate corrections with respect to ITRF values. Broad-band correlation was performed on the calibrator data using the DiFX software. The SFXC correlation of satellite data was performed testing near field delay model at extreme nearness; obtained results are described.

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1 Introduction

Reference frames of high accuracy are the basis for the analysis and interpretation of geodetic parameters and their temporal behaviour. Modern reference frames are generated by IERS (International Earth Rotation and Reference System Service) which combines solutions of the space geodetic techniques VLBI, SLR/LLR (Satellite Laser Ranging/Lunar Laser Ranging), GNSS (Global Navigation Satellite Systems) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite). The consistency in time of the analysis strategies for each data series but also between the different techniques is essential to obtain a reference frame of highest accuracy.
Presently the combination of different geodetic space techniques is based on local-ties at co-located stations. Local-ties are derived from local terrestrial geodetic surveys carried out at these stations. Some discrepancies between the local-ties derived from terrestrial surveys and coordinate differences derived from space-geodetic observations have been found in several studies, however the reason for the discrepancies is often not clear (Krügel and Angermann, 2005).

The tracking of GNSS satellites by VLBI sites permits the connection of both observing techniques at the satellite level (satellite co-location) and not at the station level. In this case the link depends neither on the local ties nor on the uncertainties of the GNSS reference point of the ground station antennas. The connection at the satellite level is a promising alternative to the connection at the stations. The independently estimated station coordinates at co-located sites could also allow a validation of the local ties (Thaller et al., 2011).
With this work we want to verify if from a technical point of view the estimate of a GNSS satellite coordinates (in this case in particular we observe GLONASS satellites) can be obtained using the VLBI technique. Observing GNSS signals, using the same optics as the VLBI signals (including gravitational and thermal deformations), the combination of the kinematic VLBI reference frame of natural celestial radio sources and the dynamical GNSS reference frames of satellite orbits is aided. The GNSS satellite

Satellite	Observation Interval [UT]	Emitted frequency [MHz]
PR11	11:59:50-12:14:50	1602.00
PR21	12:44:50-12:59:50	1604.25
PR13	13:29:50-13:44:50	1600.87

Table 1 Satellite observation setup

positions could be expressed with respect to the background natural radio sources. Furthermore, the connection of the VLBI TRF to the Earth's gravity field could be improved.

In Section 2 the observations of the GLONASS satellites in VLBI geodetic mode are described, in Section 3 data processing of GLONASS and calibrator data are recalled both for narrow-band and broad-band correlation, finally in Section 4 comments on present results and further developments are presented.

2 VLBI GLONASS experiment description

The VLBI observations were carried out on August 16, 2010 on the baseline Onsala-Medicina and three GLONASS satellites were tracked one by one. During the experiment the radio source 3c286 was observed as a calibrator for 5 minutes at the beginning and at the end of the whole satellite session. The GLONASS satellites observed in turn, for 15 minutes each, were PR11, PR21 and PR13. They were selected, according to the planning, among those simultaneously visible at both stations and very well distributed in the sky at each station. Then, during the observation interval, they had nor a very low elevation, which is good to decrease a bit the troposphere effect, nor a very high elevation which might have given antenna pointing problems. In order to track the satellites the 15 minutes observation interval was actually made up of 45 scans of 20 seconds each, where for about half of these 20 seconds both the telescopes were pointing at the satellite, and for the other half were moving to the new satellite location. Such re-pointing of the radio telescopes produced in the data residuals some glitches with a period of about 20 seconds. They could be avoided if a continuous tracking software could be installed in the Field System. Frequencies emitted by each satellite and the interval of observation can be found in Table (1).
During all the experiment 4 IFs were simultaneously recorded, there are 2 which were always tuned to 1610 MHz, 1 of these recorded RHCP (Right Hand Circular Polarization), the other LHCP (Left Hand Circular Polarization). The other 2 IFs, which again recorded RHCP and LHCP, were set to one of the 3 frequencies corresponding to the satellite being observed, and therefore changed during the experiment. A bandwidth of 16 MHz was observed in a way that eachone of the emitted frequencies was in the center of the bandwidth. Each RHCP had 16 MHz, as did each LHCP, therefore a combined total of 32 MHz per observed frequency, or 64 MHz total recorded bandwidth across the 2 frequencies. Additional attenuation for both RHCP and LHCP channels was applied in order to avoid saturation of the receiving systems by the strong satellite signal.
The calibrator 3c386 was observed at the starting of the satellite session for 5 minutes beginning 11:40:00 UT and for 5 minutes at the end of the satellite session beginning at 14:00 UT. For the calibrator 3c386 2 IFs were at 1592.88 MHz and 2 at 1610 MHz both RHPC and LHCP.

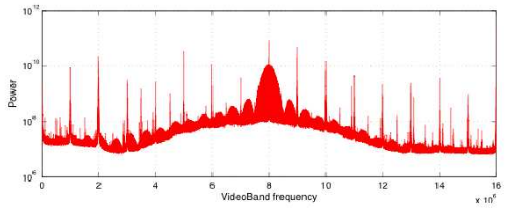

Fig. 1 Power spectrum for interval 2 (PR11) observed at Onsala radio telescope

3 Data processing of VLBI GLONASS observations

Several studies and data processing have been performed on the data recorded during the August 16, 2010 experiment.

3.1 Narrow-band correlation

The initial detection of the satellite carrier signal and sub-harmonics relative to the carrier was performed using the high-resolution software spectrometer, SWSpec (Wagner and Molera Calvés, 2007) and spacecraft tracking software, SCTracker (Wagner et al., 2010) developed at Metsähovi Radio Observatory in collaboration with JIVE in the framework of the Planetary Radio Interferometry and Doppler Experiments (PRIDE).

The first iteration of SWspec on data of the second interval (satellite PR11) observed with the Onsala radio telescope is shown in (Fig. (1)). The GLONASS signal is seen in the central lobe at 8 MHz. The narrow peaks spaced 1 MHz are caused by the Phase Calibrator signal from the receiver. We notice high level of power in the main and side lobes. For GLONASS satellite PR11 autocorrelation spectrum analysis we used $1.6x10^6$ DFT (Discrete Fourier Transform) points, 1-second integration time and Cosine-squared windowing, for a spectral resolution of 20 Hz over the 16 MHz bandwidth.

The SCtracker filters the satellite signal down to 8 kHz narrow bandwidth with spectral resolution of 4 Hz. The frequency detection noise is at a level of several mHz in 1 second. Results of the narrow-band signal processing were then analysed at JIVE.

After the PLL (Phase-Locked-Loop), the GLONASS signal is filtered out to a narrow band around the carrier line of 800 Hz and spectral resolution of 0.8 Hz. With such accuracy, we can extract the residual phase of the carrier tone. The phase fluctuations detected at each stations allow us to study the phase scintillation along the propagation path. We can see the results of analysis on the GLONASS data for the 4th interval (satellite PR13) obtained at Onsala radio telescope in the Fig. (2). The satellite phase with

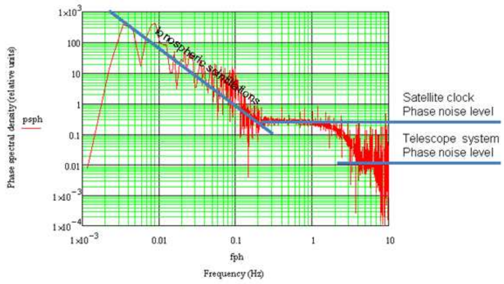

Fig. 2 Phase scintillation spectrum, as of GLONASS PR13 observations, Onsala, interval 4

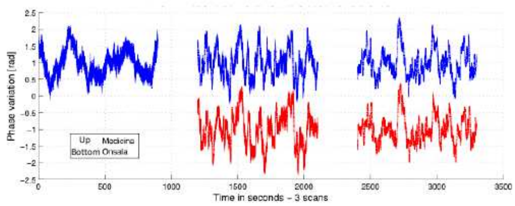

Fig. 3 Phase fluctuations for the three: GLONASS satellites PR11, PR21, PR13 observed at Medicina (top) and Onsala (bottom).

a 20 Hz sampling phase lock was extracted. The y-axis is the power spectra density of the phase scintillations and the x-axis is frequency of the phase scintillations in Hz. The phase scintillation is dominated by three components: ionosphere scintillations, GLONASS LO phase noise and receiving telescope phase noise.

The phase from the 3 satellites (PR11, PR21, PR13) observed with the Medicina and Onsala antennas on the August 16, 2010 was extracted. The H-maser clock at the antennas was used as reference. For convenience (+1) radian phase has been added to the Medicina data and (-1) radian to Onsala data. The detection of the phase was successful for 5 observation intervals out of 6. Each one elapsed 900 seconds (15 minutes). Phase fluctuations for the three satellites are shown in the Fig. (3)

The topocentric detections of the frequency/phase for Medicina and Onsala stations were reduced to the common phase centre, namely the geocentre. For this reduction, the pre-calculated geocentric VLBI delays of the satellite signal were used. Geometric part of the delay for GLONASS satellites is computed using the Sekido-Fukushima model (Sekido and Fukushima, 2006) for a near-field radio source. Contributions to the delay due to troposphere, ionosphere (using IGS TEC maps), and clock offsets/rates at the stations were taken into account as well (Duev et al., in press). On the baseline Onsala-Medicina the differential frequency of PR21 GLONASS carrier was then calculated. It shows a linear trend that is very close to zero (Fig. (4)). Such differential frequency was used to compute the differential phase, which was in turn adopted as a residual for the least-

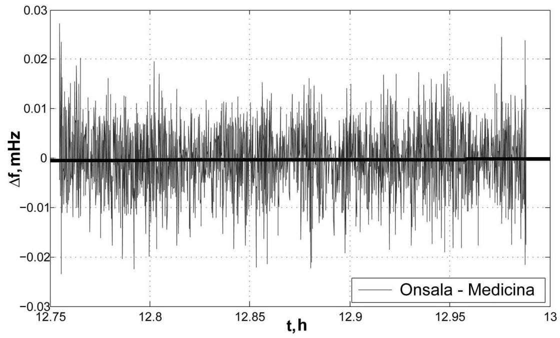

Fig. 4 Differential frequency of the GLONASS PR21 satellite carrier on the baseline Onsala-Medicina.

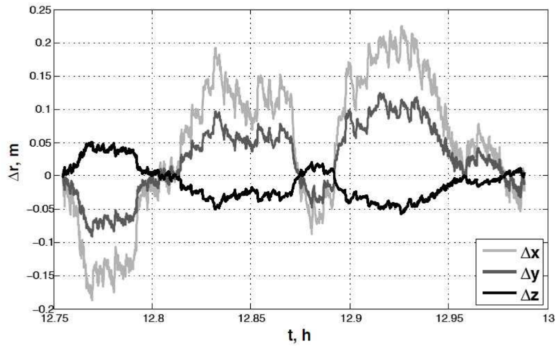

Fig. 5 Corrections to the ITRF position of the satellite PR21 on the baseline Onsala-Medicina.

squares estimation of corrections to the ITRF position of the satellite (Fig. (5)). The corrections obtained are of the order of 10 cm.

Correlation between the corrections to different coordinates is also present due to the fact that the observations were conducted only on one baseline.

3.2 Broad-band correlation

Data of August 16, 2010 experiment was processed also applying broad-band correlation. The signals of the reference source 3c286 were correlated using the DiFX software (Deller et al., 2007) in order to determine clock offsets and clock offset rates between the stations. Cross-correlation fringe and residual phase of the fringe were calculated for the calibrator radio source 3c286, as detected during our experiment on the baseline Onsala-Medicina. Clock offset calibration accuracy was at a level of 0.2ns, clock rate offset determination accuracy was better than 0.05 ps/s, phase noise at a level of 0.2 radians at 1s sampling (Tornatore et al., 2011). Also the software SFXC (http://www.jive.nl/correlator/status.html) was used to find fringes for both calibrator 3c286 (Fig. (6) top) and GLONASS satellite PR21 (Fig. (6) bottom). On the baseline Onsala-Medicina, channel 1, 16 MHz bandwidth, RCP, 16K lags

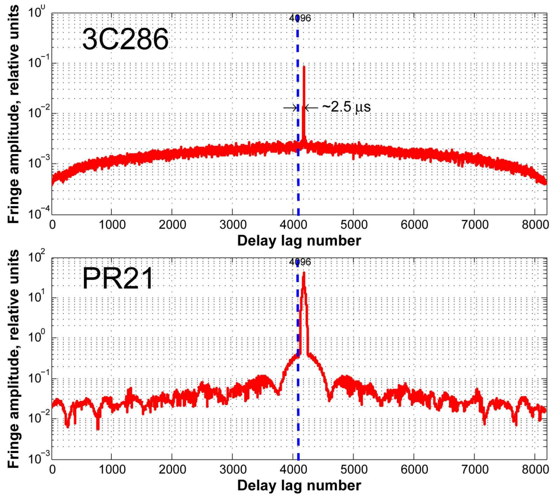

Fig. 6 Fringes for both calibrator 3c286 (top) and GLONASS satellite PR21 (bottom) on the baseline Onsala-Medicina.

with *a priori* clock offsets, averaged, vector 2s, then scalar over the full scan length. The software was run with 8000 FFT points otherwise we would miss the fringes.

Fringes were calculated also after a clock search with clock offset of 2.5 ms and clock rate offset of -1.78 ps/s, vector averaged, 10s, then scalar over the full scan length. It has to be noticed for fringes of the satellite PR21 in lag domain, that the side lobes of correlation are significantly above the noise level even at $\approx$ 100 microseconds offsets due to a high coherency of the signal. Fringes were found only in the IF correspondent to the frequency emitted by the satellite and not for the second frequency 1610 MHz. It is not clear the reason why the calibrator is not seen at 1610 MHz. Some problems are still present in the results, a bias of several nanoseconds was found in the residual delays. Currently we are busy with fine tuning of our delay model.

4 Conclusions and further developments

The obtained results show that the objectives of VLBI-observations of GNSS satellites can be achieved. To improve the present accuracy of parameter estimation additional elaboration is requested: on one hand considering the modelling part, more detailed analysis is still requested to improve delay model for near (or *very near*) field objects. On the other hand considering the observation side further experiments are encouraged in the direction of dual-frequency observations (G2/G1) to allow for ionosphere correction. Also an increasing of the number of observing telescopes, of the number of source calibrators (possibly well distributed in the sky), longer duration of observations is also expected to bring an improvement of GLONASS ephemerides accuracy from current 5 cm. Observations of other constellation satellites like for example the GPS (Global Positioning System) could also help to fix present uncertainties still present in the data or in the near field model. Together with VLBI geodetic observation mode also a phase referencing observation mode, could be attempted, even if in this case high satellite velocity could represent an obstacle to find radio source calibrators near to the satellite route.

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