Determination of GLONASS satellite coordinates with respect to natural radio sources using the VLBI technique: preliminary results

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Abstract: The main objective of this manuscript is to present tests that have been carried out using VLBI (Very Long Baseline Interferometry) in order to evaluate if this technique, primarily a radio astronomical technique, can also be used to determine positions of Earth orbiting satellites. A number of GLONASS (Global Navigation Satellite Systems) satellites, usually used for navigation and positioning purposes, were simultaneously tracked with two European VLBI radio telescopes in geodetic mode. Software, developed for VLBI tracking of spacecraft, was successfully used for the processing of these GLONASS observations. First results are presented and discussed.

Keywords: VLBI, Radio Interferometry, GLONASS, Geodesy.

1. Introduction

GLONASS is a Russian Medium Earth Orbiting (MEO) satellite constellation operating as one of today's GNSS (Global Navigation Satellite Systems). GNSS systems are used to determine coordinates of points or of moving objects on the Earth and in Space with different purposes and different precision.

GNSS coordinates are linked to the Conventional Terrestrial Reference Frame (CTRF). On the other hand, the Conventional Celestial Reference Frame (CCRF) is defined by Very Long Baseline Interferometry (VLBI) observations of signals of the most distant natural radio sources known today.

To achieve the best link between these two frames it is important to observe and process GNSS signals (transmitted in L-band) using the same optics, electronics and processing pipeline as used for natural radio sources observed with the VLBI technique.

We report about first tests that were carried out to observe GLONASS satellites using the geodetic VLBI technique. During these experiments, the VLBI radio telescopes of Medicina (Italy) and Onsala (Sweden), both equipped with L-band receivers, were used. A number of natural radio sources were also observed as calibrators at the beginning and in some tests also at the end of the satellite observing sessions. All data, collected at the two stations at several epochs, were processed using software tools primarily developed for astronomical and space applications.

2. VLBI and methods to determine satellite coordinates and velocities.

Several methods making use of the VLBI technique are today under investigation with the aim to track orbiting satellites and spacecraft. VLBI, born at the end of the sixties as an interferometry technique for radio astronomy with the aim to improve angular resolution, became during the last three decades also one of the most important techniques used in geodesy.

2.1 The VLBI technique: a few fundamentals

Radio signals emitted by distant radio sources at 2.2-/8.4-GHz (S-/X-band) are simultaneously recorded at two radio telescopes, one radio source at a time. Because of a difference in ray paths the signals will be delayed in time at one antenna relative to the other. The signals are digitized and time-tagged at each telescope. By cross-correlating the digital bitstreams the time delay and/or its time derivative can be determined. These quantities are the main observables used for the geodetic applications of VLBI and can be post-processed to determine geodetic parameters. In addition, the correlated amplitude measurements can yield source strength and structure, which are of main interest for astronomical studies.

When signals from an extragalactic object are observed, the radio source may be regarded as a fixed object because of its great distance. In this case, the time dependence of the time delay is generated by the Earth's motion but depends, of course, on source location and baseline vector between the two antennas. Therefore measurement of the time delay and/or its derivative for many sources can be used in a least-squares analysis to determine source coordinates, the baseline vector, and Earth rotation parameters, such as the Earth rotation angle and polar motion.

The delays are determined from the variation of the fringe phase with frequency and therefore are group delays, not phase delays. The measurement precision of the group delay depends strongly on the bandwidth of the observation. Thus, the widest possible frequency band should be used. Because of limitations in recording rate, usually a large effective bandwidth is synthesized from a set of much narrower frequency channels that are spread out across the band. This technique is known as bandwidth synthesis (BWS) and was first described in detail for VLBI observations by Rogers [1]. The BWS technique was the key that allowed the use of VLBI for high precision geodetic and astrometric measurements. The precision of group delays is today on the order of 30 picoseconds, (about 2-5 *mm* in equivalent differenced distance) [2]. Group delays overcome difficulties of phase delay measurements that are more precise but very difficult to solve due to ambiguities. Since 2003 studies are ongoing within the IVS (International VLBI Service for Geodesy and Astrometry) to develop a new generation of VLBI system (VLBI 2010), including all components from the antennas to the data analysis. Future requirements are under consideration to reach the goals of 1 *mm* measurement accuracy on global baselines, performing continuous measurements, and turnaround time from measurements to first geodetic results of less than 24 hours [3].

Among other geodetic spatial techniques like SLR (Satellite Laser Ranging), GNSS, DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), VLBI plays a major role to realise global reference frames, both Celestial and Terrestrial, and for the determination of EOP (Earth Orientation Parameters). A short description of the different methods that can be used to determine satellite positions by geodetic VLBI or to establish a link among different geodetic spatial techniques are given below.

2.2. Satellite observations by geodetic VLBI

High orbiting satellites, emitting radio frequency signals, can be compared to the radio sources observed with the VLBI technique. The fact that satellites are not located, unlike the radio sources, at infinite distance but in the near-field Earth space has to be regarded. The wave fronts arriving at two antennas cannot be considered as a plane wave front. Formulating the theoretical delays, the curvature of the wave front arriving at two antennas has to be taken into account [4].

First geodetic observations of a communication satellite, TACSAT I (TActical Communications SATellite), by a network of radio telescope were performed already in 1972 [5]. The TACSAT satellite was in a synchronous, nearly equatorial orbit. Three ground stations were used to track the satellite for about 7 hours (i.e. almost one third of the satellite orbital period). The work demonstrated the feasibility of the method for satellite tracking, the East-West position of the satellite relative to the ground sites was determined within 3 *m*. The uncertainty in the corresponding North-South position was almost an order of magnitude larger, because the baseline had correspondingly small components in this direction.

The basic equation to measure the differences in the two ray paths of the signal emitted by the satellite that makes use of propagation time delay obtained through correlation of GPS signals received at two antennas, was proposed by [6]. In this technique, which was called SERIES (Satellite Emission Radio Interferometric Earth Surveying), the GPS signal was considered to be pure noise. Employing VLBI and its calibration methods, a 3D baseline accuracy of 0.5 to 3 *cm* could be achieved over distances of 2 to 200 *km*, respectively, with only 2 hours of on-site data acquisition. However the realization of this proposal required rather bulky instruments, so it was not very successful, but some of these early ideas for codeless use of GPS were taken up in modern GPS receiver technology.

During the last few years several tests, using the VLBI technique, were carried out to observe GLONASS satellites in a geodetic mode by [7]. Some of these experiments will be discussed in section 4 of this paper.

2.3 Phase referencing observations for spacecraft navigation and satellite tracking

Phase referencing observations with respect to the background radio sources are often used today for Deep Spacecraft navigation, e.g. [8], [9]. The basics of this method are that a reference source, usually a known quasar, is observed, then a target, e.g. a spacecraft or a satellite, at a few degree distance from the quasar is also observed. The measurements are performed by a network of antennas. The apparent group delay of the reference source is measured and compared with the predicted one according to the known model, corrections are derived and applied to the signal from the target. Using this approach the effect of the atmosphere is corrected. However, the effect of other signal variations, e.g. due to the different TEC (Total Electron Content) in the path of the reference radio source and in the path of the satellite or spacecraft, need to be studied in more detail.

This method is mainly used in astronomy, and it has still to be tested with GNSS satellites to evaluate what results it can give. It could be worthwhile to repeat the VLBI GNSS experiments made in geodetic mode also with phase referencing mode.

2.4. Use of dedicated emitters installed on GNSS satellites.

The use of dedicated emitters directly installed on GNSS satellites sending signals to Earth radio telescopes is also a promising method for the determination of the satellite state vector. An early proposal foresaw the installing of additional transmitters on a GPS satellite and using the signal for interferometric techniques with fairly simple ground equipment [10]. The project was called Miniature Interferometer Terminal for Earth Surveying (MITES). However it was never built in the proposed way, the system was only assembled privately to prove the concept by D. Steinbrecher and C. Counselman.

A similar method is used today for tracking GNSS satellite by SLR [11], to transfer such method to emit signals in S/X band from GNSS satellites could face big difficulties in getting permission from radiofrequency authorities and the astronomy community due to the already high presence of interferences in such bands.

2.5. Hybrid systems for GNSS VLBI observations

A slightly different principle has been recently proposed by [12], and [13] to simultaneously acquire GPS and VLBI observations. The two methods foresee the presence of a normal GPS antenna nearby a VLBI antenna. According to the first method, proposed by [12], it is necessary to have also a good frame-tie between the coordinates of the two antenna reference points, plus a common local oscillator reference signal. Observing and recording simultaneously signals from astrometry calibration sources and GPS satellites, a standard IVS solution would give the atmospheric delay and clock offsets to be used in the analysis of the GPS data.
The second method proposed by [13] foresees that the GPS signals captured by the GPS antenna are down-converted to IF signals, and then sampled by the specially developed VLBI sampler VSSP32. The sampled GPS data are recorded and correlated in the same way as VLBI observation data. The correlator outputs are the group delay and the delay rate. Since the whole system uses the same frequency standard, many sources of systematic errors are common between the VLBI system and the GPS system, especially they expect that this approach will provide enough data to improve zenith delay estimates.

2.6 Multitechnique dedicated satellite.

Two projects to build geodetic multitechnique satellites are carried out by JPL (Jet Propulsion Laboratory) and GFZ (GeoForschungsZentrum): GRASP (Geodetic Reference Antenna in Space), a mission to enhance the Terrestrial Reference Frame, is developed at JPL [14] and MicroGEM (Microsatellites for GNSS Earth Monitoring), a small LEO (Low Earth Orbiting) satellite that among other things can receive GNSS signals, can also be tracked with SLR, and can send artificial VLBI signals [15], is under development at GFZ Potsdam.

3. Software to process spacecraft and satellite data recorded at radio telescopes

The initial detection of the spacecraft (S/C) carrier signal and ranging tones is performed using the high-resolution spectrometer software (SWspec) [16] and [17]. The SWspec was developed at Metsähovi Radio Observatory and JIVE in the framework of PRIDE (Planetary Radio Interferometry for Doppler Experiments). It has been successfully demonstrated in several VLBI spacecraft experiments such as the VLBI tracking of the Huygens probe landing [18], the solar wind scintillation analysis with Venus Express [19] and the Mars Express Phobos-flyby [20]. The SWSpec supports several input file formats broadly used in the radio astronomy and VLBI community such as Mark5A/B/C (developed by Haystack/MIT http://www.haystack.mit.edu/), PC-EVN (http://www.metsahovi.fi/en/vlbi/ developed by Metsähovi) and VDIF (standardized VLBI Data Interchange Format). The VLBI systems digitize and record the antenna voltages induced by incoming electromagnetic radiation simultaneously at each site. The recorded radiation data is marked with the exact arrival time at each of the reference antennas. Each station is equipped with a frequency standard, usually a hydrogen maser, which is also used to convert the radio signal to baseband frequency.
SWspec extracts one channel from the input file and calculates precise integrated auto and cross-correlation spectra on the raw data. Optionally, it detects and extracts from the data the *phase cal* signal, which can be used for troubleshooting of the receiver and baseband converters. The software supports an arbitrary number of DFT/FFT points (1.280.000 points or more), allows arbitrary integration time and windowed-overlap with several window functions. All the parameters are freely configurable according to the observations set-up. Finally, the time-integrated spectra are written into disk for the next iteration.
To compensate for the Doppler effect on the detected S/C signal a phase/frequency correction is applied to the spectral data. The moving phase of the S/C tone frequencies is visually inspected along the series of integrated spectra. An M-order (M=3-6) phase stopping polynomial, that centres the spectra in the main S/C line, is fitted into the S/C carrier line frequency detections f through the series of spectra of all time-integration steps t using a Weighted Least Mean Square (WLMS/WLS) method depending on detected SNR and nearby radio interference (RFI) considerations.
The spacecraft tone tracking software (SCTracker) [17] uses the raw telescope data, a list of S/C “ranging” tone frequencies relatives to the carrier, which usually is arbitrary set to 0, and the phase stopping polynomial coefficients. A polynomial evaluation of the phase is applied to the baseband sample sequence x[n] to stop the carrier tone phase. The time-integrated windowed-overlapped spectra of the stopped baseband signal are written onto disk. Narrow bands are extracted from the stopped baseband signal around each specified tone frequency. The extracted bands, centred on the tones, are filtered out into continuous complex time-domain signals with a bandwidth $\leq 2kHz$ using a $2nd$ order Window-Overlap-Add (WOLA) DFT-based algorithm of the Hilbert transform approximation.
Finally, the extracted signal is written to complex floating-point output files for further post-processing. This is performed with the digital Phase-Lock-Loop (PLL) software. The software runs high precision reiterations of the step-by-step on the filtered low-rate signals, achieving *Hz* or even *mHz* spectral resolution. The residual phase in a stopped band is determined with respect to a set of subsequent frequency/phase polynomials initially applied for the phase stopping.

4. Observations

Two EVN (European VLBI Network) telescopes: Medicina (32 m) in Italy and Onsala85 (25m) in Sweden equipped with L-band receiver, were used during several tests to simultaneously observe GLONASS satellites. The signal strength of satellite signals is much stronger than the signal strength of natural radio signals, so in order to avoid overload of the telescope frontends, corresponding signal attenuation was applied. Observations at the stations were performed using the standard Mark4 VLBI data acquisition rack and Mark5A disk-based recorders. The goals of the observations were to develop and test the scheduling, signal acquisition and processing routines to verify the full tracking pipeline, foreseeing the cross-correlation of the recorded data on the baseline Onsala-Medicina. Natural radio source calibrators were also observed at the beginning and for some sessions also at the end of the satellite observations.

Two successful experiments performed with slightly different observing setups will be presented in this work. The experiments were carried out on June 28 and August 16, 2010 on the baseline Onsala–Medicina and several GLONASS satellites were observed, one by one. For each experiment a planning of visible GLONASS satellites at the two sites and at the observing time was performed to select GLONASS satellites simultaneously visible at the two sites, but with a not too low elevation, to mitigate troposphere effects and also not too high elevation to avoid pointing problems with VLBI antennas.

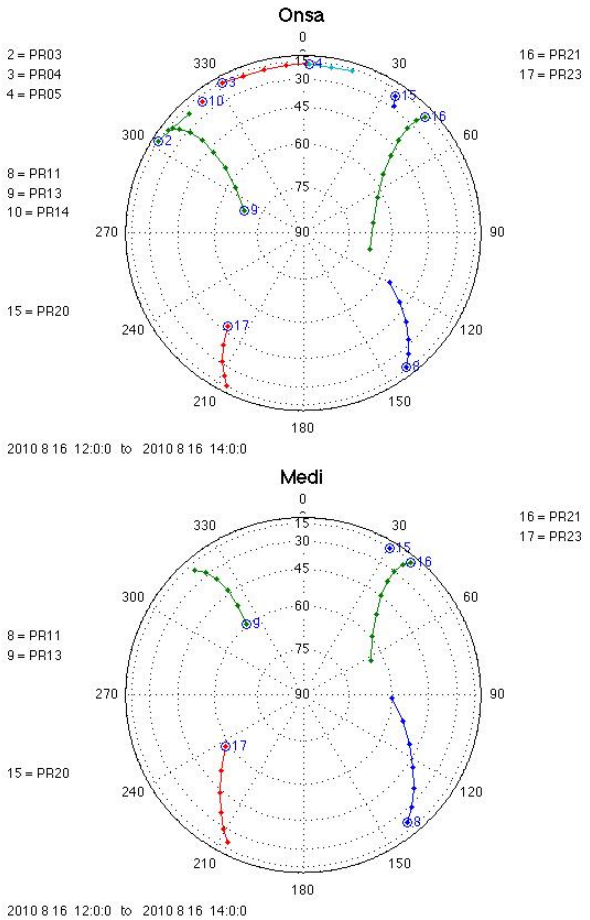

Figure 1: Sky-plots for Onsala (top) and Medicina (bottom) used for planning the observations on August 16, 2010. The plots are based on predicted orbits provided by the Center for orbit determination in Europe (CODE).

During both experiments the radio source 3c286 was observed as a calibrator. During the June experiment the calibrator was observed for only 2 minutes before the starting of the satellite sessions, while during the August session it was observed for 5 minutes before and at the end of each satellite session. The GLONASS satellites PR10, PR19 were observed for 5 minutes each on June 28, 2010, while the satellites PR13, PR11, PR21 were observed for longer sessions of 15 minutes each on August 16, 2010. Each telescope was re-positioned every 20 seconds to follow each satellite route, this not continuously tracking produced some glitches with a period of about 20 second visible in data residuals. The installation of SatTrack module [21] or of any other good satellite pointing software in the VLBI FS (Field System) would simplify the satellite tracking procedure and it is thus strongly recommended. During the June experiment a fixed frequency of 1570 *MHz* was used for all the observations, while in August 1592.88 *MHz*, 1594.00 *MHz*, 1696.25 *MHz*, according to different frequency emitted by each GLONASS satellite, were observed. A bandwidth of 16 *MHz* was observed for each frequency, and 2 RHCP (Right Hand Circular Polarization) and 2 LHCP (Left Hand Circular Polarization) channels were recorded. Additional attenuation for both RHCP and LHCP (lower for LHCP) channels was applied in order to avoid saturation of the receiving systems by the strong satellite signal. Several studies and data processing were performed on the data recorded during both experiments.

5. Data processing and preliminary results

Data recorded during experiments performed on June 28 experiment with Medicina and Onsala radio telescopes were processed using software tools SWspec and SCTracker. The software was adapted to GLONASS satellite and calibrator data. Some changes were necessary due to that the GNSS satellite power level is much higher with respect to that of natural radio source, and that the frequency detection occurs in a different frequency band. Also the spectral shape was different with respect to signals of spacecraft and needed to be modified.

Spectrum analysis of GLONASS satellites was performed with SWspec using a $1.6x10^6$ DFT (Discrete Fourier Transform) points, 1 second as integration time and Cosine-squared windowing for a spectral resolution of 20 *Hz*, over the 16 *MHz* bandwidth.

During the experiment of June 28 2010, the Onsala spectra satellite were very good centred, the carrier line was in fact in the middle of the central lobe for all the observed satellites. However because of a failure in the observing setup, the Medicina spectra were far from the centre: they happened in the far away side lobes.

The data of the August 16, 2010, session were processed like those of June 28 experiments with the SWspec and the SCtracker software. Thanks to a correct setup on both stations also a differential frequency on satellite carrier could be determined. Such differential frequency on baseline Onsala–Medicina could be used to compute the differential phase, which is then adopted for determination of spacecraft position corrections to the ITRF position of the satellite. The corrections are of the order of only 5 *cm*. For such data also a broadband correlation, at least on the calibrator 3c286, was attempted using the DiFX software

[22], cross-correlation fringe and residual phase of the fringe are shown in Figure 2 and Figure 3, respectively.

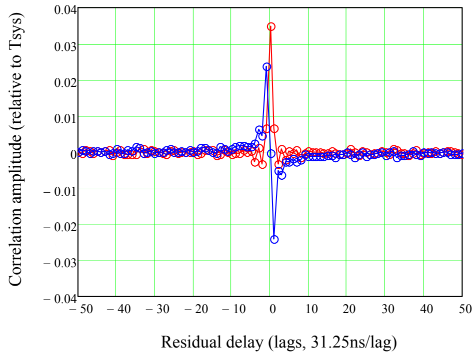

Figure 2: Cross-correlation function (fringe) of the clock offset calibrator radio source 3c286, as detected during August experiment on the baseline Onsala-Medicina using the DiFX software correlator.

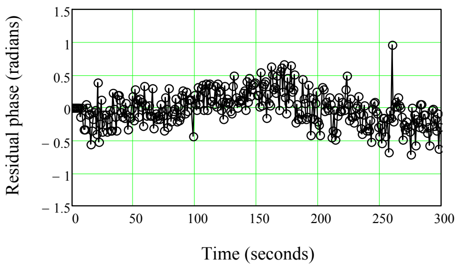

Figure 3: Residual phase of the fringe. Clock offset calibration accuracy is at a level of 0.2 ns, clock rate offset determination accuracy is better than 0.05 ps/s. Phase noise is at a level of 0.2 radians at 1 s sampling.

More details on August data processing and results will be presented in the paper [23].

5. Conclusions and further developments

Present narrow band results show that the objectives of VLBI-observations of GNSS satellites can be achieved. Broadband correlation results on calibrator 3c286 give good indications that also broadband correlation on satellite data can be obtained. Dual-frequency observations (G2/G1) are advised to allow ionospheric corrections. We expect that increasing the number of observing telescopes, the length of baselines and the duration of observations will lead to a significant improvement of the accuracy of the GNSS ephemerides to be better than the current 5 *cm*.

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8. Glossary

BWS	Bandwidth Synthesis
DFT	Discrete Fourier Transform
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EOP	Earth Orientation parameters
EVN	European VLBI Network
FFT	Fast Fourier Transform
FS	Field System
GFZ	GeoForschungsZentrum
GLONASS	Global Navigation Satellite Systems
GNSS,	Global Navigation Satellite Systems
GRASP	Geodetic Reference Antenna in Space
INAF	Istituto Nazionale di AstroFisica
IVS	International VLBI Service for Geodesy and Astrometry
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbiting satellite
LHCP	Left Hand Circular Polarization
MEO	Medium Earth Orbiting
MicroGEM	Microsatellites for GNSS Earth Monitoring
MITES	Miniature Interferometer Terminals for Earth Surveying
PLL	Phase-Lock-Loop
PRIDE	Planetary Radio Interferometry for Doppler Experiments
RFI	Radio Frequency Interference
RHCP	Right Hand Circular Polarization
S/C	SpaceCraft
SCTracker	Spacecraft tracking software
SERIES	Satellite Emission Radio Interferometric Earth Surveying
SLR	Satellite Laser Ranging
SNR	Signal-to-Noise Ratio
SWspec	Spectrometer software
TACSAT	TActical Communications SATellite
VDIF	VLBI Data Interchange Format
VLBI	Very Long Baseline Interferometry
WLMS	Weighted Least Mean Square
WLS	Weighted Least Square
WOLA	Window-Overlap-Add