TRACKING OF GLONASS SATELLITES BY VLBI RADIO TELESCOPES

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ABSTRACT

Several tests to observe signals transmitted by GLONASS (GLObal NAvigation Satellite System) satellites have been performed using the VLBI (Very Long Baseline Interferometry) technique. The radio telescopes involved in these experiments are Medicina and Onsala. The satellites transmit artificial radio signals that were considered in a similar way as natural radio signal that are emitted by natural radio sources. 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. The natural radio source 3C454.3 was used as a calibrator before the beginning of the satellite observation sessions.

We present results of a detailed analysis of the signal recorded at the Onsala telescope together with a first attempt of cross-correlation of data recorded on the baseline Onsala–Medicina.

Further plans to perform new GNSS observations are in preparation, and a study to develop the VLBI delay model for GNSS observations with astronomical VLBI telescopes is in progress.

I. INTRODUCTION

GNSS (Global Navigation Satellite Systems) are used worldwide for the determination of coordinates of points or of moving objects on the Earth and in Space with different purposes and different precision. The today existing and operationally working GNSS are the American GPS system and the Russian GLONASS system. Further GNSS-systems are currently under construction, for example the European Galileo system and the Chinese Compass system. GNSS coordinates are linked to the Conventional Terrestrial Reference Frame (CTRF). On the other hand, the Celestial Reference Frame (CRF) is defined by Very Long Baseline Interferometry (VLBI) observations. To achieve the best link between these two 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 two frames.

Several tests, using the VLBI technique, have been carried out to observe GNSS satellites. In particular the use of a network of the three radio telescopes Medicina, Noto (both in Italy) and Onsala (Sweden,) was planned to simultaneously observe GLONASS satellites. These three stations are equipped with L-band receivers. We chose to observe GLONASS instead of GPS satellites, since the L-band systems of the Italian station Medicina cannot observe at the GPS frequency (1575 MHz). A geodetic VLBI observing mode was chosen: considering that the satellites emit artificial radio signals like natural radio sources emit natural signals, the time delay of the arrival of the same wave front at several widely spaced radio telescopes can be determined.

The stations used the standard Mark4 VLBI data acquisition rack, and Mark5A recording mode. However, because of a serious technical failure at Noto, only Onsala and Medicina could finally participate in the observations.

II. OBSERVATIONS AND ANALYSIS OF GLONASS SIGNALS

Several attempts were performed to simultaneously observe GLONASS satellite signals with the Medicina telescope (32 m) and the 26.5-meter telescope at Onsala (conventionally catalogued as Onsala85). In this work we present preliminary studies performed on the data recorded during a test on June 28, 2010.

Just before the starting of the session the radio source 3C454.3 was observed for 1 minute scan length as a calibrator. The same setup was used as for the first GLONASS satellite to be tracked. The GLONASS satellites observed during this test were PR10, from 13.30 UT (Universal Time) to 13.35 UT, and PR19 from 13.50 to 13.55 UT. During the five minutes scan length the telescopes were re-positioned every 20 seconds to follow the satellite track. This step-wise tracking procedure was used because at the moment not all the VLBI stations are equipped with a software able to continuously follow a satellites track. However, the installation of SatTrack module [9] in the VLBI FS (Field System) would simplify the satellite tracking procedure and is thus strongly recommended.

For the recording setup a bandwidth of 16 MHz was used, and 2 RHCP (Right Hand Circular Polarization) and 2 LHCP (Left Hand Circular Polarization) channels were recorded. Even if the GLONASS signal is specified to have RHCP stronger than LHCP by 16 dB [5] the LHCP (Left Hand Circular Polarization) was also observed to study if there are possible imperfections in the VLBI feeds, for example insufficient polarization isolation, so that the LHCP channel might pick up some RHCP signal [13]. Additional attenuation for both RHCP and LHCP channels was applied in order to avoid saturation of the receiving systems by the strong satellite signals. The GLONASS system has satellite specific frequencies, i.e. the frequency setup was different for different satellites. At Onsala the VC frequencies were selected so that the GLONASS satellite signals should appear in the centre of the 16 MHz wide bandwidth.

A. *Signal processing of data recorded at Onsala*

The initial detection of the spacecraft (S/C) carrier signal and tones was performed using the high-resolution spectrometer software (SWSpec) [14] developed at Metsähovi Observatory and JIVE in a framework of the Planetary Radio Interferometry and Doppler Experiments (PRIDE) [10] and is based on our experience with VLBI tracking of the Huygens probe [8]. The SWSpec software supports several input file formats broadly used in the VLBI community such as Mark5A/B/C (developed by Haystack/MIT), PC-EVN (developed by Metsähovi), and VDIF (standardized VLBI Data Interchange Format). A SWSpec pass extracts one selected raw data channel from the input data file. It performs accurate windowed-overlapped discrete Fourier transforms and spectrum time integration. All parameters are freely configurable. Time-integrated spectra are written to disk for the next step of fitting a phase-stopping polynomial to select tones in the spectrum. For our GLONASS spacecraft spectrum analysis we used 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. The Onsala spectra (e.g. PR10 satellite) were very good centered, see Fig. 1, where the spectrum with 100 Hz resolution (3.2*10^5 DFT points) is shown for illustration.

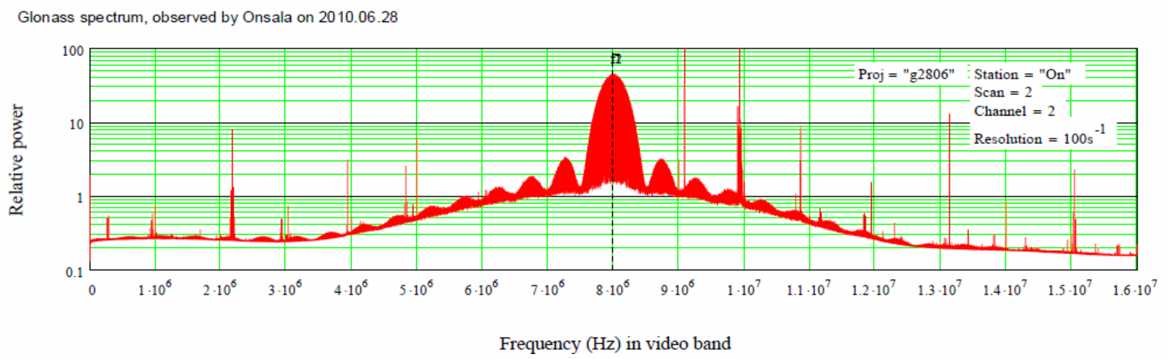

Fig. 1. Spectrum of GLONASS PR10 satellite observed at Onsala. A 16 MHz bandwidth with a spectral resolution of 100 Hz was used here, while for real operation a 20 Hz resolution was used. The carrier line is in the middle of the central lobe.

A Doppler analysis on the same data set (satellite PR10 observed at Onsala) was also performed. The output spectra of SWSpec were processed using JIVE analysis software. The moving phase of the S/C tone frequencies was visually inspected along the series of integrated spectra. An M-order (M=3-8) phase stopping polynomial was 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 detection SNR and nearby radio interference (RFI) considerations. The resulting polynomial coefficients were used as input to the subsequent processing steps: phase stopping and narrow band tone filtering and extraction.

The spacecraft tone tracking software (SCTracker) [14] accepts the raw telescope input data, a list of S/C tone frequencies (relative to carrier), and the M-order phase stopping polynomial coefficients from the WLMS fit. A polynomial evaluation of the phase was 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 to disk. Narrow bands were extracted from the stopped baseband signal around each specified tone frequency. See Fig. 2 where a zoom-view was performed for the 2 kHz band around the carrier, after adaptive stopping of the Doppler.

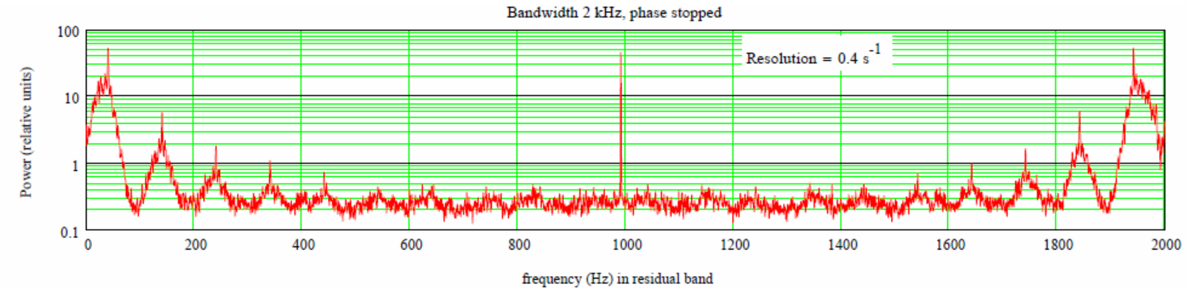

Fig. 2. SCtracker spectrum output. The GLONASS spacecraft signal is correctly stopped into a 2 KHz band around the carrier. The BW is 2 kHz with the spectral resolution of 0.4 Hz.

The current implementation of software allows a practically unlimited number of narrow bands to be filtered and down-converted simultaneously, with arbitrary distribution of them in the input band. The extracted bands (with the tones in the centre) are filtered out into continuous complex time-domain signals with a bandwidth≤4kHz using a 2nd order Window-Overlap-Add (WOLA) DFT-based algorithm of the Hilbert transform approximation. The extracted signals are 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. 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.

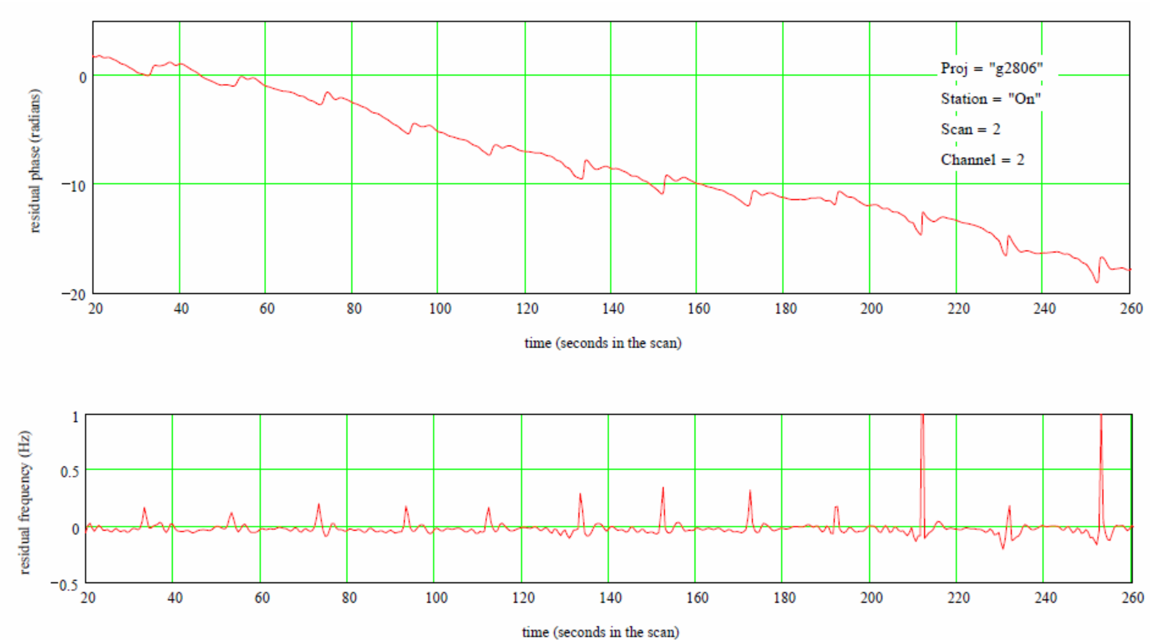

Fig. 3. Post-PLL residual phase in the 1 Hz adaptive tracking band (top) and Post-PLL residual frequency (bottom). Glitches caused by the telescope re-pointing are present with a period of about 20 seconds.

The residual phase extracted from the carrier line after the PLL (Phase-Lock-Loop) in the 1 Hz adaptive tracking band is shown in Fig. 3 (top): fluctuations along the duration of the scan are caused the by re-pointing of the antenna to track the satellite (every 20 seconds) and the variation on the frequency by the GLONASS satellite due to residuals of the Doppler effect. Post-PLL residual frequency, as $f(t)= d\phi(t)/dt$ is represented also in Fig. 3 (bottom) where the variation of the carrier frequency of the satellite has been modelled and compensated in the residual phases. The frequency detection noise is at a level of 10 mHz in 1 second. The remaining glitches are caused by the re-positioning of the telescope. It is recommended to implement SatTrack software directly in the FS (Field System); this software has been developed [9] on purpose for satellite tracking by astronomical antennas and could make more feasible satellite tracking with VLBI antennas.

III. CORRELATION TESTS

The GLONASS signal spectra detected at Onsala were very good centred for each tracked satellite, however because of a failure in the observing setup, Medicina spectra were far from the centre: they happened in the far away sidelobes. Anyway, since the satellite signal is very strong and coherent, cross-correlation was calculated too. The DiFX software [2] was used, and results for satellite PR19 are shown in Fig. 4. Cross-correlation fringes are clearly visible, though difficult to interpret.

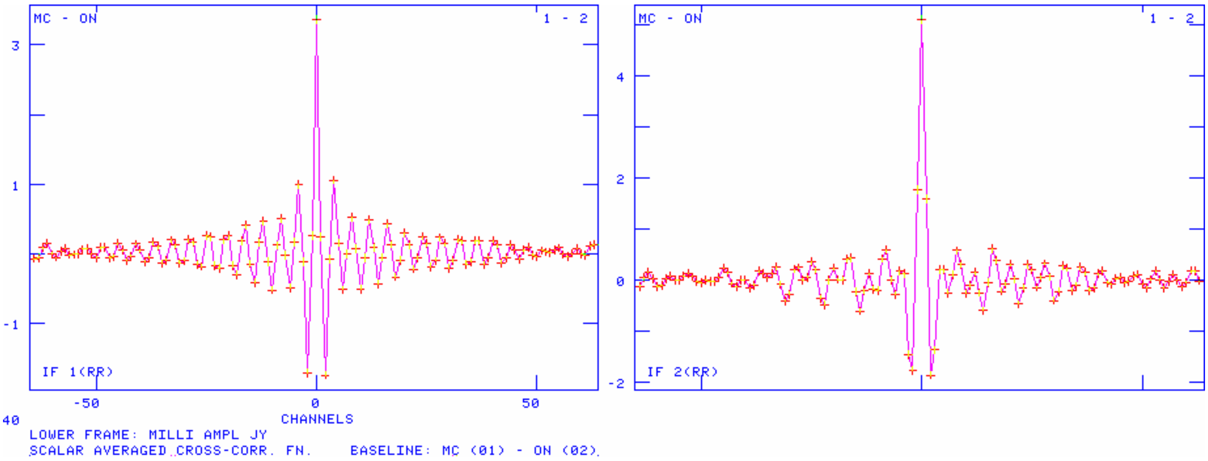

Fig. 4. Fringe plots for observations of GLONASS satellite PR19 on the Onsala–Medicina baseline. The RR polarization is presented.

IV. CONCLUSIONS AND FURTHER DEVELOPMENTS

Several tests have been performed to detect and analyze signals emitted by GLONASS satellites with VLBI technique normally used for astronomical or geodetic applications. The satellite signal spectra are very well detectable. The software tools developed for spacecraft tracking proved to be very important to be used to analyze signal emitted by Earth orbiting satellites like GLONASS. Doppler effect and signs due to artifices used to track satellites are detectable in the signal processing. A cross-correlation of the signal simultaneously recorded at two stations has been computed and, even if the power of the satellite signal was very low at one of the two stations of the baseline, fringes have been found.

New observations with more strictly constraints on a common setup for the involved radio telescopes are planned for the next months.

It is worth to note that classical astronomical tools can contribute to Space Science, too, in fact VLBI determination of GNSS state vector could also impact the GNSS field leading to improve present models and methods for orbitography especially for those constellations not yet completed (like Galileo and Compass).

Work to develop the VLBI delay model for GNSS observations with astronomical VLBI telescopes is in progress. It is based on the near-field approximation described in [11]. The delay model calculation should be consistent with the classical "Consensus model" [6] of VLBI delay calculation for astrometric and geodetic observations of the natural celestial radio sources.

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