ASC Correlator and Astro Space Locator Software: Data Processing in "Radioastron" Mission

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The "Radioastron" space mission is an unique project of Russian Space Agency (Roscosmos) and Russian Academy of Sciences to investigate the Universe by means of VLBI implementation. "Spektr-R" is a sattellite with on-board 10-m radio telescope. It has been operating since November 15, 2011 as a space element of the space-ground interferometer with the orbit apogee up to 350 000 km. Here we describe the first step in VLBI data processing is correlation. Space-VLBI brings new requirements to the correlation process due to significant uncertainties in delay model for space telescope. The software correlator (ASC Corrrelator) was developed at Astro Space Center of Lebedev Physical Institute specially for the "Radioastron" mission to accomodate all pecularities of Space-VLBI data processing. This correlator is a part of ASL (Astro Space Locator) software package. In this report the main features of the ASC Correlator are described with the emphasis on the Space-VLBI data-processing differences compared to the ground VLBI. This includes a time delay and its derivatives calculation algorithm and the procedure of correction for these parameters. It is critical for correlation of space-ground interferometer data. We also show the importance of the orbit accuracy and the requirements for correlator of the future Space-VLBI missions, such as the "Millimetron" project.

Keywords: Radioastron, VLBI, Data processing, ASC Correlator.

1 Introduction

ASC Correlator is the main correlator of "Radioastron" mission and 95 % of all observations are correlated at ASC Correlator. It support most of the raw data formats: RDF (data format developed at ASC), Mark5(*), K5, LBA, VDIF (including multi-threaded VDIF). Correlator is operated on the computer cluster with more than 1 Tflops efficiency (about 100 processor cores). "Radioastron" data processing center has 200 TB online disk storage for correlated data and 80 TB online data

storage for raw data. Usually, the data rate from one ground telescope in "Radioastron" project is 256 Mb/sec. ASC Correlator can perform correlation with more than 10 stations (45 baselines) in real time. It is also capable to perform correlation with more than 65536 frequency channels. Correlator has three data processing modes: Continuum, Maser Line and Pulsar. It has friendly and smart graphical user interface (GUI). ASC Correlator is the only software correlator which has an implemented and successfully tested "Coherent" mode of delay restoration. This mode is very useful to synchronize "Radioastron" equipment from the ground H-maser in case of on-board time/frequency devices failure.

2 Extremely high resolution with Space-VLBI. Statistics of data processing

Highest angular resolution interferometric fringes in "Radioastron" mission were obtained using ASC Correlator:

— for AGN sources the highest angular resoultion was obtained for 0851+202 (OJ287). Maximum baseline projection was 15.5 Earth diameters at K-band (observation done 17.04.2014). Next observations at 11.8 and 9.2 Earth diameters showed also significant fringes at K-band;

— for Maser sources the highest angular resolution was obtained for galactic maser W49N (14.11.2014, 7.9 Earth diameters) and for extragalactic maser NGC 4258 (17.03.2015, 19.5 Earth diameters). Both observations were performed at K-band;

— for Pulsars the highest angular resolution was obtained for B0329+54 pulsar with fringes at L-band and P-band at 26 Earth diameters. Observations were done 22.11.2013.

Interferometric fringes were detected at the following extreme baseline projections in "Radioastron" mission: 330 000 km (26.0 ED) at P-band, 345 000 km (27.1 ED) at L-band, 295 000 km (23.3 ED) at C-band, 248 000 km (19.5 ED) at K-band. These results were obtained with ASC Correlator.

From 01.11.2011 to 12.09.2016 the following number of sessions have been correlated: 2446 AGN sessions (757 with fringes with RA), 76 pulsar sessions (37 with fringes with RA), 142 maser sessions (37 with fringes with RA).

3 Correlation algorithm

Correlation algorithm for typical experiment is shown in Fig. 1. For simultaneous observations at two frequency bands: lower frequency is being correlated first, obtained residual delays and its 1-st and 2-nd derivatives are used to correlate higher frequency. Preliminary correlation in wide range of delay and fringe rate parameters for space-ground baselines is required due to the orbit uncertainties. These parameters correspond to the satellite velocity error of 2 cm/sec and the position error of 200 m. In case fringes were found for ground and space-ground baselines, the correlation will be repeated, but in narrow range of delay and fringe rate. For typical experiment (one frequency band, 4 telescopes, 6 parallel correlator tasks) the input data rate is 6.1 Gbit/sec and the output data rate (4 telescopes, 2048

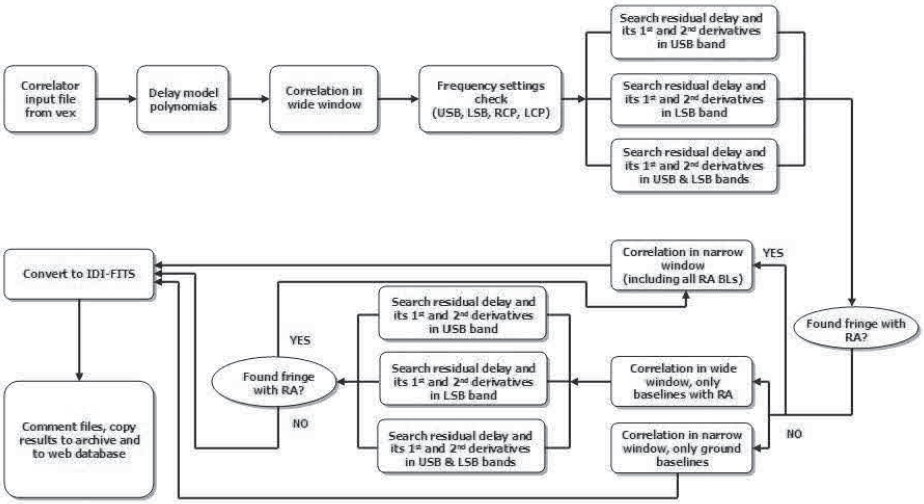

Fig. 1. Space VLBI correlation algorithm

FFT channels, 1/8 sec correlator integration time, 6 parallel tasks) is 720 Mbit/sec. Due to data transmission between computing nodes data flow through the network doubles resulting in total data flow ≈ 13.1 Gbit/sec, while our cluster network bandwidth is only 10 Gbit/sec. So the correlator processing rate largely depends on the network bandwidth and data delivery than by FFT on computing nodes. All correlated data is available at the Astro Space Center online storage.

4 Comments on Space-VLBI

Correlator performs the calculation of correlation function for a set of delays and fringe frequencies. This set of values correspond to the range of position and velocity, which is determined by the errors of SRT state-vector. Losses in correlated amplitude depend on fringe position with respect to the center of "correlator window" as $\approx \sin(x)/x$ (Fig. 2). In case the fringe is located in 30 % around the center of window, amplitude losses are less than 4 % and can be neglected from a practical point of view. "Correlator window" chosen in Radioastron project correspond to 4 % losses in correlation amplitude for the orbit accuracy $V_{err} < 2$ cm/sec and $X_{err} < 200$ m. Orbit improvement above this limit will not raise correlated amplitude or increase the chance to detect fringes. "Correlator window" is determined by the number of frequency channels and selected solution interval. The maximum size of such correlation window is only limited by computational resources.

5 Summary

Currently, ASC Correlator is fully automated. By September 20, 2016 data from 2664 sessions has been successfully correlated. Fringes on Space-Ground baselines

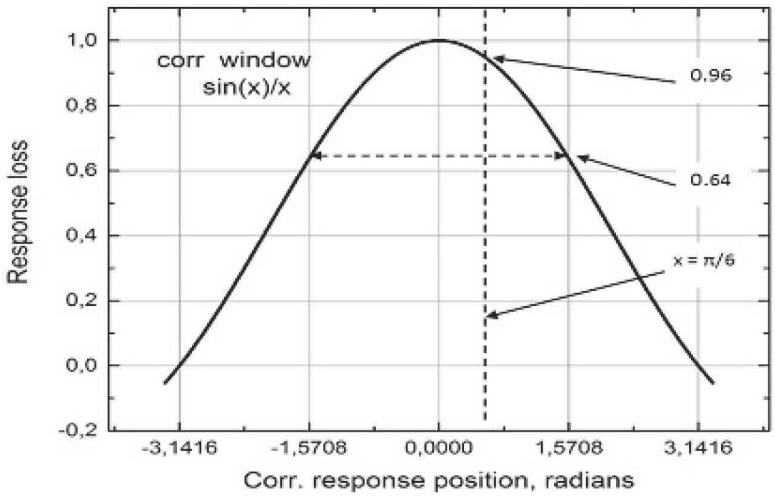

Fig. 2. Losses in visibility amplitude

were found for 831 sessions. Maximum data processing rate in "Radioastron" mission is about 200 sessions per month, while the observation rate is about 120 experiments per month. Thus, ASC Correlator performance is enough to correlate all the data in "Radioastron" project including imaging sessions. Practically, all observed experiments have been correlated with ASC Correlator (except of imaging experiments, only 25 % of imaging experiments have been correlated). ASC software correlator is the main and primary correlator of the "Radioastron" mission. It is really attractive and winning to be positioned by PI's as a Primary Processing System for their requested observing sessions, in particular long-term and multiband imaging session.