PROCEEDINGS OF SCIENCE

Analysis of VLBI Interferometer Characteristics Using Zero-baseline Lab Prototype and RASFX Correlator

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A zero-baseline radio interferometer model was created in IAA RAS at 2017 in order to analyze VLBI radio interferometer characterictics in laboratory conditions. The model consists the radio telescope RT-13 tri-band and ultra-wideband receivers (UWB) heterodyne type receivers, broadband data acquisition system (BRAS), and RASFX software correlator. The radio interferometric sessions results in S/X/Ka-bands with 512 MHz channel bandwidth and 2-bits sampling are presented in this paper. The session duration was varied from single 5..20 minutes «scan» to 1 hour consisted of 120 10-seconds «scans». To simulate cosmic radio source the noise generator signal was injected to receivers. Obtained with RASFX correlator fringe characteristics were analyzed: signal-to-noise ratio (*SNR*), group delay, group delay rate, fringe phase, and its standard deviations. Allan deviation was calculated to find the origin of delay variations. The sinusoidal ripple of fringe delay due to the frequency inaccuracy of a LO and overlapping spectra from Nyquist zones was revealed. It was shown that digital band filtration reduces the measured delay variation of zero-baseline radio interferometer.

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1. Introduction

The two element very long baseline radiointerferometer based on the RT-13 radio telescopes [1] of the Russian network «Quasar» is implemented for the Universal Time determination. In order to determine the instrumental errors of the receiving and recording equipment of the RT-13, which affect the UT accuracy, the laboratory model of a radio interferometer with zero-baseline was created in Institute of Applied Astronomy of the Russian Academy of Sciences. The model consists of two tri-band (S, X, Ka) [2] and ultra-wideband (3–16 GHz) [3] heterodyne type receivers, broadband (512 MHz) data acquisition system [4] (as back-end unit) and software RASFX correlator [5]. The goal of this work is to measure radio interferometer model stability using the characteristics of crosscorrelation fringe (group delay τ and its standard deviation σ, delay rate, and SNR) during session time. To obtain standard deviation of UT1-UTC determination less than 20 μs on «Badary» — «Zelenchukskaya» baseline we need to get delay standard deviation σ less than 20 ps.

2. Measurement scheme and technique

The block diagram of the radio interferometer model is shown at Fig. 1. The noise generator signal, imitating cosmic radio source signal, is injected to receivers through cryo unit directional coupler, while wideband match load is installed on the receiver input (feed in cryo unit). Receivers are super heterodyne type ones, that convert input band to 1–2 GHz IF band. Receiver output signals are sampled in 1024–1536 MHz band with 1024 MHz sample rate into 2-bit data stream by Broadband Acquisition System (BRAS), and then the stream is transfered and recorded on hard disk using Data Transfering System (DTS). Signals synchronization is provided by frequency standard. The RASFX correlator computes crosscorrelation spectrum of radio interferometer channels signals. During post-processing procedure, a two-dimensional cross-correlation function is calculated in the coordinates of delay and delay rate at a specified time interval.

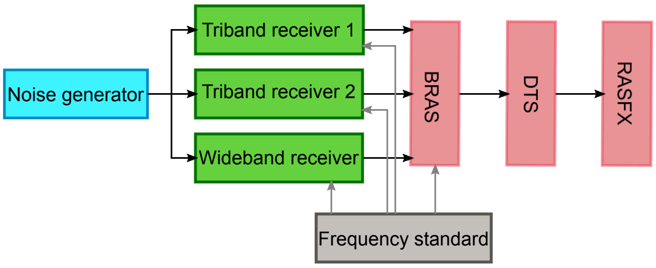


Figure 1: Zero-baseline prototype block-diagram

The studies were carried out by recording interferometric sessions and calculating the actual values of SNR, delay, delay rate and phase of correlation response. There were two types of sessions: 1) continuous 15-minute sessions to determine the nature of the correlation response characteristics variations with integration time $t = 1$ s; 2) 1-hour sessions, imitating real observations: 120 «scans» with scan duration $t = 10$ s and 20 s pauses.

The *SNR* values were set close to a routine VLBI-observations (100-300) by tunable noise generator according equation (2.1)

$$SNR = 0.88 \cdot \sqrt{\frac{T_{sig1}}{T_{sys1}} \cdot \frac{T_{sig2}}{T_{sys2}}} \cdot \sqrt{2\Delta f t} \tag{2.1}$$

where T_{sig} — is the noise generator signal noise temperature, T_{sys} — is a system (receiver+load) noise temperature, Δf — is a bandwidth, t — is an integration time.

The expected delay deviation value was calculated by equation (2.2) when substituting the actually measured *SNR* value. *SNR* and σ calculated results were compared to obtained values.

$$\sigma = \frac{\sqrt{12}}{2\pi\Delta f\ SNR} \tag{2.2}$$

3. S-band measurements

15-minutes experiments have shown that in S-band the main problem in measurements was RFI (Fig. 2a), which correlates as a signal on zero-baseline. Digital filter can solve this problem and the frequency bandwidth changes from 2164-2676 MHz to 2196-2388 MHz. After filtration delay variation σ decreased from 43 ps (Fig. 2a) to 10.2 ps (Fig. 2b). This σ value corresponds calculated one σ=10.3 ps by equation (2.2), $SNR = 280$.

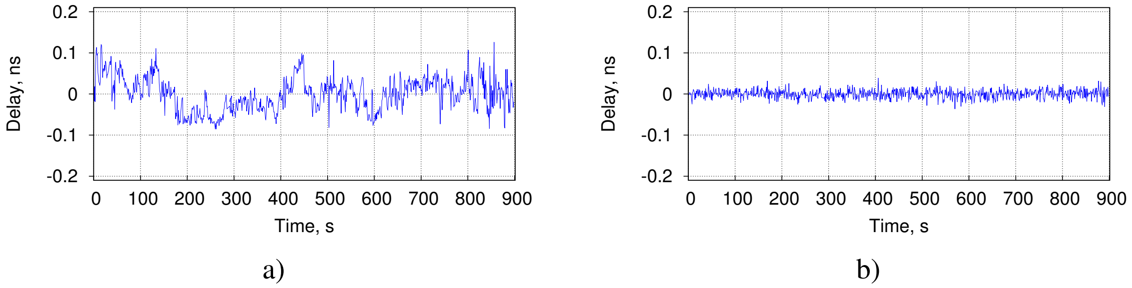
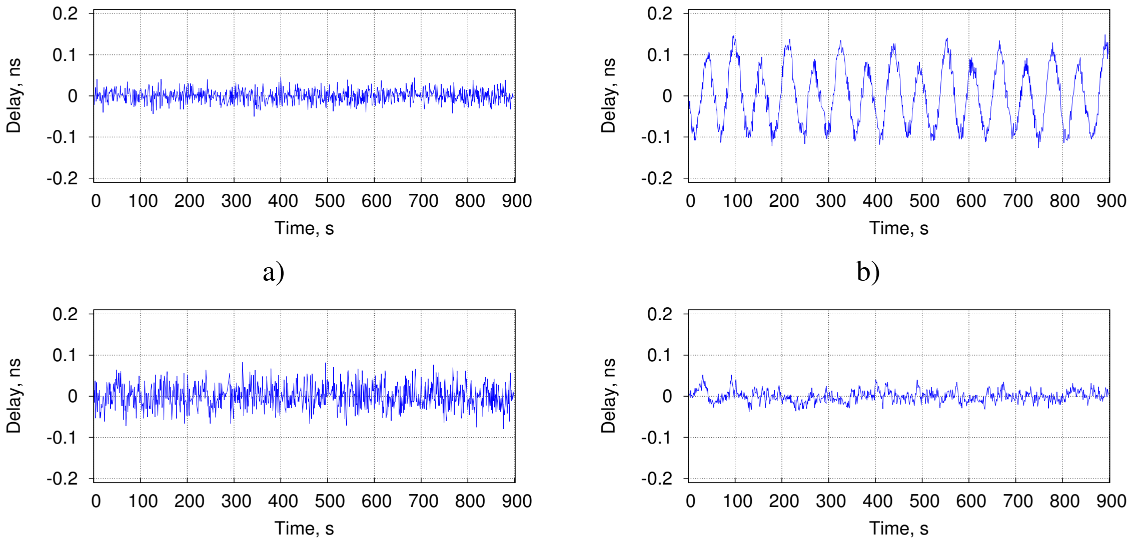


Figure 2: Fringe delay vs time in S-band: a) without filtration; b) with filtration

4. X-band measurements

A number of 15 minutes scans were carried out. We obtained $SNR = 84$ and $\sigma = 15.3$ ps for the «Triband» — «Triband» receivers (Fig. 3a). For the «Triband» — «UWB» receivers we obtained $SNR = 100$ and $\sigma = 71$ ps and sinusoidal *SNR* and delay variations with time (Fig. 3b). This was caused by the 9 mHz offset in LO frequency setup of the UWB prototype and spectra aliasing effect in the BRAS (linearly varying phases of adjacent Nyquist zones sum up with the opposite sign when overlapping). It essentially revealed in zero-baseline observations, since there is no Doppler shifting in laboratory tests.

To decrease these effects we performed cross-correlation spectrum filtration during procedure of post-processing. We cut off spectrum edges in 8..160 MHz range and found the minimal $\sigma = 28$ ps (Fig. 3c) at 128 MHz from each side cutting (so the effective bandwidth became 256 MHz). The next step was to replace LO to the new one without frequency offset. As the result we have got $\sigma = 14$ ps (Fig. 3d).



a) b) c) d)

Figure 3: Fringe delay vs time in X-band: a) Triband-Triband; b) Triband-UWB; c) Filtered Triband-UWB; d) Triband-UWB with replaced LO

5. Ka-band measurements

All experiments with 15 minutes and 1 hour scan duration (see Table 1) have shown the high delay stability. This results in $\sigma = 18.8$ ps, which is some more than in X-band since the power of signal was less than in X-band ($SNR = 62$ on 1-sec interval). The calculated σ is 17.3 ps.

6. Allan deviation

Allan deviation was calculated to find the origin of delay variations (Fig. 4). White noise prevails at 50 s averaging time for S-, X-bands of Triband receivers and 20 s for Ka-band of the receiver, then flicker noise appears. This time is optimal as scan duration at which σ minimum is achieved. Flicker noise dominates for the UWB receiver. High correlation between LO phase and delay variations due to spectra aliasing was found, correlation coefficient (0.75) and influence coefficient (2.8 ps/°) were calculated. After band digital filtration this correlation decreases, and white noise dominates in Allan deviation (plot for UWB receiver is calculated for 256 MHz bandwidth).

7. 1-hour session results

Results of 1-hour session in S, X, Ka-band are presented at Table 1. For UWB receiver values are shown for 384 MHz bandwidth after digital filtration. Difference between calculated and measured values does not exceed 20 % for SNR and 2 ps for delay standard deviation σ.

8. Summary and results

The implemented radio interferometer laboratory prototype makes possible to investigate receiving and recording radio telescope equipment in interferometric mode. It allows to produce

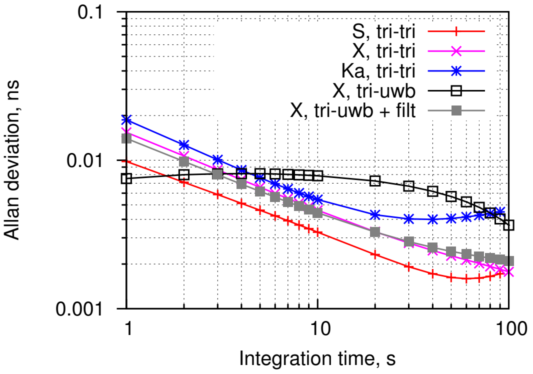


Figure 4: Delay Allan deviation for S/X/Ka bands and all receivers

Table 1: 1-hour session results

Band, Receivers	*SNR*(calc)	*SNR*(meas)	σ(calc), ps	σ(meas), ps
S-band, Tri-Tri	245	261	11.0	12.4
X-band, Tri-Tri	219	175	6.2	6.9
Ka-band, Tri-Tri	246	200	5.4	7.5
X-band, Tri-UWB	172	187	7.7	9.2

experiments which are hard to be done in real observations. Delays from Triband-Triband and Triband-UWB receivers were analysed. The sinusoidal delay ripple effect was found caused by LO frequency offset and spectra aliasing effect. The digital filtration allows sufficiently decrease σ on zero base-line, if LO frequency offset or LO phase instability is present. We carried out 1 hour sessions with all receivers combinations and found that σ did not exceed 13 ps for typical *SNR* value about 200, so the radio interferometer model meets $\sigma = 20$ ps requirement.

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