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MEASUREMENTS OF INTERFEROMETER PARAMETERS AT RECEPTION OF GLONASS AND GPS SIGNALS

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The present paper deals with the calibration method of interferometers with antennas having a small effective area, on the quasinoise signals of GLONASS and GPS navigation satellites. Algorithms for calculation of antenna coordinates and instrumental delay from the analysis of correlation interferometer response to signals of satellites in the near field of the instrument were reviewed. The method was tested in VLBI experiments on interferometers with medium and large baselines that included radio telescopes of NIRFI and VIRAC. The values of the antenna coordinates and instrumental delay with an error within the limits of one discrete were obtained. The sources of measurement errors and ways to improve the accuracy of results were analysed.

Keywords: *baseline, calibration, data processing, delay navigation space satellites, VLBI.*

1. INTRODUCTION

Calibration of radio astronomical instruments, especially precision tools, such as Very Long Baseline Interferometry (VLBI), is a necessary procedure to ensure high accuracy of coordinate and time measurements. When using radio interferometers for solving astrometric, geodetic and astrophysical problems, the special attention is devoted to the high-precision measurements of the distance between the receiving antenna, i.e., baseline calibration, because errors in the baseline projections are directly included in errors of radiation source position or reference point location on the Earth's surface. As a rule, two problems are solved: direct problem, i.e., determination of the emission source coordinates from the known parameters of the interferometer, and inverse problem, i.e., the determination of receiving station coordinates from the known source location. Interferometric observations require accurate measuring of the spatial delay, that is the difference between the time of signal arrival to the antennas of the interferometer. At instrument calibration, the component of the delay should be excluded, which is determined by clock mistiming on the stations, difference in the lengths of receiving channels, and so on, the so-called instrumental delay.

During the progress of VLBI technology, sufficiently effective methods of interferometer calibration [1], [2] were developed, but almost all of them involved the use of signals from extragalactic radiation sources (quasars, galaxies, and others) located at the "infinite" distance from the Earth and thus creating a flat front of the incident electromagnetic wave for all ground radio interferometric instruments. The discrete sources for given interferometer with sufficiently high intensity radiation are to be used for high-precision measurements. The selection of such sources is limited and high-quality calibration is carried out using antennas with a large effective area (with a mirror diameter of 15 meters and more). Traditional calibration method becomes inapplicable using radio telescopes of smaller diameters.

Putting into operation the global positioning systems in near-Earth space, a considerable number of satellites, which emit a powerful quasinoise signal, allow using small receiving antennas and are considered to be point sources for ground observers. In the case, when the sensitivity of interferometers is low, it is proposed to use the signals of GLONASS and GPS navigation space satellites (NSSs) as calibration sources for baseline measurement and instrumental delay, assuming that the coordinates of NSS are known with certain accuracy.

Calibration on NSS signals has some significant differences from the traditional interferometer calibration on extragalactic sources. One problem of measurement accuracy assessment is low precision (from the point of view of VLBI), at which the coordinates of NSS are known. Since NSSs are in the near field of the interferometer, the basic ratios should take into account the sphericity of the incident wave. A significant obstacle to achieving high accuracy for the delay measurement is a narrow frequency band of radiated GLONASS and GPS signals, thus requiring the use of mathematical and methodical methods to reduce error of the basic parameter measurement. It is also necessary to take into account that the spectrum of the NSS signals is quasinoise and the traditional procedure of primary processing for the noise signals requires correction.

Elaboration of interferometer calibration methods is a necessary preparatory task for solving the problem of measuring the space object coordinates, bearing in mind that the accuracy of the required value calculation in both problems depends on the accuracy of the delay and the interference frequency measurement.

2. EXPERIMENTS

In recent years, NIRFI and VIRAC have been carrying out joint experiments on different scientific tasks at VLBI-complex, comprising radio telescopes of small and medium diameter (Fig. 1) [3], [4], [5]. The first experiment on receiving of NSS signals with purpose to study the Earth's ionosphere was implemented in 2010 on the interferometer "Staraya Pustyn – Zimenki" with the baseline of 68 km. In 2012, the radio telescope RT-32 Irbene was involved in these experiments.

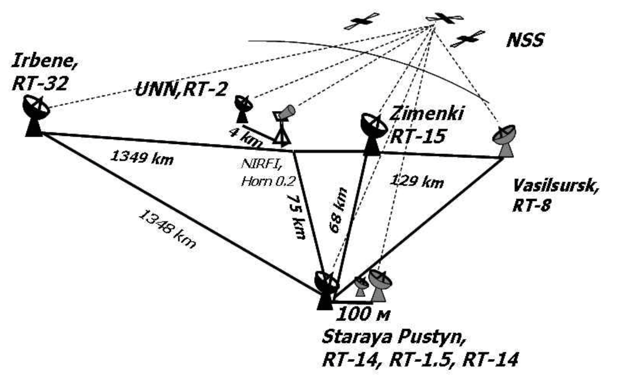

Fig. 1. VLBI-complex for the experiment on receiving of signals of navigation space satellites.

The experiments allowed accumulating an initial database, including the recording signals of NSS, on the basis of which the calibration method was tested. To calculate the interferometer parameters and verification capabilities of calibration on sources in the near field according to the developed algorithms, we used data of two experiments conducted in October of 2010 on the interferometer "St. Pustyn – Zimenki" and in September of 2012 on the interferometer "Irbene – Nizhny Novgorod State University (UNN) – St. Pustyn".

The main stages of the experiment are described briefly below. NSS signals received by antennas of the interferometer undergo cross-correlation processing, which consists of multiplying the signals with the preliminary compensation of time and frequency shifts. The delay is measured at the maximum of the correlation function and bears information about the calibration parameters, such as coordinates of the baseline and instrumental delay. Accordingly, the delay measurement is possible, when the signal emitted by the source has noise spectrum.

Figure 2 is an example of cross-correlation function obtained at reception of a signal from NSS 29601 GPS by the interferometer "St. Pustyn – Zimenki". Squares denote the values of the correlation function as a function of the delay for the single measurement. One discrete of delay measurements is inversely proportional to the sampling frequency, which in these experiments was 16 MHz at receiving bandwidth of 8 MHz. Discrete delay of 62.5 ns corresponds to one discrete in the definition of the difference between the propagation paths, which is equal to 18.7 m.

To clarify the position of the correlation function peak, we implemented an approximation of the data by a Gaussian function (solid line in Fig. 2), which describes well the maximum of cross-correlation function at reception of a noise signal in a rectangular frequency band.

Figure 3 shows the delay values depending on the time measured in the described manner. In this experiment, delay measurement was carried out with averaging time of 10 seconds at intervals with duration of 3 to 20 minutes, corresponding to the observation time of the satellite. A sequence of these values was interpolated by a polynomial function with calculation of errors. The result of the interpolation is shown in Fig. 3 by a solid line. For the given example the delay measurement error is 7.96 ns, which corresponds to an error determining the difference of propagation paths of signals 2.39 m.

Thus, application of the method allowed increasing the accuracy of the delay measurement nearly eightfold.

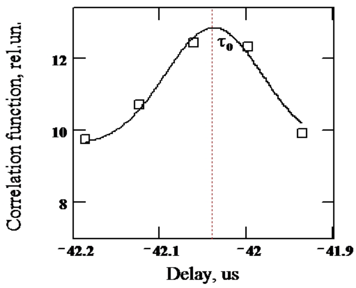

Fig. 2. Correlation function at receiving of signal of GPS 29601 at interferometer “St.Pustyn – Zimenki”. October, 26, 2010. 09:30 UT. Boxes mark measured values, bold line denotes the approximated curve.

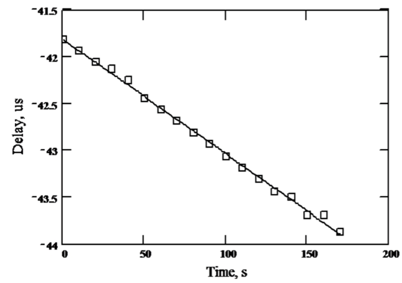

Fig. 3. Time dependence of delay obtained at receiving of signal of GPS 29601 at interferometer “St.Pustyn – Zimenki”. October, 26, 2010. 09:30 UT. Boxes are the experimental values, bold line is a polynomial function approximating the data.

The delays measured this way were used to determine the parameters of the interferometer.

The dependence of the delay τ on the position vectors of VLBI-stations and instrumental delay $\Delta\tau$ is described by the equation:

$$\tau = \frac{1}{c}\left(\left|\mathbf{r} - \mathbf{R}_1\right| - \left|\mathbf{r} - \mathbf{R}_2\right|\right) + \Delta\tau\,, \qquad (1)$$

Here c is velocity of light in vacuum. Let us assume that known values are delay τ measured in the experiment and the geocentric vector $\mathbf{r}\left\{r_x, r_y, r_z\right\}$ describing the position of the satellite. Satellite coordinates were taken from the official website of GLONASS – Information-Analytical Centre of Federal Space Agency (https://www.glonass-iac.ru/archive/).

The unknown quantities in (1) are the geocentric vectors of radio telescopes $\mathbf{R}_1\left\{R_{1_x}, R_{1_y}, R_{1_z}\right\}$, $\mathbf{R}_2\left\{R_{2_x}, R_{2_y}, R_{2_z}\right\}$ and instrumental delay $\Delta\tau$.

Since NSSs are arranged in the near field of the interferometer, it is impossible to describe the dependence of the delay on the baseline coordinates by linear equation, as it is done in the traditional method of interferometer calibration on extragalactic radio sources. Thus, the coordinates of radio telescopes will be calculated, from which baseline parameters will be further obtained.

The number of equations increases the accuracy of the solution. As the number of measurements obtained in reviewed observations was little for the qualitative statistical evaluation, the task was simplified: it was assumed that the coordinates of one antenna were known. Thus, the task was reduced to finding the coordinates of the second antenna and instrumental delay.

We made calculations on the results of the experiment of 2010 measuring the delay from 9 NSSs on interferometer “St. Pustyn – Zimenki”. Estimates of the coordinates of the antenna Zimenki at a given position of the antenna in the St. Pustyn are presented in Table 1.

The first column lists the coordinates of the antenna known from geodetic measurements and time shift between time scales in two different stations fixed during observations. The second column shows the results of calculations of the antenna coordinates and the instrumental delay and corresponding values of dispersion. The difference between the calculated parameters and the given values are displayed in the last column. As can be seen from the table, the discrepancy of antenna coordinates amounts to 2–4 meters and the dispersion is comparable in magnitude with an error of determination of the difference of signal propagation paths.

Table 1

Calculation of Antenna Coordinates in Experiment of 2010

Given parameters		Result of calculations and variance	Difference between the known and calculated values
R_{2x}, km	2549.035	2549.033 ± 0.009 km	2 m
R_{2y}, km	2486.162	2486.160 ± 0.011 km	2 m
R_{2z}, km	5274.220	5274.196 ± 0.018 km	4 m
$\Delta\tau$, mcs	16	16.894 ± 0.046 mcs	0.894 mcs

Thus, the differences of calculated and predetermined parameters are within the accuracy of delay measurement.

Despite the good results obtained on the middle baseline, the calculations made on the interferometers with large baselines “Irbene – UNN” and “Irbene – St. Pustyn”, were unsatisfactory. The discrepancy between the known and calculated antenna coordinates significantly exceeded the expected values. It was necessary to perform the study of the causes, which touched all stages of solving the problem: the organization of the experiment, the procedure of processing and interpretation of results.

3. DISCUSSION

Following the analysis, two factors were revealed, which negatively affected the result of the calculation of the antenna coordinates in experiments at interferometers with large baselines.

Non-optimal schedule of observing session can be considered one of the reasons of the decrease in accuracy. For calculation of the baseline parameters, it was necessary to use the data of experiment on the study of artificial ionospheric turbulence at radio sounding by NSS signals. In this experiment, the antennas received the signals from the satellites located in a narrow sector of angles in azimuth, in the direction of the heating facility “Sura” acting on the ionosphere [6]. Such arrangement of NSSs relative to VLBI baselines is not optimal for the calibration of the interferometer, because the best accuracy is achieved at regular distribution of sources on the celestial sphere. In addition, part of the measurements used in the calculations was made on one satellite and disturbed the condition of equation independence. Most errors were also associated with insufficient number of measurements for the statistical analysis.

A solution to this problem consists in the modification of the experiment schedule, which will provide the choice of NSS in a wide range of angles. It is necessary to reduce the time of observation of one satellite to 5–10 minutes and to increase the number of independent measurements.

The second and the most important factor in the loss of accuracy is a large error when measuring the delay. If the averaging time at the correlation was 10–30 seconds in the experiment with the middle baseline, then in the experiment with large baselines the averaging time was reduced to 1 second in order to evaluate the impact of the ionosphere on the passing signals in short time intervals. The small averaging time led to a large spread of delays. In addition, failures of synchronization of recording system were detected.

Figures 4a and 4b show examples of graphs of the difference between the measured and calculated delay for the two satellites observed on the interferometer “Irbene – UNN”. One step of delay change corresponds to one discrete of 62.5 ns. Approximation of the maximum of the correlation function to clarify its position was not performed.

a b

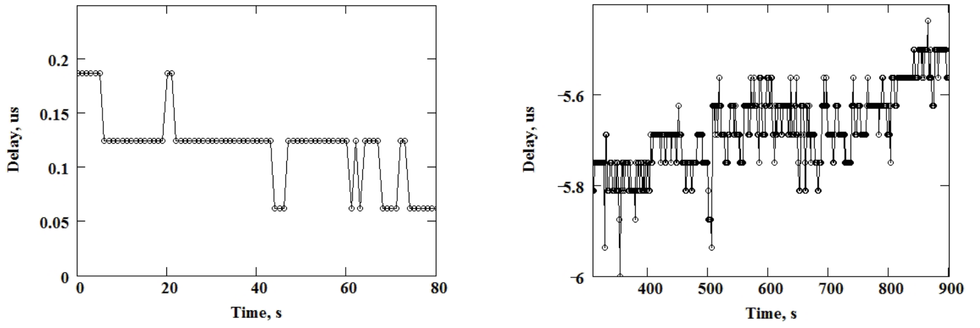

Fig. 4. Difference between the calculated and experimental delay depending on time at observation on interferometer “Irbene – UNN”. September, 5, 2012.

(a) – GPS 29601, 10:45 UT; (b) – GPS 28474, 09:35 UT.

To improve the accuracy of the delay measurement, it is necessary to increase the frequency reception bandwidth to the maximum possible, i.e., to the bandwidth of the signal emitted by the satellite. The signal band of GLONASS satellites is 10 MHz, and that of GPS is 20 MHz. The discrete of delay is equal to 50 and 25 ns, respectively. It is necessary to use the mathematical methods for the accurate measurement of delay in maximum of the correlation function as it was done in the experiment with the small baseline. This way will allow increasing the accuracy of the delay measurement by several times.

To sum up, it should be noted that the experimental verification of the calibration method of the interferometer on signals of NSSs showed the possibility to measure the coordinates of the receiving stations of the interferometer with an accuracy of 2–4 m, which was a good result considering that the NSS coordinates were known for limited accuracy. The results of the analysis of the revealed problems will be taken into account in future research and will allow improving the accuracy of the method for calibration of interferometers with large baselines.

ACKNOWLEDGMENTS

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INTERFEROMETRU PARAMETRU MĒRĪJUMI, IZMANTOJOT GLONASS UN GPS SIGNĀLUS

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K o p s a v i l k u m s

Aplūkota interferometru ar maza efektīvā laukuma antenām kalibrēšana, izmantojot sistēmu GLONASS un GPS pavadoņu signālus, kuru raksturlielumi ir līdzīgi trokšņu raksturlielumiem. Apskatīti radiointerferometru punktu koordināšu un iekārtās radušos signāla aizkavēšanos aprēķina algoritmi, izmantojot interferometra atsauci uz satelītiem tā tuvajā zonā. Metode pārbaudīta VLBI eksperimentos ar vidēju un lielu bāzu interferometriem, kuru sastāvā bija VSRC un Krievijas Radiofizikas institūta Nižņijnovgorodā radioteleskopi. Iegūtas antenas koordinātu un aparatūras izsaukto signāla aizkavju vērtības ar precizitāti līdz aizkaves diskretizācijas kvanta daļām. Analizēti kļūdu avoti un rezultātu precizitātes uzlabošanas iespējas.

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