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The Receiving System for a Compact Antenna of the Mobile VLBI Station

Maksim Zotov *

[a] *Institute of Applied Astronomy of the Russian Academy of Sciences, Zhdanovskaya street 8, St. Petersburg, Russia*

E-mail: zmb@iaaras.ru

Improving the resolution of the VLBI network and achieving maximum sensitivity of the radio telescope are the main issues in the creation and modernization of existing networks. An improvement in the resolution of the VLBI network can be achieved by changing the relative position of the network elements. This problem can be solved using mobile stations with small-diameter radio telescopes and further expanding the capabilities of the VLBI network in solving problems of astrophysics and space geodesy. An X-band receiving system for a mobile VLBI station was developed at IAA RAS. This system performs cryogenic cooling of the first stages of amplification by a closed-cycle microcryogenic system. It provides the inclusion of a mobile VLBI station in the Quasar VLBI network. This receiving system has the best characteristics achievable for a compact antenna of a mobile VLBI station. The paper presents the design features of the developed receiving system for a mobile VLBI station. The methods of testing the receiving system and the results of laboratory studies of the characteristics of individual units and the receiving system as a whole are described.

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*Speaker

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1. Introduction

Very long baseline radio interferometry (VLBI) provides the maximum available angular resolution. For radio source imaging, increasing the efficiency of observations, and solving astrometric problems, radio interferometers are needed with baselines of various lengths and relative positions. Therefore, further development of VLBI follows the path of creating global networks that incorporate radio telescopes located in different countries and on different continents. The main issues of creating new and upgrading existing networks are improving the resolution of the VLBI network and achieving maximum radio telescope sensitivity. The obvious ways to implement them are associated with an increase in the effective area of the radio telescopes, an increase in the signal-to-noise ratio (SNR), and a widening of the received frequency band, determined by the operating bandwidth of the receiving system and digital acquisition system. The signal-to-noise ratio can be increased by increasing the sensitivity of the radio telescope-radiometer system, primarily by reducing the inherent noise of the receiving equipment. The increase of the effective area of a radio telescope (Aeff) is directly connected to the increase of antenna dimensions and improvement of the feeding system, which affects the manufacturing cost. Improving the resolution of the VLBI network can be achieved by changing the relative position of the network elements. Moreover, by combining large ($A_{eff} \approx 10^2 \div 10^3$ m^2) and very small ($A_{eff} \approx 10$ m^2) antennas, a flexible network of almost any size and direction of the bases can be created [1]. The use of mobile stations with small-diameter radio telescopes makes it possible to further expand the capabilities of such a network in solving problems of astrophysics and space geodesy. In this case, the SNR of the correlation response will be determined by large radio telescopes.

2. Compact antenna

As part of this work, an assessment of the possibility of using small antennas for VLBI observations with radio telescopes of the Quasar VLBI network was made. It was made taking into account the observing programs of the International VLBI Service (IVS). The SNR of the correlation response is used as a criterion for the possibility of using a mobile VLBI station (2.1).

$$SNR = \frac{\eta \pi F \cdot 10^{-26} \cdot D_1 D_2}{8\mathrm{k}} \sqrt{\frac{\varepsilon_{a1} \varepsilon_{a2}}{T_{sys1} T_{sys2}}} \cdot \sqrt{2\Delta \mathrm{ft}} \quad ; \qquad (2.1)$$

where k is the Boltzmann constant [J/K], D is the diameter of the radio telescope [m], with the corresponding aperture efficiency ε_a, F is the radio source flux density [Jan], T_{sys} is the system noise temperature, Δf is the bandwidth, t is the integration time, η is a coefficient that takes into account signal quantization and processing loss; for 2-bit quantization η = 0.88. Based on this assessment, it was concluded that for operating as part of the Quasar VLBI network, the antenna diameter of the mobile VLBI station must be at least 4 meters. Such operation implies joint work with the RT-13 radio telescopes under the IVS observation programs. In addition, the receiving system must be compatible with the receiving systems of other radio telescopes of the VLBI network.

The IAA RAS has several decommissioned Tesla satellite communication stations (SCS). These stations are equipped with a dual-mirror antenna system with a primary mirror diameter of 4.3 m. A prototype of a mobile VLBI station for joint observations with the radio telescopes of the Quasar VLBI network was created on this basis and installed at Svetloe observatory. Equipping the SCS with new encoders and replacing the hardware of the electric-drive control system made it possible to obtain the required tracking accuracy in conjunction with the dynamic characteristics of the antenna. These results allow us to use the mechanical part of the TESLA SCS as a basis for the RT-4 radio telescope of the mobile VLBI station prototype [2].

3. Receiving system

The receiving system (RS) is a device consisting of several units, designed for reception in the 8.2–9.1 GHz frequency band, amplification, and conversion to an intermediate frequency (0.1–1 GHz) of cosmic source radio signals. The main operation mode of the RS is working as part of the VLBI network; additionally, a radiometric operating mode is also available. Thus, when choosing a radiometer scheme, we can abandon the complicated modulation radiometer in favor of the total power radiometer.

Only a feed horn can be placed in the limited amount of focal space. The polarization separator and input low-noise amplifieres are placed in the Dewar. The Dewar is cooled to cryogenic temperatures to achieve minimum noise temperature for the RS. The Dewar is located behind the mirror; the frequency conversion units (FCU) and amplitude and phase calibration equipment are also located there.

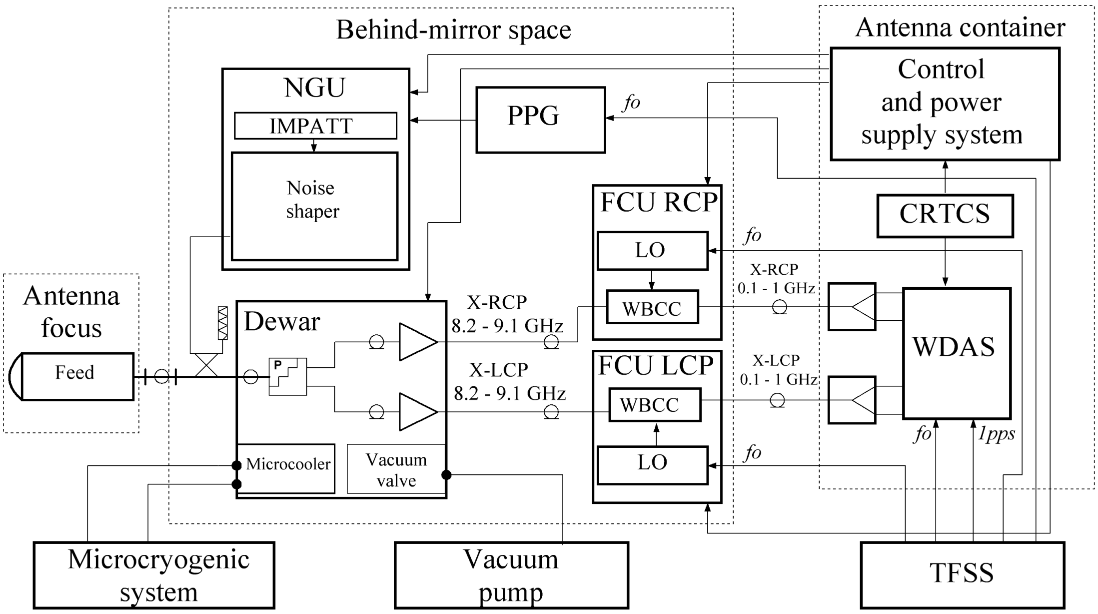

Figure 1: The structure of the receiving system of the mobile VLBI station: (NGU) noise generator unit, (IMPATT) impact ionization avalanche transit-time diode, (FCU) frequency conversion unit, (WDAS) wideband digital acquisition system, (WBCC) wideband conversion channel, (LO) local oscillator, (TFSS) time-frequency synchronization system, (CRTCS) central system radio telescope control, (PPG) picosecond pulse generator, (RCP, LCP) right and left circular polarizations.

The functional diagram of the developed receiving system is shown in Fig. 1. The Dewar performs the initial amplification and separation of the received signal into signals with right and left circular polarizations (RCP and LCP). Two frequency conversion units (FCU) perform the final amplification, filtering, and conversion of a microwave signal into an intermediate frequency signal. One noise generator unit (NGU) provides amplitude and phase calibration of the receiving system section; also shown are the communication and control units.

The feed is a conical horn. It provides reception of signals from cosmic radio sources in the 8.2–9.1 GHz frequency band. The feeder beamwidth at minus 10 dB level is 51–54° (its optimal design value is 50°). The axial ellipticity coefficient of the input microwave elements of the RT-4 radio telescope receiving system in the entire operating frequency range does not exceed 1 dB.

The Gifford-McMahon microcryogenic system provides cooling of Dewar elements to temperatures of 20–30 K. Due to this, the Dewar gain is 28 dB with a flatness of no more than 2.5 dB. Dewar noise temperature is 15 K, which made it possible to obtain a total receiving system noise temperature of 35 K. The standard deviation of the Dewar phase frequency characteristic (PFC) from linear does not exceed σ=6°, thus deterioration of the SNR due to the deviation of the PFC from linear does not exceed 1.5%. This has practically no effect to the result of correlation processing.

The FCU includes a wideband conversion channel (WBCC) microassembly, a local oscillator microassembly, a thermostat system, and secondary power supply boards. In it, the high-frequency signal is amplified and converted into the intermediate frequency range (100−1000 MHz). The average value of the FCU gain was 32 dB, and its flatness did not exceed 2 dB in the operating frequency band. The total RS gain exceeds 60 dB; this value is optimal for the selected WDAS. The unevenness of the amplitude-frequency characteristic of the RS does not exceed 3 dB, which will lead to less than 2.5% SNR degradation. Noise temperature of the FCU did not exceed 500 K, so the contribution of the FCU to the RS noise temperature will be less than 1 K. Conducted studies of the characteristics of the NGU show that, taking into account the transient attenuation of the directional coupler before the CRU (30 dB), the amplitude calibration signal level is 5–120 K in the operating frequency band. This is sufficient for carrying out measurements with the RT-4 radio telescope.

4. Measurements and results

The noise temperature of the receiving system was determined by the Y-factor method using a special low-temperature noise generator. The noise temperature of the RS excluding feed and waveguide is 15 K; with a waveguide it is 26 K. This made it possible to verify the calculation of the contributions of various components to the noise temperature of the RS. The correctness of the chosen design solutions confirm that the use of the input waveguide path in the created receiving system leads to minimization of losses and, as a result, reduces the system noise temperature. Amplitude calibrations were set in the range of 5–6 K. This will allow us to monitor the characteristics of the RS of the radio telescope.

Studies of non-linear distortions of the Dewar and the entire RS were carried out. Methods for measuring and processing nonlinearity parameters are given in [3]. Table 1 shows the results of the assessment of the dynamic range, the compression points and spurious-free dynamic range for both channels of the receiving system.

Table 1: The main parameters of the developed receiving system

Parameter	Value	
Polarization	RCP	LCP
Received frequency band	8.2–9.1 GHz	8.2–9.1 GHz
Output frequency band	0.1–1.0 GHz	0.1–1.0 GHz
Feed beam width -10 dB	51–54°	51–54°
Ellipticity factor	no more than 1 dB	
Noise temperature (without feed and waveguide)	15 K	14 K
Gain	62 dB	60 dB
Gain flatness	<3 dB	<3 dB
Compassion point P_{1dB}	-57 dBm	-63 dBm
Dynamic Range (in 1 Hz band)	116 dB	110 dB
Spurious-Free Dynamic Range (in 1 Hz band)	88 dB	80 dB

Joint operation of the receiving system with the WDAS and TFSS was carried out in laboratory conditions. For this, a "zero-baseline interferometer" was created [4]. It consists of the developed RS, the Tri-band receiving system (Tri) [5], Ultra-wideband receiver system (UWB) [6], as well as WDAS and TFSS. All four receiving systems are used to compare the parameters of the correlation response. This installation allowed us to evaluate the possibility of operation of the developed RS as part of the Quasar VLBI network and get a correlation response in the laboratory. For comparison, Table 2 presents the results of determining the correlation response parameters such as SNR and standard deviation (RMS) of the delay (σ). Studies of the developed RS for a mobile VLBI station showed that the RMS of the delay introduced by the RS and WDAS does not exceed 5 ps (with a 30-minute experiment). The results showed a good agreement between the calculated values and the experimental ones obtained with the bases formed by the receiving systems of the Quasar network and the developed receiving system.

Table 2: 30-minutes session results

Receivers	SNR (calc)	SNR (meas)	σ(calc), ps	σ(meas), ps
RS–UWB	445	443	2.5	4.8
RS–Tri	275	277	4.0	7.3
Tri–UWB	354	353	3.1	6.7

5. Summary

The X-band receiving system with cryogenic cooling of the frontend by the Gifford-McMahon microcryogenic system for the mobile VLBI station was developed. It meets all the requirements for a mobile VLBI station for its inclusion in the Quasar VLBI network. This will further expand the capabilities of the network in terms of solving problems of astrophysics and

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space geodesy. The created receiving system has the best achievable characteristics for a compact antenna of a mobile VLBI station. As a result of the work carried out, it was possible to achieve the noise temperature of the receiving system without a waveguide and feed of less than 15 K. This value corresponds to the noise temperature level of similar receiving systems used in large-sized radio telescopes in VLBI practice, and significantly exceeds the parameters for mobile stations.

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