IAA Technology Development Center Report for 2021–2022

Dmitry Marshalov, Evgeny Khvostov, Maxim Zotov, Dmitrii Ivanov, Vladimir Bykov, Victor Stempkovskiy, Alexander Shishikin, Vitaliy Chernov, Sergey Grenkov, Anton Berdnikov, Leonid Fedotov, Alexey Melnikov, Ilia Pozdnyakov, Ismail Rahimov, Igor Shakhnabiev, Alexey Lavrov, Yury Vekshin

Abstract The main activities of the IAA Center for Technological Development in 2021–2022 were focused on the work with a mobile VLBI station prototype and modernization of the Multifunctional Digital Backend system for upgrading the 32-m radio telescope equipment. This report provides a brief overview of these activities.

1 The Prototype of a Mobile VLBI Station

One of the most effective ways of expanding the "Quasar" VLBI network is to create a mobile VLBI station. Mobile stations provide direct measurements of coordinates and time at any location with an accuracy of about 1 cm in coordinates and 0.1 ns in time per day [1]. In 2017, the concept of a mobile VLBI station with a radio telescope with a 1–5 m main reflector diameter was proposed. In 2021, the prototype of a mobile VLBI radio telescope compatible with the "Quasar" VLBI Network was developed.

The decommissioned ground based satellite station (GBSS) TESLA S11 DD 424 served as the antenna system (Figure 1). GBSS is equipped with a double-reflector antenna system with a 4.3-m primary reflector diameter. The surface quality of the reflector system satisfies the frequency range of 8.0–12.0 GHz (X-band). Significant limitations for GBSS use are low speed (2°/min), limited pointing accuracy, and azimuth limits (±40°). As a result of the refinement of this antenna system, it was possible to partially eliminate these shortcomings. The antenna position sensors were replaced, which ensured rotation in absolute coordinates in azimuth and elevation with a resolution of 20″. The problem of low speed and limited angle of motion is solved by a modified procedure for planning VLBI observations.

Institute of Applied Astronomy (IAA RAS)

IAA Technology Development Center

IVS 2021+2022 Biennial Report

Fig. 1 The TESLA S11 DD 424 ground-based satellite communication station.

For slewing and tracking, a modified software part of the RT-32 monitoring and control workstation was used. The control computer software calculates the trajectory of the source and provides control of the electric drive and execution of the slew algorithm. The tracking algorithm was improved to achieve the best accuracy [2].

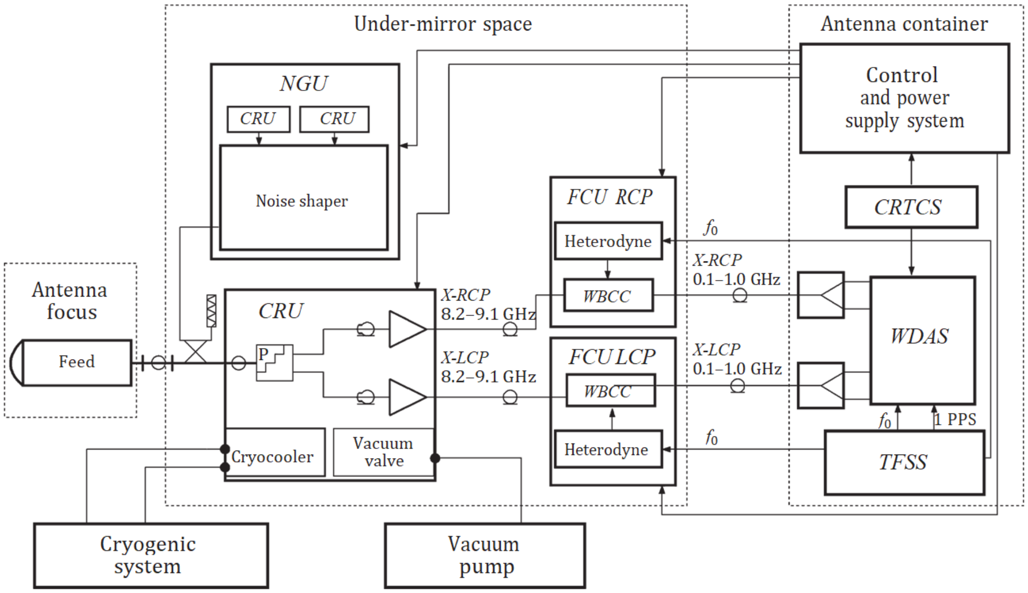

Fig. 2 The structure of the of the mobile VLBI station prototype: Cryogenic Receiver Unit (CRU), Noise Generator Unit (NGU), Frequency Converter Unit (FCU), Wideband Data-Acquisition System (WDAS), and Time-and-Frequency Synchronization System (TFSS).

For the radio telescope, a receiving system was developed for the frequency range of 8.2–9.1 GHz, which simultaneously receives signals of right and left circular polarization. An X-band feed was developed using a conical scalar horn whose phase center coincides with the secondary focus of the antenna system.

To reduce the receiver temperature, two cooled low-noise amplifiers based on HEMTs, together with a polarization separator, are installed in the cryochamber. The amplifier has a built-in directional coupler with a 20-dB attenuation. Such a coupler is used for the injection of both the amplitude and phase calibration signals. The cryogenic system with a closed cooling cycle on the basis of a two-stage cryocooler (15/77 K) and an air-cooled compressor is used to cool the polarization separator and low-noise amplifiers to temperatures of about 15 K. The functional diagram of the developed receiver system [3] is shown in Figure 2.

The modules of CRU, NGU, and FCUs are located in the backside antenna space.

The radio frequency (RF) signal (8.2–9.1 GHz) is converted to an intermediate frequency (IF) range of 100–1,000 MHz. The signals from the outputs of the corresponding FCUs are transmitted over RF cables to the power dividers and the corresponding inputs of the wideband data-acquisition system (WDAS). The control and power-supply system, the WDAS, and several time-and-frequency synchronization system (TFSS) units are located in the antenna container near the radio telescope.

The noise temperature of the receiving system was determined by the Y-factor method using a special low-temperature noise generator. The receiving system noise temperature without feed and waveguide is 25 K, and with a waveguide it is 36 K. The estimated system noise temperature is 59 K. More information on measurements can be found in [4].

The system equivalent flux density (SEFD) parameter was measured to determine the radio telescope aperture efficiency. The measurements were carried out using the Cygnus A cosmic radio source. The SEFD and the aperture efficiency were measured as 17 kJy and 0.7, respectively.

To determine the position of the mobile station prototype, observations were carried out with the “Quasar” VLBI network. Mobile station prototype coordinates were estimated from two sessions independently and from the joint processing of the two sessions. The coordinates obtained with geodetic measurements and those refined as a result of joint equalization by VLBI sessions with the formal errors of X, Y, Z (cm): 8, 3, and 6, respectively. Taking into account the limitations associated with the design of the mobile station prototype and the relatively short observation sessions, we can consider the obtained positions accuracy to be acceptable. In the case of a daily session, by increasing the number of observations, it is possible to achieve 1 cm accuracy.

2 Multifunctional Digital Backend

In 2020, the IAA RAS developed the Multifunctional Digital Backend (MDBE) system that performs digital signal processing in the intermediate frequency range (up to 2 GHz) in a digital form [6]. The MDBE is built on a modular principle, has ample opportunities for reconfiguring operating modes due to the programmable logic integrated circuits (FPGA) used in its composition, and the design of the system ensures its placement on the focal cabin of the antenna. Since the end of 2020, the MDBE prototype has been routinely operated on the 13-meter radio telescope of the Svetloe observatory of the “Quasar” VLBI network.

The MDBE prototype was upgraded in 2021–2022 to use the MDBE on the RT-32 radio telescopes. It was supplemented with modules of intermediate frequency distributors and a set of software tools that implement support for VLBI modes of operation with narrow frequency bands, broadband radiometric recording of signals, and spectral selective radiometer modes.

Work was carried out to interface the MDBE with the data recording and transmission system (DTRS) [7] and the radio telescope time-frequency synchronization system. A set of MDBE control programs for the central control computer of the radio telescope was created, which provides tuning and diagnostics of the system operation during VLBI and radiometric observations. After a series of experiments, the MDBE was installed on the RT-32 radio telescope and used for regular VLBI observations at Svetloe observatory.

For RT-32 radio telescopes, four digital processing modules (DSP) are enough to capture and process IF signals coming from the radio astronomy receiving system in the frequency range of 100–1,000 MHz. To provide selection of IF signals from ten receivers in five frequency bands (L, S, C, X, and K) in two polarizations, two cassettes of IF signal distributors are used in the upgraded MDBE.

The MDBE is based on a 19-inch Europac PRO 3U chassis (Figure 3) designed for rugged environments. The chassis contains four DSP modules (positions 1, 2, 7, and 8 in Figure 3), a module of synchronization and control, and two IF distributor cassettes (positions 3–6 and 9–12).

Fig. 3 The MDBE prototype for the RT-32 radio telescope.

The functions performed by the MDBE are determined by the embedded software (ES) loaded in the form of firmware into the FPGA. The upgraded MDBE prototype implements the following firmware configurations:

- VLBI mode with broadband channels (512 or 1,024 MHz);
- VLBI mode with narrowband channels (up to 16 channels of 0.5, 2, 4, 8, 16, or 32 MHz bandwidth);
- Spectral-selective radiometer mode.

Table 1 The main results of the MDBE installation on the RT-32 radio telescope.

Parameter	R1002M+Mark5B+	MDBE+DTRS
Frequency range	0.1–1 GHz	0.1–1 GHz
Number of wide- / narrowband channels	– / 16	4 / 4*16
Channel bandwidth	0.5; 2; 4; 8; 16; 32 MHz	0.5; 2; 4; 8; 16; 32; 512; 1024 MHz
Data rate	2 Gbps	16 Gbps
Output format	Mark5B	VDIF, 10GE
Continuous amplitude calibration	No	Yes
Upgradable, including remote	No	Yes
Operating modes	Only VLBI	VLBI; Radiometer; Spectral–selective
Placement in the signal path of the radio telescope	Control room, the presence of AZ and EL loops	Focal cabin, connection to receiver outputs

The radiometric registration of signals in the MDBE is implemented in all modes listed above. A separate power measurement is carried out on two half-cycles of modulation, both in the entire input frequency band (at analog to digital converter input), and for the given bands of narrowband or wideband channels.

To fully support the modes and functions on the radio telescopes of the “Quasar” VLBI network, the software for controlling the MDBE was integrated into the software structure of the central control computer of the radio telescope, which is a standard for international VLBI networks.

As a result of the installation of the upgraded MDBE, an improvement in the technical and operational parameters of the data acquisition equipment of the radio telescope is noticeable (see Table 1). An equipment upgrade for the remaining “Quasar” observatories is scheduled for 2023–2024.

References

1. Ichikawa R., Ishii A., Takiguchi H., Takefuji K., Ujihara H., Koyama Y., Kondo T., Kurihara S., Miura Y., Kawabata R., Kokado K., Machida M., Takashima K., Fujisaku J., Tanimoto D., and Nozawa K., *J. Natl. Inst. Inf. Commun. Technol., 2010, vol. 57, nos. 3/4*, p. 241.
2. Stempkovskii, V. G., Antenna’s system mathematic model, *IAA RAS Trans., 24*, pp. 87–91, 2012.
3. Zotov M. B., Ivanov D. V., Pozdnyakov I. A., Khvostov E. Yu., and Chernov V. K., Two-channel X-band receiving system for 4m dish radio telescope prototipe, *IAA RAS Trans., 48*, pp. 50–55, 2019.
4. Zotov M. B., Ivanov D. V., Bikov V. Yu., Grenkov S. A., Pozdnyakov I. A., Rahimov I. A., Stempkovsky V. G., Tsaruk A. A., Chernov V. K., Shakhnabiev I. V., and Shishikin A. M., The Results of the Development of the Mobile VLBI Station Prototype, *Instrum. Exp. Tech., Vol. 63, No. 6*, pp. 91–96., 2020.
5. Nosov E., Khvostov E., Vytnov A., IAA Technology Development Center Report for 2017–2018, *International VLBI Service for Geodesy and Astrometry 2017+2018 Biennial Report*. Edited by K.L. Armstrong, K.D. Baver, and D. Behrend NASA/TP-2020-219041, pp. 271–274.
6. Nosov E., Marshalov D., Fedotov L., Sheynman Y., Multifunctional Digital Backend for Quasar VLBI network. *Journal of Instrumentation, V.16*, doi:10.1088/1748-0221/16/05/p05003, P05003, 2021.
7. Bezrukov I. A., Salnikov A. I., Yakovlev V. A., Vylegzhanin A. V., A Data Buffering and Transmission System: A Study of the Performance of a Disk Subsystem. *Instrum. Exp. Tech., 61*, doi:10.1134/S0020441218040164, pp. 467–472, 2018.