Russian New Generation VLBI Network

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Abstract In 2012, the new generation VLBI system VGOS project was launched in Russia. At the end of 2015 the two-element interferometer with 13.2–m multi-fast rotating antennas (RT-13) was completed at the Badary and Zelenchukskaya observatories. In 2020, the new generation VLBI network was replenished with the third antenna at the Svetloe observatory. Since then, observations are regularly carried out with the VLBI network in three band S, X and Ka mode. The radio telescopes have identical equipment, except for the installed multifunctional digital backend system at the RT-13 in Svetloe. Additionally, the RT-13 is equipped with the ultra-wideband receiver to provide compatibility with international VGOS observations. This paper presents the current state and the first results obtained with the VLBI network. The nearest prospects for the expansion of the network to the East will also be considered, taking into account the start of construction of a new co-location station.

Keywords VGOS, Quasar VLBI network

1 Intoduction

In 2010, the concept of the next generation VLBI Global Observing System (VGOS) network was finally formed [1]. The Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS) started work on the VGOS radio telescopes in 2012. The radio telescopes are designed for routine 24/7 determination of Universal Time corrections UT1-UTC with highest accuracy. The first two new generation VGOS radio telescopes (RT-13) at Badary and Zelenchukskaya observatories were commissioned in 2015 and since then perform regular geodetic observations up to five sessions every day [2]. After the Svetloe radio telescope was commissioned in 2020 [3], regular observations began with the Russian new generation VLBI network (see Figure 1).

In 2021, we started the design of a co-located station in Ussuriysk, and upon completion of the project we will have a VLBI network with a baseline of about 6,500 km.

This became possible by our development of unique equipment for the new generation VLBI network. We have developed VGOS software correlator RASFX [4], tri-band and ultra-wideband receivers [5, 6, 7], digital backend systems [8, 9], and a data transferring and recording system [10]. Next, we will consider the key elements and technologies that made it possible to create and put into operation a new generation network.

2 RASFX GPU-based Software Correlator

The development of the RASFX correlator began in 2012. It was designed to be run on GPUs in high performance computing cluster under GNU/Linux. RASFX can process data of up to six VGOS-compatible stations in quasi-real time mode with the maximum input data rate of 96 Gb/s at the correlator input. RASFX is designed as based on all the requirements of VGOS-compatible broadband data processing, which also include the ability to process

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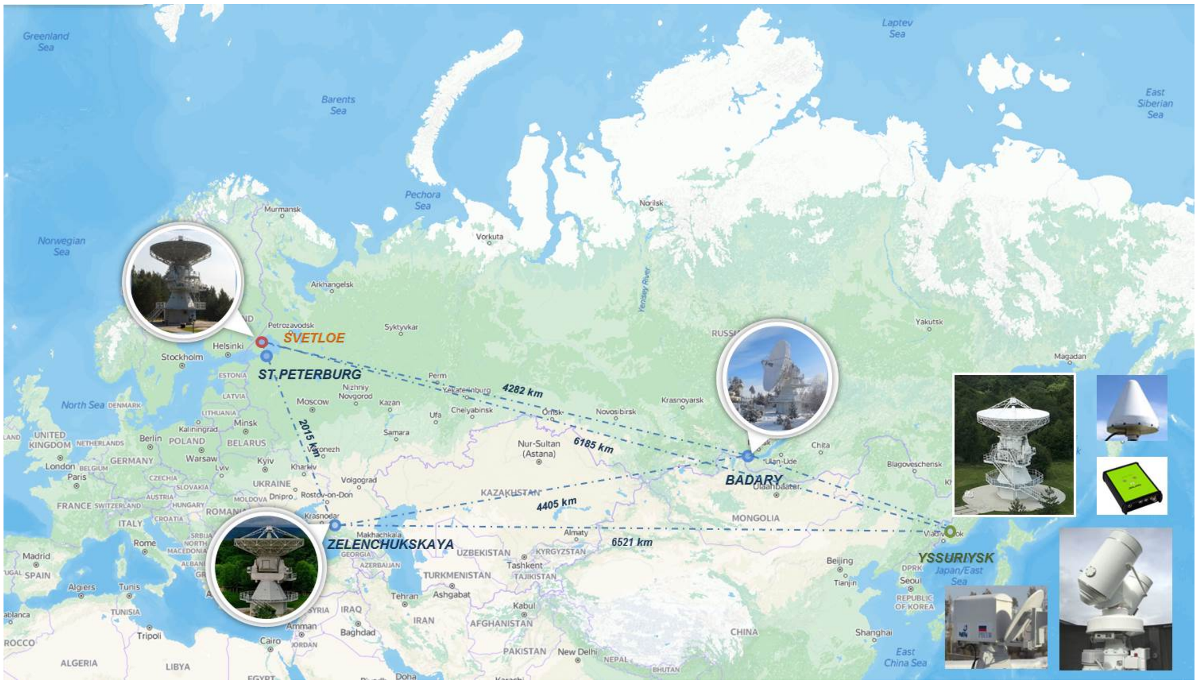

Fig. 1 Russian New Generation VLBI Network.

data recorded in circular and linear polarizations and to calculate high-resolution spectra.

The correlator hardware is a hybrid blade server cluster of the T-Platforms Corporation. It includes V200F blade servers, Intel R2216GZ4GCLX servers, network equipment, a high-speed RAID array, control and process synchronization systems, a power supply, and cooling systems. Each blade and Intel server is equipped with two Intel E5-2670 processors, two NVIDIA Tesla K20 GPUs, and InfiniBand network ports. The parallel LINPACK benchmark ranked the performance of the RASFX cluster as 85.34 Tflops.

Since 2016, RASFX has processed about 10,000 VLBI sessions.

Fig. 2 RASFX GPU-based software correlator.

3 Fast VGOS Radio Telescopes

The Russian new generation VLBI network consists of fast-rotating antennas manufactured by Vertex Antennentechnik GmbH. The antennas are built according to the Cassegrain scheme and have an alt-azimuth mount and a main reflector with a diameter of 13.2 m (see Figure 3). The hexapod is used for precise positioning of the 1.48 m counterreflector. An irradiation scheme with an ring focus was used. The antenna has velocities up to six degrees per second for elevation and up to 12 degrees per second for azimuth. The surface quality of the main mirror and counterreflector with a reserve provides performance to specification (see Table 1). The antennas are adapted for harsh climatic conditions. The temperature in the focal cabin is maintained within a few degrees. The receiving and processing equipment is located in the focal cabin of the radio telescope.

3.1 Receivers

The RT-13 radio telescope is equipped with a tri-band highly sensitive receiver capable of operating simul-

Fig. 3 VGOS antenna of the Svetloe Observatory.

Table 1 Specifications of the Fast VGOS Antenna

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	ringfocus
Main mirror diameter	13.2 m
Subreflector diameter	1.48 m
Focal length	3.7 m
Azimuth speed	12°/sec
Elevation speed	6°/sec
Limits by Az	±245°
Limits by El	6°–109°
Operation	24 h / 7 d
Tracking accuracy	±15 arcsec
Surface accuracy (RMS)	< 0.15 mm
Frequency range	2–40 GHz
The surface efficiency	> 0.7
Polarization	LCP + RCP

taneously in two circular polarizations in the S/X/Ka bands. All input stages of the receiver including the feed and low-noise amplifier are cooled. Such design makes it possible to achieve high sensitivity in three frequency bands: S (2.2–2.6 GHz), X (7.0–9.5 GHz), and Ka (28–34 GHz) in both circular polarizations simultaneously [5].

The tri-band receiver has a dewar that has cooled combined S, X, and Ka feed horns and low-noise amplifiers. Double frequency conversion is used for the X- and Ka-bands. Single frequency conversion is used for the S-band. The frequency converters are placed in thermostatically controlled units, which are attached to the supporting structure frame. The total system noise temperature with the tri-band receiver is about 35 K in the S frequency band, 30 K in the X-band, and 75 K in the Ka-band. This corresponds to system equivalent flux densities of 1,000, 750, and 2,000 Jansky for the S-, X-, and Ka-bands.

The next step was the development of an ultra-wideband receiver compatible with the VGOS specification. The receiver operating frequency range is 3–16 GHz [6]. The signals are received in two linear polarizations. The design of the receiver is similar, but in this case a wideband quadruple-ridge flared horn is placed in the dewar together with low-noise amplifiers. Four dual channel frequency converters are used in the receiver. The bandwidth of each channel is 1 GHz. The total system noise temperature with the ultra-wideband receiver is about 35 K at most of the band and increases up to 50 K at the band edges.

3.2 Digital Backends

Digital backend systems were specially developed for recording signals in the frequency range over 500 MHz. The eight channel BRoadband Acquisition System was created for the two-element interferometer [8]. The system is plugged into the output of the receiving system and works with intermediate frequency signals from 1 to 1.5 GHz. Each channel of the system utilizes 512 MHz bandwidth and generates a digital data stream in the VDIF format. For two-bit data, the total data rate from the system is 16 Gb/s.

The next step was the development of the multifunctional digital backend system (MDBE), which was completed in 2020 [9]. MDBE has fully VGOS-compatible digital backends. The system is technologically more advanced. The input bandwidth is up to 2 GHz, and the sampling frequency is 4,096 MHz. The system is easy to reconfigure and supports different VLBI operating modes:

- broadband with 512 and 1,024 MHz bands,

- tunable digital converters – with 32, 16 MHz bands,
- old systems with narrow bands 8, 4 , 2 and 1 MHz.

There is a wide range of possibilities for adding new modes of operation.

3.3 Data Transferring and Recording System

We have developed the data transferring and recording system (DTRS) based on commercially available components and technology [10]. The DTRS hardware platform is made on the Dell PowerEdge R720/R740 servers with two Intel Xeon processors E5-2660v2 and SuperMicro disk chassis. Each server has four two-port Intel X520 network cards installed. Thus the DTRS has ten 10 Gb Ethernet network interfaces, eight of which are used to capture data from the digital backend and two of which are utilized to transfer data to the correlator at the processing center. It allows us to simultaneously record up to eight streams of 2 Gb/s data and transfer them for processing.

To process a high-speed packet stream on a 10 Gb/s Ethernet interface, PTC-CAPREC software uses the net API of the FreeBSD OS kernel. The netmap framework takes advantage of modern ethernet controllers directly, bypassing the OS network stack based on a classic memory buffer. The database runs under the FreeBSD operating system (Version 11); the ZFS file system is used to write data. The storage capacity of the DTRS at each station is about 200 Tbytes.

4 UT1 Results

Since the end of 2015, observations to determine UT1 have been regularly carried out up to five times per day. For such observations Tri-band receivers are used in dual band mode; these are the S- and X-bands. Figure 4 shows the UT1 obtained by the Russian VLBI network in comparison with the IERS finals series. It follows from the figure that with the addition of the third radio telescope (early 2019) errors of UT1 determination have decreased. The RMS for the series in the interval from 2015 to the end of 2021 varies from 18 µs up to 38.5 µs.

A comparison of our results with the VGOS-Intensive and IVS-Intensive series relative to the IERS finals series for 2021 is shown in Figure 5. The resulting RMS of 25.9 µs for our series is the same as for the VGOS-Intensive series. The difference in bias is 10 µs.

5 Future Plans

We have begun expanding our VLBI network to the East. Now we are developing a co-located station on the basis of the Ussuriysk Astrophysical Observatory. This observatory became part of IAA RAS in 2018. The Ussuriysk Observatory was founded in 1953 as a Solar Service. At present, there are several optical telescopes and some engineering infrastructure. In addition, the observatory has staff ready to learn and develop new techniques and insruments.

We hope that in the near future the station will acquire new space geodesy instruments.

6 Conclusions

The new generation VLBI network has been created in Russia. Since 2020, Russia's next generation three-element VLBI network has been in regular operation. A unique equipment for radio telescopes has been developed. The results obtained are in good agreement with international data. The errors of determining the UT1 are at the same level as the VGOS Intensive. In 2021, work began on the design of the co-location station in Ussuriysk. There is every reason to believe that in the near future the Russian VLBI network will include a new modern co-location station equipped with the latest means of space geodesy.

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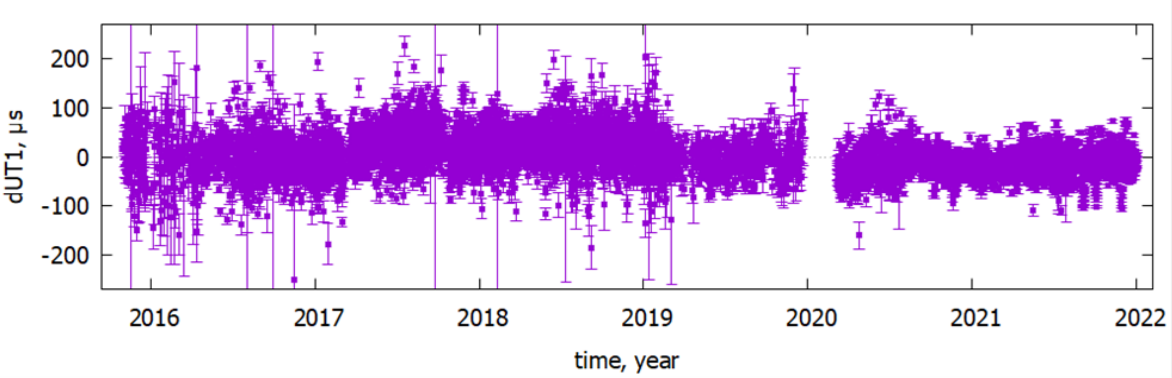

Fig. 4 Comparison of the UT1-UTC “R”-series vs. the IERS finals series.

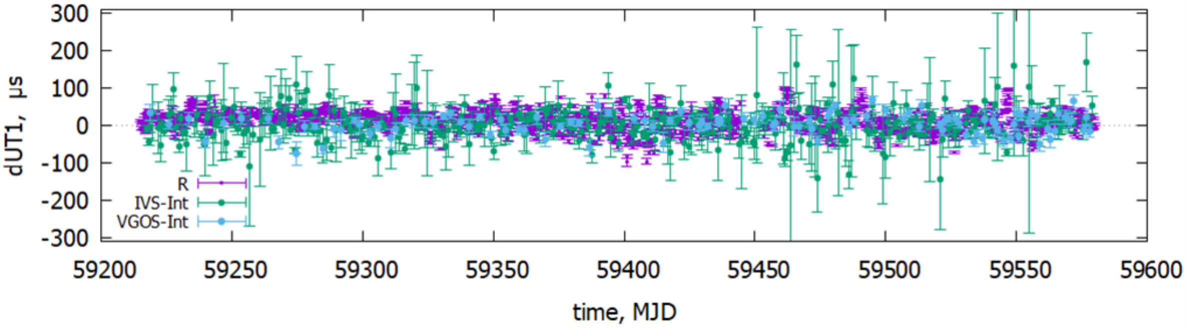

Fig. 5 Comparison of the UT1-UTC “R”-series vs. the IVS-Intensives and the VGOS-Intensives.

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