New Generation VLBI: Intraday UT1 Estimations

Alexander Ipatov, Dmitriy Ivanov, Gennadiy Ilin, Sergei Smolentsev, Iskander Gayazov, Vyacheslav Mardyshkin, Leonid Fedotov, Victor Stempkovski, Alexander Vytnov, Alexander Salnikov, Igor Surkis, Andrey Mikhailov, Dmitriy Marshalov, Ilya Bezrukov, Alexey Melnikov, Voytsekh Ken, Sergei Kurdubov

Abstract IAA finished work on the creation of the new generation radio interferometer with two VGOS antennas co-located at Badary and Zelenchukskaya. 48 single baseline one-hour VLBI sessions (up to four sessions per day) were performed from 04 Nov to 18 Nov 2015. Observations were carried out using wideband S/X receivers, three X-band and one S-band 512 MHz channels at one or two circular polarizations. Sessions consisted of about 60 scans with a 22-second minimum scan duration. The stations' broadband acquisition systems generated 1.5–3 TB data per session, which were transferred via Internet to the IAA FX correlator. The accuracy of the group delay in a single channel was 10-20 ps, which allows the use of every single channel's observations for geodetic analysis without synthesis. 156 single channel NGS-cards were obtained in total. The RMS of the differences between UT1–UTC estimates and IERS finals values is 19 µs.

Keywords VLBI, VGOS, UT1

1 Introduction

The construction of the new generation VGOS interferometer proposed at the previous General Meeting [1] was finished in 2015. In order to test the capabilities and the performance of the newly built facility, we started a special UT1–UTC estimation program. This paper reports the state-of-the-art conditions of the interferometer components and the first results of the UT1 campaign.

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2 Antenna System and Feed

The 13.2-m antenna system produced by Vertex Antennentechnik GmbH was chosen for the purpose of fulfilling VLBI2010 (VGOS) requirements. The main antenna characteristics are shown in Table 1.

Table 1 13-m antenna specifications.

Main mirror diameter	13.2 m
Mount	alt-azimuth
Sub-reflector scheme	Ringfocus
Sub-reflector Mount	Hexapod
Azimuth speed	12°/sec
Elevation speed	6°/sec
Limits by Az, El	±270°, 0°–110°
Operation	24h/7d
Tracking accuracy	±15 arcsec
Surface accuracy (RMS)	Bv 0.053 mm / Zv 0.057 mm
Frequency range	2–40 GHz
Surface efficiency	> 0.7
Polarization	LCP and RCP
Ambient temperature	−35°C to +50°C
Humidity	up to 100%
Snow load	100 kg/m2
Wind velocity	50 m/sec

The new tri-band S-X-Ka receiving systems were developed and mounted for VGOS observations [2]. General receiver system parameters are presented in Table 2. In order to improve the signal-to-noise ratio, the tri-band feed and the frontend LNAs were mounted in a single unit and cooled by a closed cycle refrigerator to the temperature of liquid helium (20 K).

Synchronization of the frequency converters is provided by the frequency-time synchronization system of the radio telescope. The radio telescope receiver units are placed in the focal cabin.

Table 2 Tri-band receiving system parameters, results of on-site measurements, 14.04.2014, Badary, 60°.

Band	S (13 cm)	X (3.5 cm)	Ka (1 cm)
Freq. (GHz)	2.2–2.6	7.0–9.5	28.0–34.0
Polarization	RCP and LCP		
$T_{sys}(K)$	35	25	70
SEFD (Ja)	1000	670	2100
Surface efficiency	0.7	0.8	0.7

3 Broadband Data Acquisition System

The Broadband Acquisition System (BRAS) contains eight identical units (wideband channels) that allow the digitization of the input signals of 512 MHz bandwidth (Figure 1) into the intermediate frequency range from 1024 to 1536 MHz [1].

Each unit is based on a high-speed 8-bit analog-to-digital converter (ADC) and low-cost field-programmable gate array (FPGA) performing the necessary signal processing. The main purpose of the FPGA is to receive data from the high-speed ADC, pack the input samples into frames in VLBI Data Interchange Format (VDIF) with timestamps, and to send the derived frames to the recording systems through a 10 Gigabit Ethernet fiber link. The BRAS is designed based on standard plug-in 6U Europack units, which provide ease of operation. Vibration resistance and good electromagnetic shielding of the housing made it possible to place the system in the focal cabin of the antenna close to the receivers. This eliminates the transmission of analog signals over a long distance and all related instabilities and performance degradation. More information on the BRAS structure, performance, and applications can be found in [3].

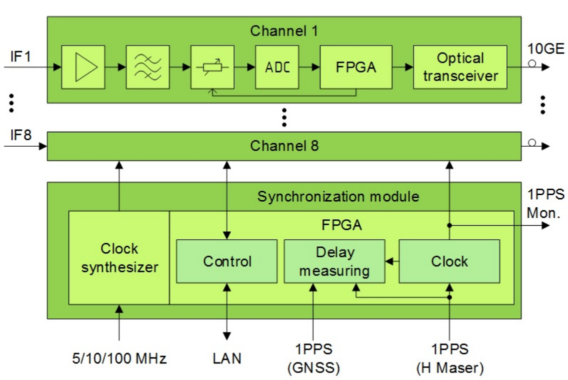

Fig. 1 BRAS structure.

4 Buffering and Data Transmission System

In 2015 IAA RAS created the Data Transmission and Registration System (DTRS) for the new two-station radiointerferometer based on the 13.2-m diameter antennas (RT-13). DTRS may be used in the international VGOS program. The main objectives of the new system are:

- Recording eight data streams (with scalability up to 16) in the VDIF format at a 2 Gbps data rate for each channel;
- Transferring data to the Correlation and Processing Center (CPC) at a 10 Gbps rate simultaneously with recording and buffering;
- Storing up to 20 TB of observation data with a set of disk pools.

DTRS is based on a Dell PowerEdge R720 rack server with two Dell PowerVault MD1220 disk enclosures. Up to four dual-port 10 G Ethernet Intel network cards (Intel X520) are used. DTRS runs FreeBSD 10.1 with ZFS. For data registration and recording, DTRS uses special software developed by IAA RAS. This software exploits the netmap framework for high-speed packet processing.

To solve the problem of efficient transfer of large amounts of data it is necessary to use modern high-speed protocols. It is important to avoid losses and errors during simultaneous data transfer and registration at 16 Gbps. Maximum utilization of the channel bandwidth is essential for broadband communications over the Internet. That can be provided by transmitting data with multiple streams. The implementation of the UDP protocol provides such an opportunity. A software package (server) includes an algorithm which adapts to channel capacity, which is essential in case of data transmission during simultaneous recording. Observation data from stations were transferred to the CPC via broadband channel over the Internet. During research we used 2 Gbps links to each station and a 4 Gbps link to the CPC at St. Petersburg. One-hour VLBI data transmission was carried out by four or eight UDT streams: four streams were used for simultaneous transfer and registration, and when the observations ended we switched to eight streams. Analysis of the experiment results shows that multi-threaded data transmission in a broadband communication channel provides the desired efficiency of data delivery to the CPC from stations.

5 Software Correlator

The six-station software corrrelator was developed and assembled by the end of 2014. The correlator is able to process VDIF data from up to six stations simultaneously at a maximum rate of 16 Gb/s from each station in a near-real time mode. Table 3 presents the main correlator specifications.

Table 3 Correlator specifications in near-real time mode.

Input data format	VDIF
Sampling	1/2 bit
VGOS station	up to six
Spectra channels	up to 4096
Input data stream	up to 16 Gb/s
Frequency bands	four
Polarization	1/2
Pcal tones	up to 32
Delay (RMS)	$<$ 10 ps

The main design feature is the use of graphical processing units (GPUs) for the main computations such as fringe stopping, bit repacking, Fourier transformation, spectra multiplication, and phase calibration signal extraction.

The correlator hardware is based on a hybrid blade server cluster. The present hardware contains 32 hybrid blade servers, which are inserted into seven chassis, and eight 19-inch cache servers. Each blade server contains two Intel CPUs, two Nvidia Tesla K20 GPUs, and 64 GB RAM. These servers are used for FX data processing algorithms (fringe stopping, FFT, and spectra multiplication) computing. The 19-inch servers also contain two CPUs, two GPUs, and 2x10 Gb fiber optic input, but the RAM is increased up to 256 GB. Each of them provides data reception, pcal extraction, delay tracking, and bit repacking. The 256 GB memory allows the VGOS data to be cached in response to any delays during data transmission. Data storage is based on the PANASAS system with a total capacity of 196 TB. The interblock data communication is provided by the infiniband network. Cluster components are mounted in a four rack unit. The air conditioning system is mounted in a three rack unit.

6 Observation Schedule for UT1 Estimations

Regular UT1–UTC sessions on the BADAR13M–ZELEN13M baseline were launched 4 Nov 2015. The 93 one-hour sessions were conducted in X/S band up to four times per day in November. A data stream of 4,096 Mbps was recorded for four-channel sessions, and 8,192 Mbps were recorded for eight-channel sessions (two polarizations). The bandwidth of each channel was 512 MHz. There are about 60 scans per hour in the November sessions. In late November we performed several experiments with scheduling parameter optimizations in order to increase the average number of scans per hour by two or more times. Test sessions with a six second minimum scan duration and disabled calibration were carried out and yielded 137 scans per hour. In subsequent sessions we set a ten-second minimum scan duration requirement and 15 dB minimum SNR. This mode yielded about 120 scans/hour, which allowed the generation of half-hour sessions while retaining the same number of scans per session. During the period from December 2015 to March 2016 the 145 half-hour sessions were carried out in two frequency channels (S and X) with 2,048 Mbps rate. Regular test observations in X/Ka bands started in Feb 2016. From February to March, 20 one-hour sessions were observed at the 2,048 Mbps rate in two frequency channels (X/Ka). Several tests were carried out with two X-channels with maximum spacing at 1.5 GHz.

7 Frequency Channel Setup

As one can see from above, VLBI observations with RT-13 were conducted using two, four, or eight BRAS frequency channels, corresponding to data streams of 2,048, 4,096, or 8,192 Mbps, respectively. Figure 2 shows a schematic arrangement of frequency channels in the S, X, and Ka bands. The rectangles with a gray (light) background show the boundaries of the operating ranges of the S, X, and Ka RT-13 receivers. The red (dark) rectangles show the actual frequency channel setup in different sessions. The scheme of the frequency channel setup for the RT-13 UT1–UTC sessions was:

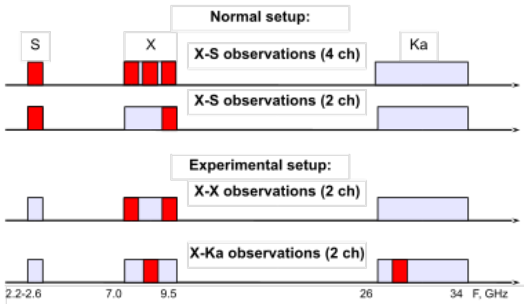

Fig. 2 Bands and channels.

- observation in November 2015 with one S channel (2,164–2,676 MHz) and three X channels (7,568–8,080 MHz, 8,080-8,592 MHz, and 8,592–9,104 MHz), with the three X channels forming a continuous channel strip and two polarizations doubling the channel set;
- observations from December 2015 to March 2016 with one S channel (2,164–2,676 MHz) and one X channel (8,592–9,104 MHz);
- experimental observations in X/Ka-band, in which the X channel was set to the frequency of 8,080–8,592 MHz and the Ka channel to 27,952–28,464 MHz;
- experimental observations in X-band with a maximum spacing of two frequency channels: 7,464–7,976 MHz and 8,964–9,476 MHz.

8 Session Features

When the single channel registration bandwidth is 512 MHz, the group delay accuracy from the correlator ranges from a few to tens of picoseconds in the single channel (depending on the scan length and brightness of the source). Thus at the picosecond level, the delay formal errors are apparently predominated by instrumental effects, and further enhancement of the formal precision at this stage is meaningless. Based on this, now we process observations in independent channels separately without wideband synthesis and consider different channels of observations as independent VLBI sessions. As a result, a one hour session with four channels gives us three independent determinations of universal time. Observations in the S channel were used to calibrate the ionospheric delay. In this case observations in two polarizations doubled the number of independent observations. In November 2015, in the presence of a 2 Gbps data channel to the observatories, one-hour sessions were conducted daily for four or eight channels. After processing each of those sessions, we obtained three to six independent estimations of UT1. From December to March the communication channel was decreased to average 0.2 Gbps, and we could only observe two half-hour sessions per day, with two frequency channels (one S + one X or one X + one Ka) and obtained only one UT1 estimation per session.

The data analysis was accomplished with the QUASAR software [5], and a set of seven parameters was estimated: the linear clock offset, a linear wet tropospheric zenith delay for each station, and the UT1–UTC correction.

9 Comparisons with IERS and IVS

In order to show the quality of the results, we calculated the differences of our UT1–UTC estimates and the IERS finals values. The results of the comparison are presented in Figure 3. Dark/blue points present the IVS-Intensive results on the WETTZELL–KOKEE baseline. Light/green points present the ZELEN13M–BADAR13M results during the same period. The one-hour S/X sessions held in November 2015 give us a WRMS of 21 µs when differenced with the IERS finals values. The WRMS of the differences to the half-hour sessions from December 2015 to March 2016 is 27 µs; the entire set's WRMS is 24 µs. The IVS-Intensive series from Nov 2015 to Mar 2016 has a 16 µs WRMS with respect to the IERS finals.

Comparison of the results for S-X and X-Ka observations are presented in Figure 4. Despite the fact that the X-Ka band pair looks more promising, at this moment the X-Ka estimations of UT1–UTC have a bit more scatter and worse formal errors. Apparently this is due to the usage of radio source S-X positions and the current lack of a catalog of good X-Ka positions.

10 For Further Investigations

Currently, with the brand new wideband VLBI, we encountered several problems, such as:

- When making a synthesis of a wide-wide band from several 512 MHz channels it was found that the

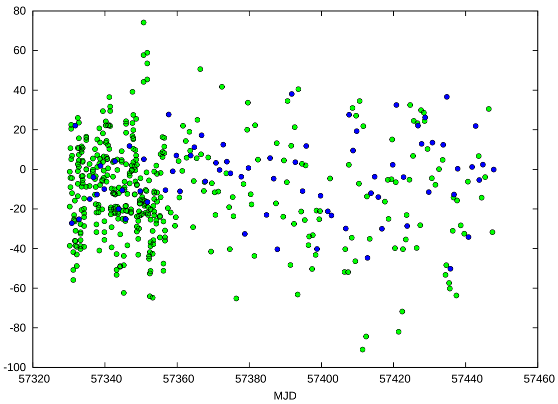

Fig. 3 Differences vs. IERS finals (light/green points are ZELEN13M–BADAR13M (S/X); dark/blue points are WETTZELL–KOKEE).

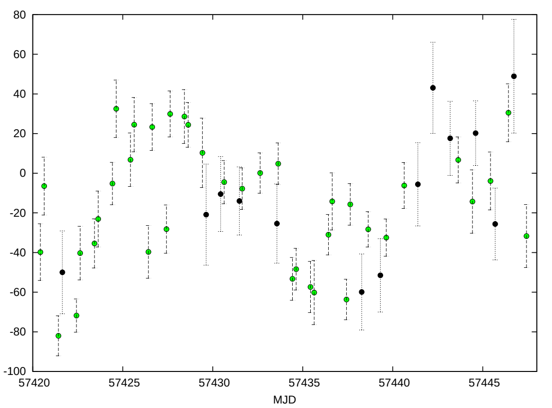

Fig. 4 Differences vs. IERS finals (light/green points are ZELEN13M–BADAR13M (S/X); dark/black points are ZELEN13M–BADAR13M (X/Ka)).

synthesized result is worse than the results for individual channels.

- In processing the observations in different frequency channels, the UT1 estimates obtained from different X band channels lies within units of microseconds, whereas the use of different S channel causes a shift in the results of several tens of microseconds.
- Some observations produce formal errors significantly less than 10 ps; often such observations significantly affect UT1 estimation due to their excessive weight.
- To obtain more accurate results in the prospective pair of X-Ka bands, we need to build an X-Ka version of ICRF.
- Joint processing of the new broadband with the old narrow-band observations is needed.

11 Conclusions

Since 2012, we have improved the accuracy of the national UT1 estimates from 60 to 20 microseconds. The accuracy obtained on small 13-m antennas is comparable to the accuracy of the IVS-Intensives, which is reached at 2.5 times less base. Our UT1 estimates are much more rapid than the standard IVS-Intensives; the delay between the beginning of the observations and the UT1–UTC result is about two to three hours. Currently, the IAA holds three sessions per day for the estimation of Universal Time (two half-hour sessions with the 13-m antennas and one one-hour session with the 32-m antennas). We encourage the IVS Analysis Centers to begin to use our observations in routine processing—it would significantly improve the quality of the IVS products, as IVS begins to provide UT1 four times per day and makes a step forward towards VGOS standards.

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