Overview of RASFX: IAA RAS VLBI Software Correlator

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Absract

The paper describes the implementation of the RASFX correlator based on Graphical Processing Unit (GPU). The main principles, hardware and software solutions for the quasi-real time VLBI data processing with up to 96 Gb/s data rate are described. RASFX is developed for geodetic VLBI observations processing and supported by IAA RAS. The RASFX software is designed to run on GPU-based High Performance Computing (HPC) cluster. At present, the RASFX correlator is mainly used to process local 1-hour broadband S/X sessions; approximately 8000 sessions have been processed. The paper presents a comparison of group delays from the RASFX correlator with group delays obtained from the DiFX correlator output using PIMA software. RASFX is also used in the laboratory and VLBI tests of receiving and recording equipment.

Keywords: RASFX, correlator, data processing, group delay, HPC.

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Received 20 January, 2020, accepted 15 May, 2020, published 30 December, 2020.

For citation: Ken V. O. Overview of RASFX: IAA RAS VLBI software correlator // Transactions of IAA RAS. 2020. Vol. 55. P. 41–44.

https://doi.org/10.32876/ApplAstron.55.41-44

Introduction

At present, the Quasar VLBI Network is equipped with (among others) RT-13 radio telescopes. By September 2018, these radio telescopes were built at the Badary, Zelenchukskaya, and Svetloe observatories [1]. The new RT-13 radio telescopes, which were developed based on VGOS recommendations, have better mechanical characteristics in comparison with the RT-32 telescopes (e. g. aiming speed, surface quality) and also impose some requirements on data processing and correlator design.

Firstly, data processing obtained with VGOS-compatible radio telescopes means that the data stream rate increases from 0.25–2 Gb/s (typical rate for RT-32 telescopes) up to 16 Gb/s because the output sample rate was raised in order to compensate for sensitivity loss. Secondly, the designed VGOS correlator should process more data not only from the Quasar VLBI Network stations but from other geodetic stations. As well as a result, it was necessary to design a new correlator that could process data from the new interferometer in quasi-real time.

The development of the RASFX correlator began in 2012; it was designed to be run on GPUs in high-performance computing (HPC) 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.

The RASFX software was developed using C/C++ and Fortran languages, MPI, CUDA, and QT libraries.

RASFX Correlator Specifications

RASFX is designed as based on all the requirements of VGOS-compatible broadband data processing, which also include the ability to process data recorded in circular and linear polarizations and calculate high-resolution spectra (we have tested processing with up to 128k spectral channels). The correlator includes the native VLBI delay model computing software, native postprocessing software (WOPS) and graphical user interface (GUI). Therefore, RASFX provides automated processing of VLBI observations: from the first stage of preparing the tasks from vex or skd session file to the final stage of obtaining group delays and group delay rates in the output NGS card file.

The main RASFX specifications are given in Table 1.

Table 1

Correlator specifications

Correlator type	Software, FX
Input data format	VDIF / VSI
Spectra data format	Baseline / FITS-IDI
Output data format	NGS
Sampling	1-, 2 bits
VGOS stations	up to 6
Input data stream per station	up to 16 Gb/s
Spectral resolution	4096

RASFX HPC Cluster

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, and power supply and cooling systems. The V200F blade server contains two Intel E5-2670 general purpose processors (eight cores, 2.6 GHz clock frequency), two NVIDIA Tesla K20 GPUs, and 64 GB RAM. The servers are connected to each other by an InfiniBand local area network based on Mellanox switches that allow simultaneous transmission at a speed of up to 56 Gb/s between any two clients. Each Intel R2216GZ4GCLX server has also two Intel E5-2670 processors, two NVIDIA Tesla K20 GPUs, and InfiniBand network ports. These servers are designed to receive input data streams (up to 16 Gbps) through two 10 Gb Ethernet ports and RAM expanded to 256 GB to keep up to 50 s input data stream. The computing system of the correlator contains 32 V200F blade servers and 8 Intel R2216GZ4GCLX servers (80 Intel processors and 80 GPUs in total) [2].

The cluster also includes the Panasas data storage of 190 TB capacity, 96 kW APC uninterruptible power supply system (UPS), and Stulz air conditioning system. Cluster server components are mounted on four cabinets. The air condition system is mounted on three cabinets. The UPS system is mounted on the ground floor. The picture of the RASFX cluster front view is shown in Fig. 1.

The parallel LINPACK benchmark ranked the performance of the RASFX cluster as 85.34 Tflops.

Fig 1. RASFX high-performance computing cluster

RASFX Design Ideas and Principles

RASFX is designed using main ideas of the DiFX2 correlator [3], except for a few important distinctions. The main distinctive feature is the software implementation of the most laborious computations such as the fast Fourier transformation (FFT), spectra multiplication, bit repacking, fractional sample correction, and phase calibration signal (PCal) extraction using GPUs. The second one is that all the interblock streams are transferred in a bit mode, and conversion into a float type is performed in the GPU memory only. This reduces the data transfer between the RASFX hardware modules considerably. The correlator software is also developed to be launched on a HPC cluster based on the hybrid blade server technology; each server should be equipped with NVidia GPUs.

The RASFX software topology is basically formed by a head module (HM), station modules (SM), correlation modules (CM), and wideband observation postprocessing system *WOPS*.

SM runs on a single server equipped with 256 GB RAM. The VDIF or Mark5B stream from each station goes into the data decoder, where the packing procedure is run in a separate thread. It packs the data that comes from different input streams into one single block which contains data from all the input frequency channels in a certain time interval. These samples are then deleted or duplicated in order to track the signal in accordance with the geocentric time scale. After the delay tracking procedure, the samples are separated back into channels. Finally, the per-channel blocks are sent to a CM. Simultaneously with the delay tracking PCal, extraction is done in another thread. All these operations can be performed in quasi-real time.

Each CM provides correlation processing for all the stations for one channel. It provides bit-to-float type transformation of the delay tracked data, fringe stopping, fractional sample correction, FFT and spectra multiplication operations. As a result, we obtain computed cross-correlation spectra. The total amount of CMs is chosen according to the required computing performance. When computation is completed, the computed data are copied to the HM.

The HM controls all the modules and obtains calculated spectra.

WOPS is the native postprocessing software of RASFX, which performs calculations of the group delays, group delay rates, their formal errors, and signal-to-noise ratios. *WOPS* produces the NGS card files from these data.

Benchmark Test

In order to test the correlator in the six-station quasi-real time mode, we used 40-s scans of the session which was carried out on the Badary–Zelenchukskaya baseline with the following setup: one frequency channel of 512 MHz bandwidth with 2-bit sampling and one circular polarization with 2 Gb/s data rate. Then these single frequency channel scans were multiplicated to get 8 frequency channel scans to simulate 6-station 4 frequency bands 2 polarizations mode, so as to make the input data stream rate from one station equal 16 Gb/s. These scans were copied directly into RAM to simulate an e-VLBI

Table 2

RASFX hardware requirements for quasi-real time processing in different modes

Stations	Number of Polarizations	Baselines	GPUs	Blades
2	1	3	8	4
2	2	10	14	7
3	1	6	10	5
3	2	21	22	11
4	1	10	14	7
4	2	36	27	14
5	1	15	16	8
5	2	55	41	21
6	1	21	22	11
6	2	78	55	28

mode, this way the data storage access lag was eliminated. Once the benchmark test was run, 78 spectra (cross- and auto-) with 4096 channels were obtained. The scan was processed in 42 s including initialization and memory allocation operations; 6 Intel servers and 28 V200F blade servers were involved in this test [4].

All possible combinations of processing with 16 Gb/s data streams of 4 frequency channels from each station and 4096 FFT channels mode are shown in Table 2. In the most laborious cases, 28 V200F blades are needed to process the data in a quasi-real time mode.

The DiFX correlator (version 2.4.1) is also installed on the same HPC cluster. In addition to routine processing, we use DiFX to compare its processing performance with RASFX in several modes. For instance, the aforementioned e-VLBI simulation technique was used in “2 stations 4 channels”, “2 stations 8 channels”, and “6 stations 4 channels” modes with the data rates of 16, 32, and 96 Gb/s, respectively. In the first mode, we achieved quasi-real time processing with 95 CPU cores which are equivalent to 7 V200F blades. In the second mode, we obtained performance saturation (increasing the number of cores did not boost the processing) with 180 cores (12 blades) and 1.45:1 ratio to quasi-real time. The most laborious mode was performed with 280 cores (19 blades) and 2.6:1 time ratio. The only explanation for the saturation observed is limitations of the InfiniBand network, because the DiFX operates with float type data during interblocks exchange. It appears that multi-station processing using DiFX at high rate requires different InfiniBand facilities.

Comparison of Geodetic Processing Results

Because DiFX and RASFX are mainly used for UT1-UTC measurements at IAA RAS, we searched for the origin of the UT1-UTC differences and found that they are mainly due to different realization of mathematical computations of the postprocessing algorithms. In addition to using DiFX for benchmark tests, we compared calculated group delays using common software, namely, PIMA [5]. PIMA is a dedicated multi-purpose postprocessing software suite which accepts FITS-IDI files and makes calculations of various parameters including the group delays and rates, their formal errors, signal-to-noise ratios, and many others. In order to compare the two correlators, we developed a *pima2ngs* data converter to produce NGS card file from the plain text PIMA database files [6].

A series of intensive sessions for UT1-UTC determination with RT-13 and RT-32 radio telescopes were processed using this routine. RT-13 sessions were done on 07.09.2018–26.09.2018 in five 1-hour sessions per day with S-band channel in right and left circular polarization (RCP and LCP) and two X-band channels in RCP only. RT-32 sessions were done daily on 16.08.2018–02.09.2018 in the legacy geodetic mode. These sessions were processed with both correlators; postprocessing procedures were performed with PIMA. So, we obtained the group delays of the 18 RT-32 sessions and 97 RT-13 sessions. Afterwards, systematic shifts resulting from the use of different models were calculated and taken into account for the series of the obtained delays. The residual RMS of group delays differences did not exceed 10 ps for RT-32 sessions and 15.4 ps for RT-13 sessions.

The results obtained are in good agreement with the mean accuracy of group delay: at least 95.5 % and 90.3 % of the calculated group delays coincided for RT-32 and RT-13, respectively [7].

Non-Routine Processing

RASFX is also used for determination of instrumental errors of the receiving and recording equipment of the RT-13, which affect the accuracy of the UT calculation.

In the last years, we assembled a laboratory prototype of a radio interferometer with zero-baseline [8], which consisted of two tri-band (S, X, and Ka) or ultra-wideband (3–16 GHz) heterodyne type receivers [9], broadband (512 MHz) data acquisition system (as a backend unit) and RASFX. We conducted more than 200 laboratory sessions (the scan duration varied from 10 s to 60 min) to determine the delay stability of the radio interferometer model, and we found that the deviation of group delay RMS from theoretical values did not exceed 2 ps, while the RMS absolute value for the X-band $\sigma_\tau \sigma_\tau$ was 6.9 ps.

We then ran a series of real VLBI-sessions of 1-hour scan duration with tri-band receivers. These sessions proved our laboratory result of 2 ps and allowed us to determine the flicker noise caused by frontend and backend delay instability. The noise prevails after the observation time of approximately 50 s and limits the final RMS delay [10].

Conclusions

The RASFX software VLBI GPU-based correlator, which can process signals with data streams as high as 16 Gb/s from up to 6 VGOS-compatible stations in quasi-real time mode, was developed by IAA RAS in 2014. About 8000 sessions had been processed by January, 2020. RASFX also processed several hundreds of quasi-VLBI test sessions. In the near future, we are going to move forward with spacecraft signal data processing, asteroids processing with radar observations in VLBI mode, and pulsars processing (including development of a pulsar-based timescale), and make further comparisons with other correlators.

Acknowledgements

The author is grateful to his colleagues Igor Surkis, Alexey Melnikov, Yana Kurdubova, Vladimir Mishin, Nadezhda Mishina, Dmitry Pavlov, Violetta Shantyr, Yuriy Vekshin and others for their help with cooperative RASFX development, improvements, testing, and processing and in many aspects of life and science.

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