# Advances in VLBI observations and data processing with automatic e-VLBI system in VIRAC

Karina Krinkele*, Normunds Jekabsons, Ivars Smelds

Engineering Research Institute "Ventspils International Radio Astronomy Centre", Ventspils University College, Inzenieru 101a, LV-3600 Ventspils, Latvia
E-mail:karina.krinkele@venta.lv
*Corresponding author

**Abstract.** Engineering Research Institute "Ventspils International Radio Astronomy Centre" of Ventspils University College (VIRAC) participates in several Very Long Baseline Interferometry (VLBI) observations with a radio telescope RT-32. VIRAC, Joint Institute for VLBI in Europe (JIVE), Onsala Space Observatory (OSO), Poznan Super Computing and Networking centre (PSNC) participate in EU funded FP7 project NEXPReS (Novel EXplorations Pushing Robust e-VLBI Services) workpackage No.7 (Computing in a Shared Infrastructure) with the main goal - to develop and implement a distributed version of software correlation and other e-VLBI (electronic VLBI) components in order to automate VLBI observations, data workflow and data processing. Automatic transfer and correlation system for single-dish RT-32 observations is deployed and implemented at VIRAC.

## 1 Introduction

VLBI [4] is a method to observe astronomical objects (such as pulsars, quasars, black holes, etc.) with multiple radio telescopes simultaneously. In such a way VLBI emulates a telescope with an aperture that has a size comparable to the maximum separation between the individual telescopes, sometimes reaching 1000 km and more. As a consequence, VLBI is one of the most accurate methods of astronomical observations.

Already thirty years EVN (European VLBI network) performs high angular resolution observations of cosmic radio sources. The EVN is a large scale astronomical facility that is open to astronomers from all over Europe and the rest of the world. More than 25 radio telescopes in Eastern and Western Europe (included VIRAC), Russia, China and South Africa participate in EVN observations. Data processing centre in JIVE takes care of data processing of the bulk of EVN data. Specially designed hardware - the EVN MkIV correlator, still is a main data processor there, although it is about to be replaced by the SFXC software correlator now. Most data from radio telescopes are shipped to the correlator on physical media (disk packs). Data transfers – shiping the disks – and correlation take at least two weeks and there are no opportunity to create real-time correlation. Nowadays, often data are sent to the correlator via internet so the real time processing is possible, therefore an astronomer can control and monitor an entire observation session. This method is called an e-VLBI or electronic very long baseline interferometry. In e-VLBI observation, data are sent to correlation centre and results are sent back to an astronomer during the session. In order to fulfill e-VLBI goal - real time data processing – SFXC correlator has to be executed on a high performance computer cluster, using parallel programming technologies based on Message Passing Interface (MPI). SFXC also gives an opportunity to create a distributed correlation on separate EVN clusters. e-VLBI main advantage is – to allow to control and monitor VLBI observation in real time. To make this easier there is an opportunity to automate the e-VLBI processes by using developed software components.

## 2 VLBI basics

Radio interferometry is an accurate method to establish small set of physical changes. Method is based on the measurement of path difference of approaching electromagnetic wave fronts, which can be established by cross-correlation between two received distant signals from the same source. VLBI method is used for both - far objects of visible Universe (pulsars, quasars, masers, black holes, etc.) and near field objects like cosmic apparatus inside the Solar system. The data processing is different at each observation type.

The basic elements of a two-element interferometer are shown in Figure 1.

The two-element interferometry consists from two distant radio telescopes observing radio source of interest simultaneously. Both radio telescopes emulate a telescope with size $D$ which is equal to separation between telescopes called baseline. Angular resolution of emulated telescope can be estimated as: $R \approx \frac{\lambda}{D}$ where $R$ is an angular resolution, $D$ is a diameter of emulated telescope and $\lambda$ is wavelength. So, as larger is baseline, as better is angular resolution.

Electromagnetic radiation reaches both radio telescope receivers at different time moments, thus time delay compensation $\tau$ between telescopes is required: $\tau = \frac{\mathbf{b} \cdot \mathbf{s}}{c}$, where $\mathbf{s}$ is unit vector pointing to the radio source, $c = 299782458 (\mathrm{m/s})$ is the speed of light and $\mathbf{b}$ is the baseline vector [6].

Let's take a look on two signals: $g(t+\tau)$ and $h(t)$ received by respective pair of radio telescopes. The cross-correlation of both signals: $\Gamma(h(t), g(t+\tau))$ is defined as

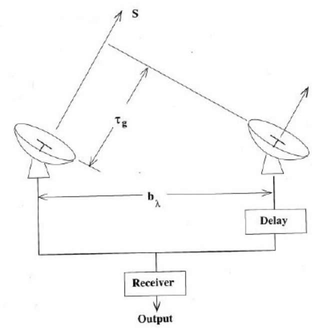


**Fig. 1.** An interferometer scheme with two radio telescopes: $b_\lambda$ - base line, S - signal of radio source, $\tau$ - geometric time delay [4]

$$\Gamma(h(t), g(t+\tau)) = \int h^*(t) g(t+\tau) d\tau,$$

where $f^*$ denotes the complex conjugate of $f$ [2]. For efficient computation of correlation function the correlation theorem [10] is used. Thus, cross-product of Fourier transformed signals is constructed in the frequency domain. Inverse transform yields $\Gamma$ in the time domain. When Fast Fourier Transformation (FFT) is employed overall algorithmic complexity reduces to $O(N \log(N))$.

There is an explicit maximum of correlation function by respect to the time delay $\tau$, $\tau_m$, related to the wave front path difference $\mathbf{b} \cdot \mathbf{s} = c\tau_m$. With the aid of

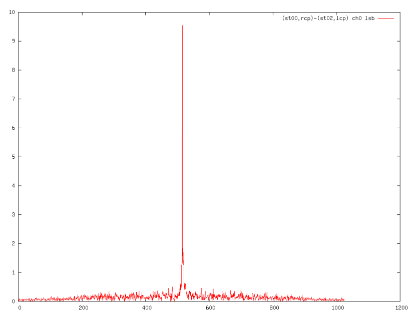


**Fig. 2.** Fringe function - correlation between Irbene RT-32 radio telescope and Torun radio telescope, April 12, 2012

simple trigonometric conversations so called fringe function [2] (see at Figure 2.) can be constructed. Fringe function is the main factor, which will make immediately clear whether a source is detected or not on a particular baseline between two telescopes. If no fringe is detected, this is a sure sign that there is a problem at one of the telescopes. By looking at multiple baselines that include one of these telescopes it is possible to narrow down the problematic telescope. Theoretically three VLBI stations are required to measure both celestial angles, however in practice more stations are needed for cancellation of numerous measurement errors and to produce the detailed radio map of object observed.

## 3 Automatic e-VLBI system and it components at VIRAC site

There are advances in e-VLBI system and VLBI data processing at VIRAC. The notable components of e-VLBI system are: Translation Nodes (location - radio telescope RT32), distributed software FX correlator (SFXC, location at VIRAC HPC), VLBI Broker, and WorkFlow manager (both - software modules, located at separate servers), see Figure 3. Lets focus on more detail description of these.

### 3.1 Radiotelescopes

Radiotelescopes - a single-dish radio telescope consists of a parabolic reflector which focuses incoming radio frequency energy on to a receiver/detector [9]. Two radio telescopes - RT-16 and RT-32 (16 and 32 meter diameters respectively) are located at VIRAC Irbene site. Two kinds of observation sessions were carried out with RT-32 - observations of rather far objects (quasars, pulsars) and near Earth objects (notably satellites and space debris). Observed signal from radio telescope is amplified, filtered, sampled, digitally split into frequency bands/channels. Sampled data are recorded on disk packs in special VLBI data format MARK5B [11].

### 3.2 Translation Node

Translation Node (TN) – e-VLBI software module is responsible for handling data from radio telescopes, preparing data for correlation and set up observed data distribution over GridFTP protocol or via SCP. Here is the list of TN related operations:

– before the experiment starts, a radio astronomer defines the data flow from the radio telescopes to the distributed software correlator;

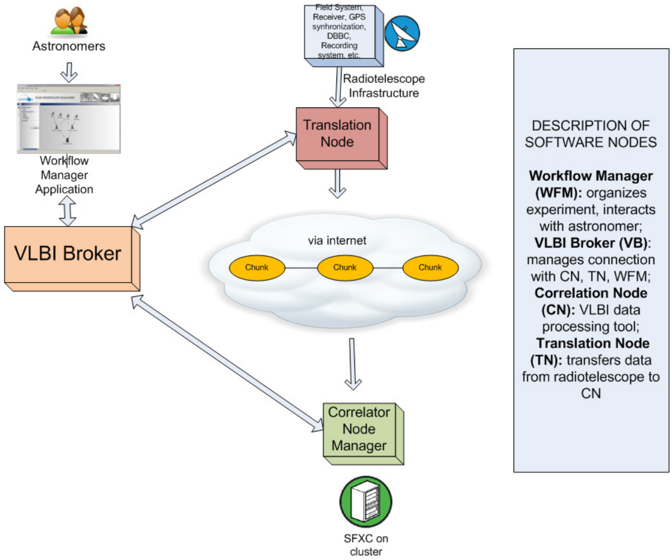


**Fig. 3.** An automatic e-VLBI scheme at VIRAC

– each TN is informed about the new experiment;
– TN splits received data into the packets and sets up data transfer connections to the distributed correlator nodes;
– number of data packets are sent from radio telescope to the correlator;
– after acknowledgement of successful correlation from the distributed correlator TN deletes all data processed. If there is an error, TN re-sends non-correlated data to CN again.

### 3.3 VLBI broker

VLBI Broker (VB) is the glue element of the e-VLBI System. It provides the automated control of the entire experiment. The plan of the experiment as a bundle of ASCII files of different formats has to be submitted by the radio astronomer before the observation starts. VB is responsible for coordination of tasks on Correlation and Translation Nodes.

Description of VB operations:

– a radio astronomer informs VB about the new experiment;
– VB manages communication with radio telescope (TN) and computational resource (CNM);

– VB gets status information from CNM and represents them.

### 3.4 Correlation Node at VIRAC site

Each computational resource represents a separate, independent distributed software correlator module called Correlation Node (CN) which can be used to correlate VLBI data.

Three main components are responsible of VLBI data processing at VIRAC site:

**HPC in VIRAC**. VLBI data processing or correlation is time and resource consuming process and there is requirement of high performance computing (HPC). Until now there is one cluster in VIRAC with following parameters: 30 nodes each with 2 CPU x 2Cores Intel(R) Xeon(R) CPU 5160 @ 3.00GHz (summary 4 cores per node), 4GB ram per diskless node. For calculation nodes there are Debian Linux, shared NFS, rsh infrastructure, gigabit ethernet. For master node there are Debian Linux OS, Single master node with SATA disks, provides NFS and boottp services to 30 calculation nodes. Cluster has two gateways - external to internet and internal to organization network. Open MPI (Message Passing Interface) deployment allows communications between cluster nodes.

**Data processing tool - SFXC**. During the EU funded FP6 project EXPReS (Express Production Real-time e-VLBI Service) observational data processing tool called software FX correlator (SFXC) was deployed by JIVE. SFXC is adapted in VIRAC HPC and on the moment it is in test mode. As on today implemented SFXC does not support live data streaming which leads to quasi-real-time processing, however in the near future data will be streamed directly to the processing centre. SFXC is developed using programming language C++ and it supports cross-correlation (the correlation of a signal from one radio telescope with a signal from another radio telescope) and autocorrelation (the cross-correlation of a signal with itself). Correlation on SFXC requires two main files - JSON file with correlation parameters (channel numbers, reference station, integration time, correlation start time and end time, etc.) and VEX or VLBI experiment file with experiment parameters (channel frequency, bit stream, tracks, session start time and end time, etc). SFXC is capable to process MARK5A/B [11] and VDIF [12] data formats of VLBI data. Each frequency band of data can be processed independently of the other frequency bands, data can be processed in parallel using parallel programming technologies based on MPI.

**Correlation Node manager (CNM)** is responsible for managing and executing correlator (adapted for SFXC) jobs on the HPC cluster at VIRAC. CNM starts and stops the correlator on computer facilities, gets the correlation status information from the correlator and sends it back to a radio astronomer after

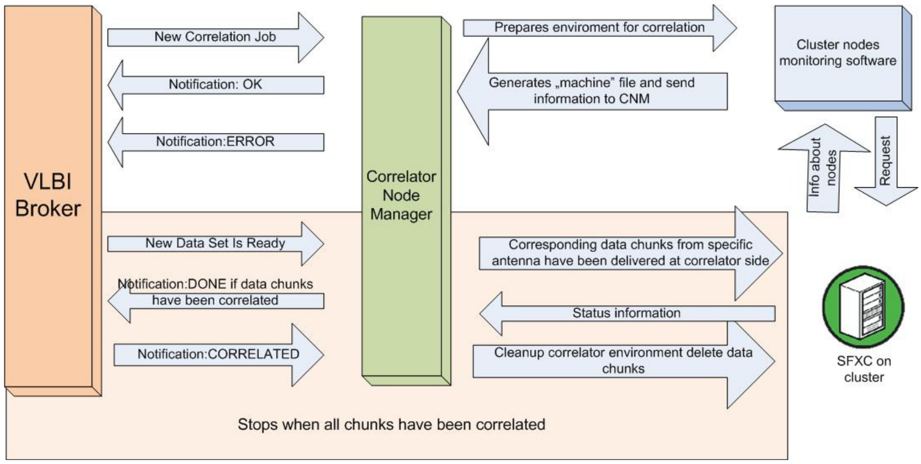


**Fig. 4.** An algorithm of Correlation Node at VIRAC site

data processing. CNM module is deployed using object-oriented programming language JAVA, a C programming language, an open source web server Apache Tomcat and a core engine for Web services - Apache Axis2 technologies. After VLBI broker request CNM prepares cluster environments for correlations and calls cluster node monitoring utility developed by VIRAC. The above mentioned utility gets information of capacity of all cluster nodes and generates file with list of active tasks on nodes and task users. Utility also generates MPI parameter file for SFXC processes. Radio telescope data have been delivered to correlation side. During correlation, status information is prepared and sent to an astronomer. At the end, CNM sends correlated results to an archive and deletes raw data.

### 3.5 Workflow Manager

The Workflow Manager (WFM) is a GUI (graphical user interface) software, which has been created to allow radio astronomer to design and execute an observation workflows easily. WFM is like a "translator" between radio astronomer and automatic e-VLBI system.

The main steps to start new experiment are - to create an experiment description (VEX file) using the SCHED application, to set an experiment control parameters, to set all resource elements (TNs and CNs) and to inform VB about the new experiment with all necessary parameters. The first version of the WFM was deployed as a stand-alone Java application at PSNC during the EU funded

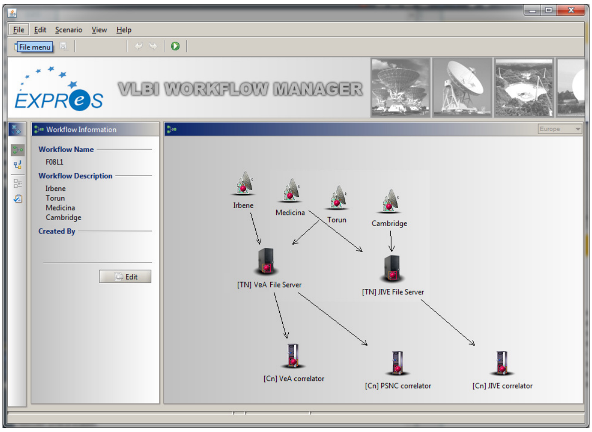


**Fig. 5.** An example of the Workflow manager usage

FP6 Project "EXPReS". VIRAC and PSNC are developing the new WFM based on open source web platform Liferay.

### 3.6 Summary

To develop automatic e-VLBI system IT specialists are working together with astronomers and an implementation of e-VLBI system in EVN is under way. High performance computing elements such as +10 Gb/s internet, cluster computing, etc. are mandatory for advancing e - VLBI technologies. An automatic e-VLBI system for single dish RT-32 observations at VIRAC is developed and implemented. Together with other NEXPReS participants, VIRAC are working on a full e-VLBI system (which allows real-time correlation on several distributed correlation nodes) development and implementation at EVN.

## 4 ACKNOWLEDGMENTS

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