Article

The *RadioAstron* dedicated DiFX distribution

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Abstract: DiFX is a software VLBI correlator currently adopted by several main correlation sites around the globe. After the launch of the RadioAstron Space-VLBI mission in 2011, an extension was necessary to handle processing of an orbiting antenna, to be correlated with supporting ground arrays. We present here a branch of the main DiFX distribution (2.4), recently uploaded on the publicly available repository, that MPIfR developed to process data of the three AGN-imaging RadioAstron key science projects. It can account for general relativistic correction of an orbiting antenna with variable position/velocity, providing a routine to covert the native RDF format to the more common M5B one. Also, a fringe-finding algorithm able to manage arbitrary large fringe-search window is included, allowing one to increase the search space normally adopted by common software packages like HOPS.

Keywords: VLBI; Space-VLBI; Correlation; RadioAstron; AGN

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1. Introduction

The Distributed FX-architecture (DiFX) software correlator has been first introduced in 2007 [2] to offer a versatile alternative to the previous generation hardware correlators. Designed to run on computer clusters, it was initially adopted by Swinburne University (Australia) for the Long Baseline Array (LBA) correlation. Subsequently, it was installed also at the National Radio Astronomy Observatory (NRAO, USA), as well as by single users. Indeed, due to the exponential improvement of computing facilities, DiFX can now be run also on a single powerful machine, given a modest volume of input data. In 2011, a second version was made available to the community (DiFX-2, [3]), including a number of improvements and new utilities, including multiple phase-centers correlation in a single pass, phase-calibration tones extraction for geodetic applications, zoom-mode for correlation of disparate but overlapping sub-bands, full support for VDIF data format, arbitrary-order polynomial clock, and many more.

The *RadioAstron* space radio telescope has been launched in July 2011 by the Russian space agency (Roscosmos) and it is led by Astro Space Center (ASC, Moscow). It is a 10-meters single dish, mounted onboard the *Spekt-R* satellite, and able to perform interferometry observations with ground arrays of radio telescopes [5]. It can reach extreme baselines of ∼25 Earth diameters, thanks to an elliptical orbit with an apogee of ∼330.000 km - almost the distance between Earth and the Moon. For the first time since the *VSOP* mission in the '90s, a space-VLBI mission required correlation with ground antennas, thus implying a number of complication given by an orbiting (moving) telescope, under the influence of both Earth and Moon gravitational fields. As a contribution to the mission, the Max Planck Institute for Radio Astronomy (MPIfR) developed a dedicated version of the DiFX, named *ra*-DiFX, implementing the code necessary to deal with RadioAstron [1]. It is now running on the MPIfR cluster, and used to process data from three Key Science Projects (KSPs) aiming at imaging AGN jets at the highest angular resolution possible from space. With this paper, we present the second, improved version of this publicly-available software, branched from DiFX 2.4 in September 2015.

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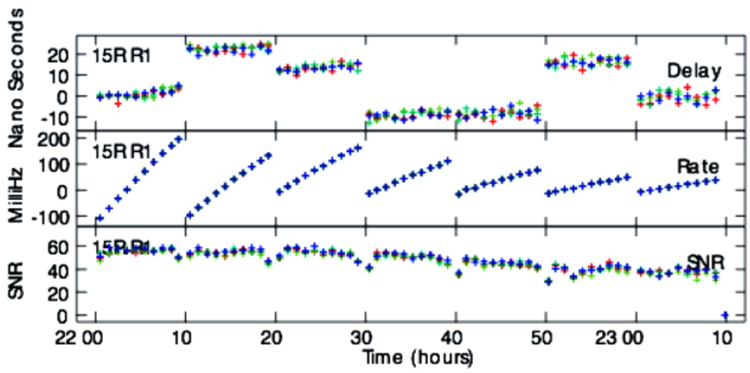

Figure 1. Example of residual acceleration terms for *RadioAstron*, visible as a steepening of the fringe-rate solutions near to perigee (towards left-side of the timeline).

2. The RadioAstron DiFX distribution

As described in [1], the *ra*-DiFX implements since the first version additional code that allows to handle an antenna with an arbitrary position and velocity in time, but still these modification do not involve the main algorithm used for data correlation of ground antennas by DiFX. Indeed, mainly the delay model server (Calc, from the Calc/Solve package[1]) was modified, in order to take into account the orbit, and general relativistic corrections due to Earth and Moon gravitational fields. Also, the DiFX metadata system was modified to deal with the changing position and velocity of the spacecraft as a function of time.

In the following, a list of the modification and capabilities already present in the first branch is given:

- Implementing RDF-Mark5B conversion routine, to read in data from the *RadioAstron* spaceborne antenna
- Enabling delay model server Calc (Calc/Solve Package) to calculate delay information for a spaceborne antenna
- Introducing general relativistic corrections in the delay model
- Changing DiFX metadata system to deal with variable position/velocity of the spaceborne antenna
- Calculating the delay for the transmission of the signal from the spacecraft to the tracking station
- Calculating the equivalent of parallactic angle correction for the spaceborne antenna from the antenna orientation obtained from the telemetry information.
- Enabling the use of wide fringe-search windows, thanks to the customized fringe-fitting software.

The main motivation to produce a second branch was to include all the DiFX enhancements introduced since 2010, thus improving the efficiency of the KSPs data processing. Full VDIF compatibility is now available, and moreover the possibility to introduce a polynomial clock allows to mitigate the residual fringe rate due to acceleration terms of the spacecraft, specially important for near-perigee observations like the AGN-imaging projects. In Figure 1, an example of this effect is visible from AIPS plots as a steepening of the rate solutions towards the beginning of the experiment, where *RadioAstron* approaches the perigee (AO-1 observations of BL Lac from the AGN Polarization KSP, [4]). While the applied calibration in AIPS could compensate for this effect, a strong SNR is necessary to obtain solutions close enough in time to properly fit the trend. This could not be the case for faint sources, for which baseline stacking in the data-reduction stage is needed,resulting in a loss of signal. Thus, the polynomial clock of this new version of *ra*-DiFX can help in recovering signal by

[1] http://gemini.gsfc.nasa.gov/solve/

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properly setting the correlation window across the experiment, following the spacecraft delay/rate trend in time.

The *ra*-DiFX software correlator is regularly used at the MPIfR to correlate RadioAstron KSP projects. Since July 2016, it is also publicly available on the DiFX repository[2], for download and use under the GPL license.

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Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
AGN: Active Galactic Nuclei
DiFX: Distributed FX
M5B: Mark5 B
MDPI: Multidisciplinary Digital Publishing Institute
MPIfR: Max-Planck Institut für Radioastronomie
RDF: RadioAstron Data Format
VLBI: Very Long Baseline Interferometry

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