Geodetic Capabilities at the JIVE SFXC Correlator

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Abstract We are implementing geodetic capabilities for the EVN SFXC correlator at JIVE, as part of the EC H2020 JUMPING JIVE project (JJ WP6). The correlator is now capable of processing complex geodetic-like schedules with many subarrays. Moreover, SFXC output is converted into Mk4 format, that includes the correlator model ("totals") and measures phase-cal values. Tests are being performed at JIVE to process geodetic VLBI data, with the main goal of improving the accuracy with which positions of non-IVS EVN stations are known.

Keywords Correlation, legacy S/X, VGOS

1 Introduction

Astronomers typically use the European VLBI Network (EVN) for self-calibrated or phase-referenced imaging, or for phase-referenced relative astrometry, and the VLBI processors at the Joint Institute for VLBI ERIC (JIVE) were developed with these priorities in mind. The data produced by the EVN software correlator at JIVE (SFXC) now contain visibility phases residual to the a priori correlator model (based on CALC10). The correlator model, although it can be linked to the output visibilities, has not yet been included in the files that the astronomer receives. The few EVN experiments that have conducted absolute astrometry have usually been correlated up to now at the MPIfR/BKG correlator in Bonn.

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The EVN also contains some telescopes that are not able to participate in standard IVS programs due to a lack of S/X receivers. There were two experiments that were able to estimate positions for these stations from single-band observations:

- TP001: A dedicated geodesy-like C-band experiment (23–24 November 2000) including Torun, JodrellBand_Mark2, Westerbork_RT7, and Onsala_85$'$, plus other EVN telescopes that have regularly participated in geodetic programs (Charlot et al., 2001; 2002). The estimates of the positions of these antennas in ITRF2000 derived from TP001, plus station velocities computed in NNR-NUVEL-1A (DeMetz et al., 1994), were included in the NRAO `sched` station location catalog. Positions for the MERLIN out-stations were derived from the Jb_Mark2 position via baseline solutions from the MERLIN correlator. At the time, there was a desire to repeat such an observation at K-band once Torun obtained a receiver (Tr participated in K-band sessions starting in February 2013).
- EP066: A K-band experiment (27–29 October 2009) underlying the EVN Galactic Plane Survey (Petrov 2012). It also provided a more precise estimate for the Jb_Mark2 antenna, at the time the only of the above telescopes with K-band capability. (The TP001 position carried forward with the modeled station velocity was consistent at the 1–2σ level.)

A preliminary assessment of the astrometric quality of SFXC was carried out by L. Petrov and the JIVE staff in the summer of 2015. Four stations from R1680 were re-correlated, and the combination of the standard residual visibilities plus the correlator-model "de-

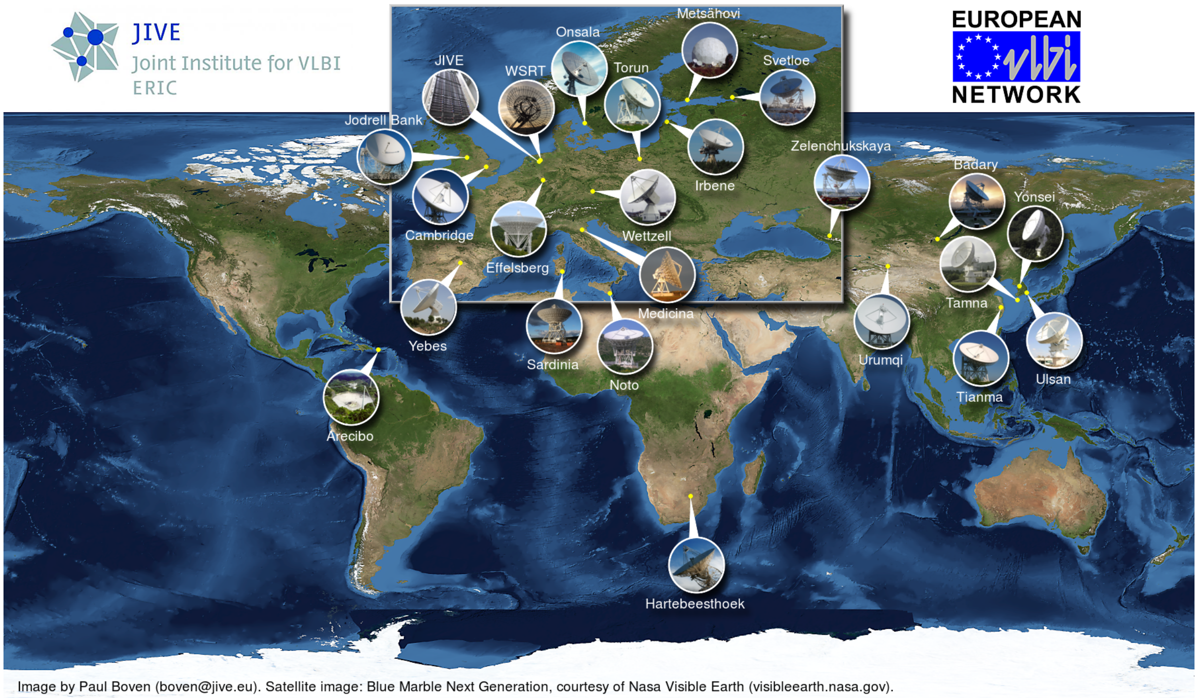

Fig. 1 The European VLBI Network (EVN) and JIVE.

lay files" was compared to the original IVS geodetic correlation. The success of this comparison motivated the pursuit of ways to incorporate model information into SFXC output in a manner that users could directly accommodate.

2 JUMPING JIVE Design & Progress

JIVE and collaborators are involved in the EC H2020-INFRADEV-2016-1 project "JUMPING JIVE" (see `http://jumping.jive.eu`), in which Work Package 6 focuses on developing geodetic capabilities for SFXC. It comprises three tasks:

1. Provide the ability to process sub-netted schedules.
2. Attach the correlator model and phase-cal information directly into the correlator output.
3. Conduct a K-band geodetic-style experiment to provide a new estimate of station positions for non-geodetic EVN telescopes—as a result of such an experiment some telescopes would obtain an empirical station velocity estimate (Jb_Mark2, Torun) and some would obtain their first position estimated directly from VLBI (e-MERLIN out-stations). There are also some telescopes that do not appear in standard global station-location catalogs (Sardinia, KVN). This experiment would provide an end-to-end test of the new geodetic capabilities. Use of K-band does preclude participation of the EVN telescopes Westerbork, Irbene, and Kunming.

The first task has already been accomplished. Since SFXC was designed for astronomy, one of the underlying assumptions in its control system was that time-range suffices as the identifier of what data to accept from the assembled telescopes to treat as a scan. This leads to ambiguity if there are multiple scans at any given time, as can be the case with sub-netting. JIVE added an optional scan label into the control file that drives SFXC, which, if present, would break any such ambiguity by allowing look-ups that pertain to the subset of telescopes involved in the specified scan and to a sub-interval within the requested time-range for each individual telescope. JIVE also modified "runjob", the GUI interface that sits between the correlator operators and SFXC, to always provide such a label in the control files it generates, consistent with the scans selected by the operators for correlation within a job. Testing these modifications again used data from R1680, comparing correlations run with the original SFXC system after removing the sub-netting from the schedule manually (i.e., splitting the schedule into two non-sub-netted parts, and correlating each separately; for an example see Figure 2) against those run with the modified SFXC system in a single pass using the original sub-netted schedule. The new system produced the same net correlator output as did the union of the two passes of the original system (i.e., nothing missing or extraneous), with consistent values for the complex visibilities in both. (Note that the correlation of R1680 used for the preliminary assessment discussed above followed the manual de-sub-netting route.)

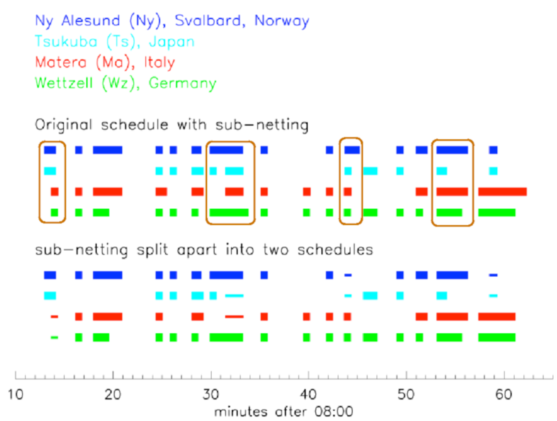

Fig. 2 Schematic of scans over one hour in R1680. Scans with sub-netting among the four antennas in the original schedule are circled in brown (top half). The width of the time-ranges per station in the bottom half denote which station/scans were split off into a separate schedule to remove sub-netting to allow correlation in the original system (thin bars split off).

Within the second task, CNRS/Bordeaux and JIVE decided on mark4 as the file format to pursue initially to allow processing of the data with the Haystack Observatory Processing System (HOPS) software. JIVE has designed and implemented programs to create and populate the mark4-file format output with visibilities from SFXC and the appropriate correlator-model information. The correlator model used by SFXC interpolates the delays computed with one-second sampling from CALC10 via Akima splines. The model is translated into the representation supported in the mark4 data format by fitting a fifth order polynomial to the

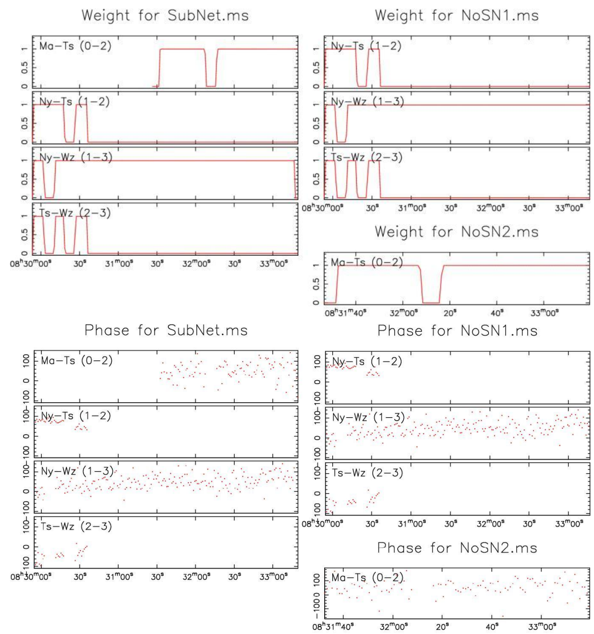

Fig. 3 Weight (top) and phase (bottom) as a function of time for an instance of sub-netting, with panels from the single-pass run in the new system to the left, and the two-pass, de-sub-netted run in the original system to the right.

results from evaluating the Akima splines at regular intervals. The difference between these two models is smaller than $1 \cdot 10^{-15} s$ at any point within an accumulation period. Phase-cal information, used to align phases in the various observed sub-bands to estimate meaningful multi-band delays without a separate fringing step, is also now included (standard astronomical analysis does not use these). Initial testing at JIVE has successfully loaded the resulting mark4-format data into HOPS and compared results to correlations of the same data run through the DiFX correlator. (The path to include model-related information in FITS-IDI tables, as had been done by the VLBA hardware correlator, is not being pursued at this time, although it is not ruled out for the future.)

The geodetic-style EVN experiment forming the basis of the third task has been proposed and observed (EC065; 13–14 June 2018). During the course of preparing the observing schedule, some limitations in the sub-band tunability were uncovered in the e-MERLIN out-stations (two sub-bands of 64 MHz, such that the separation between them is a multiple of 64 MHz) and KVN stations (limited to separations of integral steps of the combined LSB+USB

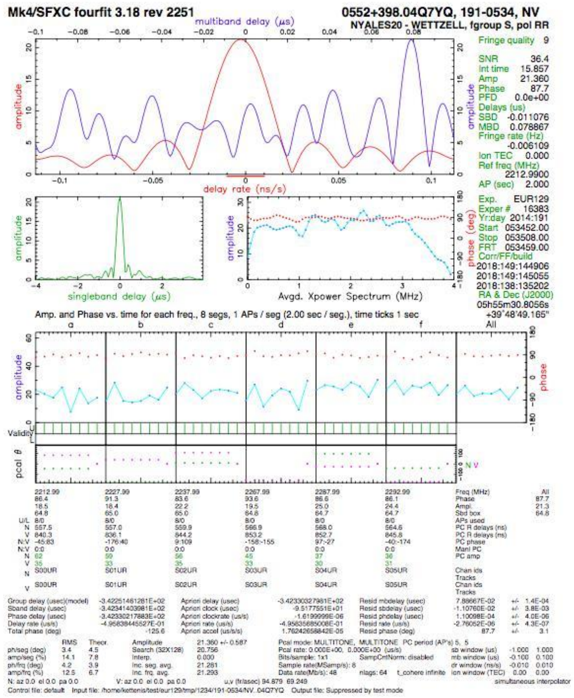

Fig. 4 HOPS fourfit plot of a scan from geodetic observation EUR129 re-correlated with SFXC.

bandwidth), which affected the freedom to sculpt the delay-response function. Initial feedback from the stations suggests that only one KVN telescope was able to participate, and Tianma/Urumqi were both unable to join because of Chang-E4 obligations. High winds may have affected pointing at the UK telescopes (Jb_Mark2, four e-MERLIN out-stations).

3 Future Prospects

A validated path for SFXC to provide "totals" in its output data in a standard fashion would lower the threshold to EVN experiments pursuing absolute astrometry choosing to correlate at JIVE. For such purpose, providing the correlator model in the default FITS-IDI output would be essential. Since the representation of the correlator model is very similar to the representation used in the mark4 data format, providing this information should be relatively easy. An approach to attach the required tables using the Python PyFITS module is being considered. This approach has been used sucessfully to attach system temperature measurements and weather information to FITS-IDI files.

Future broadband data, in VGOS or in astronomical observations, will have to properly estimate the ionospheric contribution. Current developments in radio astronomy (such as "RINGS", WP7 in EC H2020 project RADIONET, see `https://www.radionet-org.eu`) provide interesting synergies that should be explored.

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