

Recent Results from the EVN Mk IV Data Processor at JIVE

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We review the capabilities of the EVN Mark IV Data Processor at JIVE in terms of both spectral and output capacity. We then move on to operational issues for EVN/global astronomy experiments — how the various stages of your experiments unfold, and the kinds of assistance available at each turn. Links are provided to the principal on-line facilities (*e.g.*, the EVN Users' Guide, Proposal Tool, calculator, Archive, pipeline). We end with a brief glimpse at selected new capabilities: including multiple MERLIN out-stations in the EVN correlation, and software correlation at JIVE in use for ftp fringe tests during NMEs.

Real-time e-VLBI correlation is not explicitly addressed in this paper (see Szomoru, these proceedings), other to mention the operational differences between e-VLBI and traditional disk-based VLBI in the pre-observation stages. Here, because the time-frame from appearance of the e-VLBI block schedule to the observations themselves is significantly compressed, JIVE handles the scheduling. Thus, it is critical that e-VLBI proposals contain sufficient information to permit this, and an extra premium is placed upon consulting with the Science Operations & Support group at JIVE when creating your proposal.

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1. Current Capabilities

The EVN Mk IV data processor can correlate simultaneously up to 16 stations with 16 channels per station (*i.e.*, either 8 dual-pol subbands or 16 single-pol SBs), each having a maximum sampling rate of 32 Msample/s (16 MHz Nyquist-sampled BW_{sb}). This provides for a total recording rate of 1 Gbps per station using 2-bit sampling. The EVN Mk IV data processor can currently correlate/provide:

- 1- and 2-bit sampling (VLBA antennas can participate in global observations in which EVN stations record at 1 Gbps by using 1-bit sampling to maintain uniform N_{sb} and BW_{sb} throughout the global array).
- parallel- and cross-hand polarization products as desired in dual-polarization observations.
- up to 2048 frequency points per baseline/subband/polarization (*cf.* § 1.1).
- full-correlator integration times (t_{int}) down to 0.25 s (*cf.* § 1.2).
- oversampling at 2 or 4 times the Nyquist frequency, to provide BW_{sb} down to 500 kHz.
- multi-pass correlation (*e.g.*, by sub-sets of stations for observations having >16 stations at any given time; by sub-sets of SBs to increase frequency resolution and/or BW-smearing field-of-view).

1.1 Correlator Capacity

The single-pass correlator capacity can be expressed as:

$$N_{sta}^2 \cdot N_{sb} \cdot N_{pol} \cdot N_{frq} \leq 131072 \quad (1.1)$$

Here, N_{frq} is the number of frequency points per baseline/SB/polarization. N_{pol} is the number of polarizations in the correlation (1, 2, or 4). N_{sb} represents the number of different subbands, counting lower- and upper-sidebands from the same BBC as distinct. The value to use for N_{sta} is “granular” in multiples of 4 (*e.g.*, if you have 5–8 stations, use “8”). Independent of this equation, the maximum number of input channels ($N_{sb} \cdot N_{pol}$) is 16, and the maximum N_{frq} is 2048 (a single interferometer must fit onto a single correlator board). The minimum N_{frq} is 16. Table 1 shows some configurations that would require the full correlator capacity to configure. You can evaluate interactively whether your experiment adheres to equation (1.1) via the EVN calculator.

The combination of N_{frq} and BW_{sb} sets the velocity resolution of an observation/correlation in terms of velocity per frequency-point. The basic equation is:

$$\Delta v = c \frac{BW_{sb}/N_{frq}}{v_{obs}} \quad (1.2)$$

Table 2 shows velocity resolutions provided by $N_{frq} = 2048$ for various spectral lines and BW_{sb} ’s.

Recirculation, which is currently under development, is means of time-sharing correlator resources for observations that do not drive the correlator at the maximum 32 Msample/s rate. This would effectively increase the right-hand side of equation (1.1) by a factor $\mathcal{R} = 16\text{MHz}/BW_{sb}$ (to

| N_{sta} | N_{sb} | N_{pol} | N_{frq} | comment |
|------------------|-----------------|------------------|------------------|--|
| 8 | 1 | 1 | 2048 | EVN spectral-line |
| 16 | 1 | 1 | 512 | 9 th sta: $N_{\text{frq}} \rightarrow N_{\text{frq}}/4$ |
| 16 | 8 | 4 | 16 | global cross-polarization |
| 16 | 2 | 2 | 128 | re-arrange $\{N_{\text{sb}}, N_{\text{pol}}, N_{\text{frq}}\}$ |
| 8 | 16 | 1 | 128 | How N_{sta} increase can be |
| 12 | 7 | 1 | 128 | absorbed by N_{sb} |
| 16 | 4 | 1 | 128 | (not constrained to be 2^n) |

Table 1: Examples of “maximal” correlator configurations.

| BW_{sb} [MHz] | HI ₁₄₂₀ | OH ₁₆₆₅ | CH ₃ OH ₆₆₆₈ | H ₂ O ₂₂₂₃₅ |
|------------------------|--------------------|--------------------|------------------------------------|-----------------------------------|
| 16 | 1651 | 1408 | 351 | 105 |
| 2 | 206 | 176 | 44 | 13 |
| 0.5 | 52 | 44 | 11 | 3.3 |

Table 2: Velocity resolution [m/s] for $N_{\text{frq}} = 2048$, for various spectral lines and BW_{sb} .

a maximum of 8). However, the maximum N_{frq} would remain 2048. The most significant benefit of recirculation would be increased spectral resolution for narrow-band global spectral-line observations; these could get $N_{\text{frq}} = 2048$, just as 8-station experiments can now achieve.

1.2 Output Capacity

The minimum t_{int} for a configuration using the whole correlator is now 1/4 s; some modes using no more than half the correlator can achieve 1/8 s. However, should recirculation be used, the minimum integration time would be increased by a factor of \mathcal{R} from its nominal value.

These low integration times, together with the fine spectral resolution afforded by large N_{frq} , provide the possibility to map considerably wider fields of view through reduced bandwidth- and time-smearing effects in the u - v plane. For example, the fields of view having $\leq 10\%$ decrease in the response to a point source arising from each of these two effects are (Wrobel [3], § 21.7.5):

$$FoV_{\text{BW}} \sim 49'' \frac{1}{B_{1000}} \frac{N_{\text{frq}}}{BW_{\text{sb}}}; \quad FoV_{\text{time}} \sim 18'' \frac{\lambda_{\text{cm}}}{B_{1000}} \frac{1}{t_{\text{int}}} \quad (1.3)$$

Here, B_{1000} is the longest baseline length in units of 1000 km, and BW_{sb} is in MHz. A goal of such wide-field correlations would be to map the entire primary beam of each antenna composing the array with only a single correlation pass. The EVN calculator also evaluates BW- and time-smearing fields of view in accordance with equation (1.3). A characteristic of such wide-field correlations, with their short t_{int} and large N_{frq} , is the rapid growth of the size of the FITS file seen by the user—reaching about 7 GB per hour of observation (per correlator pass). The current record for output FITS-files size for a single experiment stands at 1028.7 GB.

There is also a perhaps non-intuitive conflict between Gbps recordings and FoV_{BW} : a Gbps rate implies that $N_{\text{sb}} \cdot N_{\text{pol}}$ in equation (1.1) will be 16 (no cross-pols) or 32 (with cross-pols),

and BW_{sb} will be 16 MHz. Thus an 8-station Gbps experiment without cross-pols can get at most $N_{\text{frq}} = 128$ in a single correlator pass, with a resulting $FoV_{\text{BW}} \sim 6.6/B_{1000}$ (numbers halved if using cross-pols, and quartered if $N_{\text{sta}} \geq 9$).

2. Operations and Interactions with PIs

The Science Operations & Support Group at JIVE provides assistance for all segments of your experiment—from proposing/scheduling, through correlation, to analysis of the resulting FITS data. The JIVE (www.jive.nl) and the EVN (www.evlbi.org) web pages provide much information, and the EVN Users' Guide on the EVN web page (www.evlbi.org/user_guide/) remains the best “first stop” for on-line help. It has direct links to more explicit help geared towards the specific tasks encountered in conducting EVN experiments (proposing, scheduling, correlating, analyzing), as well as to the EVN Data Archive (see § 2.2), to travel support information, to handy tools & documents (the EVN calculator, the EVN data analysis guide), and to EVN facts & figures (frequency availability, u - v coverage, resolution, baseline/image sensitivity, imaging limitations).

2.1 Pre-observation, pre-correlation

The first step in any EVN observation is the proposal. There are three proposal deadlines per year (1 Feb, 1 Jun, 1 Oct), announced by a Call for Proposals distributed to the standard VLBI exploders and linked from the EVN proposals page (www.evlbi.org/proposals/prop.html). EVN and global VLBI proposals should now be submitted via the web-based EVN Proposal Tool (proposal.jive.nl). The exceptions are Target of Opportunity observations and short (≤ 4 hr) observations (details in the proposals web page).

The left-hand panel of figure 1 summarizes operational and communication flow among the PI, JIVE, and EVN assets for your experiment (once it appears on the EVN block schedule for a specific session). We actively encourage the PI to consult with Science Operations & Support group at JIVE during scheduling, in order to help side-step the myriad little pitfalls that may lead to unpleasant surprises when (and after) the observations are carried out. Following the observation but prior to the correlation itself beginning, we confer with the PI to make sure the correlation parameters (*cf.* § 1.1 & 1.2) are appropriate, to discover any other desired changes (*e.g.*, improved source coordinates), and to ascertain which sources should receive the one-year proprietary protection in the EVN Archive (*cf.* § 2.2). Because of the considerably shorter lead-times, JIVE typically schedules e-VLBI observation(s) using guidelines provided by the PI in the proposal (or via subsequent liaison). Each experiment is assigned a support scientist, who shepherds it through the correlation and post-correlation analysis stages discussed next.

2.2 Post-correlation Data Review

The right-hand panel of figure 1 illustrates the post-correlation data flow. The support scientist investigates the AIPS++ Measurement Set to detect and diagnose various problems in the recorded or correlated data, and to find any scans for which re-correlation would be profitable. At this stage, we also attach the UVWs to the correlated data, apply various corrections (*e.g.*, 2-bit van Vleck, fractional bit-shift delays), and flag subsets of the data for low weights and other known problems resulting in spurious correlation amplitudes and/or phases. Finally, we convert

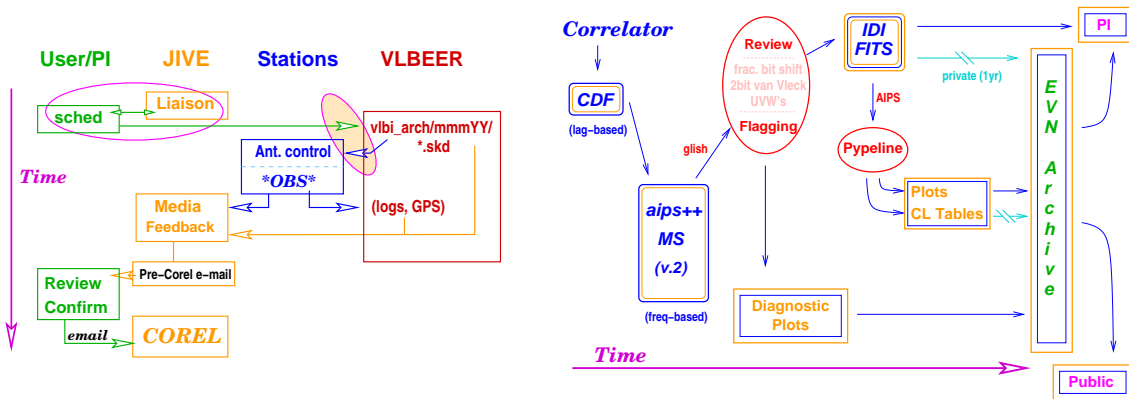


Figure 1: Operational flow within an experiment. Left-hand panel: observations and correlation; Right-hand panel: post-correlation review.

the final MS into IDI FITS format, which can be read into (classic) AIPS directly using FITLDD. At this stage, the support scientist sends e-mail to the PI describing the correlation, any points of interest noticed during data review, and how to download the FITS files from the EVN Archive (www.jive.nl/archive/scripts/portal.php)

Feedback from the stations and the diagnostic plots from the MS-based review go into the EVN Archive immediately to allow the PI to get an idea about the success of the correlation even before receiving the data. The standard plots typically comprise automatically generated time- and frequency-based plots. More extensive plots may be also be made if the situation warrants. The FITS files in the EVN Archive are kept private for a one-year proprietary period (see the *EVN Data Access Policy* in the EVN Users' Guide for more details).

Once we receive the ANTAB files from the stations, the pipelining of the experiment can begin. The EVN pipeline (www.evlbi.org/pipeline/user_expts.html; Reynolds *et al.* [2]). flags data known to be invalid (*e.g.*, antenna off-source), applies an *a priori* amplitude calibration using the T_{sys} and gain curves from the stations, makes preliminary CLEAN images using a fixed scheme for phase and amplitude self-calibration, and creates a set of AIPS tables from various stages of the calibration/fringe-fitting process that the PI can apply directly to the raw data to help simplify the initial stages of the analysis. A variety of plots saved during the above process can provide more information with which to assess network performance. Plots specifically associated with sources identified as private in the pre-correlation liaison are also password protected in the EVN Archive for the one-year proprietary period. The quality of the preliminary images may be affected by the lack of interactive data editing inherent in the pipeline concept.

To supplement the review products mentioned above, we encourage the PI to discuss the experiment/correlation with the responsible JIVE support scientist and/or to arrange a visit JIVE for help in data reduction, if desired. In order to facilitate such visits, the EC provides a trans-national access program for European PIs. A new incarnation of this programme under FP7 RadioNet begins in 2009; see www.evlbi.org/access/ for the latest details.

3. Multiple MERLIN stations in EVN correlations

Typically, only the Jb–Cm baseline has been common to both the EVN and MERLIN correla-

tions in combined EVN + MERLIN observations. This can sometimes lead to difficulty in tying the two u - v data-sets together. Because of the BW-limit in the MERLIN out-station micro-wave link, the Cm recording has “unused” SBs in recording modes ≥ 256 Mbps. For dual-pol observations above this rate, an additional out-station can be recorded onto the “unused” SBs; single-pol observations can incorporate three additional out-stations. Observations ≤ 128 Mbps would require a separate schedule for Cm to accommodate additional outstations. Each recorded MERLIN station would correlate as a separate station at JIVE; for disk-based observations this would entail making copies of the Cm disk-pack, requiring additional disk availability. Preliminary tests with multiple MERLIN stations transmitted via e-VLBI show promise for a more natural exploitation in e-VLBI observations. The additional intra-MERLIN baselines included in the EVN correlation would increase the robustness of the tie between the EVN and MERLIN u - v data-sets. Developments in the roll-out of e-MERLIN in the near future may limit the availability of specific outstations at specific times. Implementation of these schemes with the full e-MERLIN remains to be investigated.

4. Software Correlation at JIVE

An automatic-ftp feature added to the Field System has been exercised since the November 2006 EVN session to copy a specified portion of a scan from the Mark 5 disk to a linux file and ftp it directly to a cluster at JIVE, where the arrival of new data is detected, correlation performed, and results posted to a web page available to the stations. Such ftp fringe tests in the standard Network Monitoring Experiments have been very successful in identifying problems early enough to allow stations to repair them before user experiments would have been affected. Since June 2007, we have processed the ftp fringe tests on the XF software correlator we are developing as part of the EXPRoS JRA FABRIC, adapting the algorithms developed for observing the descent of the Huygens probe onto Titan [1] to wide-field applications. It currently runs on a single node, quad-processor CPU, and can correlate 1 second of data on an 8-station, 8×8 MHz subbands with all four Stokes parameters per subband, 1024 frequency points per SB/pol in ~ 50 s.

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