1. Introduction

There are at least four well known Very Long Baseline Interferometer (VLBI) networks that provide open access to astronomers around the world. These include:

- European VLBI Network, www.evlbi.org
- Very Long Baseline Array, www.aoc.nrao.edu/vlba/html/VLBA.html
- Coordinated Millimeter VLBI Array, web.haystack.mit.edu/cmva
- Australian Long Baseline Array, www.atnf.csiro.au/vlbi & the Asia-Pacific Telescope, www.atnf.csiro.au/apt.

For a comprehensive guide to the various array characteristics, corresponding correlator capabilities, range of diverse observing modes, different proposal submission procedures, user support etc., I refer the reader to the on-line web pages highlighted above. In this paper I have chosen to focus on a sub-set of these facilities, in particular the European VLBI Network (EVN) both in stand-alone mode but also as a major component of a Global VLBI Network, involving MERLIN (see www.merlin.ac.uk) and the Very Long Baseline Array (VLBA – see Zensus, Diamond & Napier 1995, for a comprehensive review).

2. The European VLBI Network

The EVN is a “part-time” VLBI network that observes in 3 “block sessions” per year. Each of these block sessions is 3-4 weeks long, and usually 3 or more different observing frequencies are available within any given session. Observing sessions are scheduled in February-March, May-June and October-November of each year and often involve both Global and EVN-only observations. The EVN and Global VLBI “Call for Proposals” is issued
three times per year with deadlines of February 1, June 1, and October 1. Please refer to the web-based EVN User Guide at www.evlbi.org for more details on how to apply for EVN observing time.

The locations of the telescopes, and in addition the EVN MkIV Correlator at JIVE (Joint Institute for VLBI in Europe), are shown in Figure 1. Members of the EVN with radio telescopes are listed in table 1. There are several categories of EVN membership – these recognise the different levels of commitment by the various participating institutes – full or associate membership, and affiliated telescopes. These three categories are separated in table 1 by dividing lines. The table also indicates the diameters of the individual telescopes and their system noise in Jy (at the main EVN observing wavelengths).

2.1. EVN SENSITIVITY

The obvious advantage that the EVN has over other networks is the enormous collecting area it can routinely draw upon across a broad range of frequencies. It is worth remembering that in terms of collecting area, the larger EVN telescopes such as the Effelsberg 100-m, Westerbork tied array and Lovell 76-m, are either individually larger or comparable to the combined collecting area of the ten 25-m antennas that comprise the VLBA. In practical terms, this large collecting area permits much fainter sources
| Institute     | Telescope     | Diam (m) | SEFD (Jy) | \( \lambda \leq 18 \) cm |
|---------------|---------------|----------|-----------|---------------------------|
| MPIfR (DE)    | Effelsberg    | 100      | 20        | 19|20|55|20|140|600 |
| ASTRON (NL)   | WSRT          | 14 \( \times \) 25 | 30|30|600|120|910| |
| JBO (UK)      | Lovell        | 76       | 35         | 35|25|25|25|255| |
|               | Mk2           | 25       | 350        | 320|320|910|910| |
|               | Cambridge     | 32       | 220        | 212|136|136|720| |
| IRA (IT)      | Medicina      | 32       | 390        | 582|296|900|270| |
|               | Noto          | 32       | 820        | 784|136|136|270| |
|               | Sardinia      | 64       | Not yet known |              | |
| OSO (SE)      | Onsala-85     | 25       | 450        | 390|600|1500| |
|               | Onsala-60     | 20       | -          | -|1630|1380| |
| SHAO (CN)     | Shanghai      | 25       | -1090|520|590|1600| |
| UAO (CN)      | Urumqi        | 25       | 1068|1068|353|396| |
| TCfA (PL)     | Torun         | 32       | 250|230|250|300| |
| OAN (ES)      | Yebes 14-m    | 14       | -          | -|3300|4160| |
|               | Yebes 40-m    | 40       | -          | -|9000| |
| MRO (FI)      | Metsahovi     | 14       | -          | -|2608|4500| |
| NAIC (USA)    | Arecibo       | 305      | -          | -|3|6| |
| HRAO (ZA)     | Hartebeesthoek | 26     | -450|700|800|940| |
| IFAG (DE)     | Wettzell      | 20       | -          | -|750| |
| DSN (USA/ES)  | Robledo 70-m  | 70       | -42         | -|23|100| |
|               | Robledo 34-m  | 34       | -          | -|88| |
|               | Matera        | 20       | -          | -|900| |
| CGS|ASI (IT)     | Ny-Alesund    | 20       | -          | -|1255| |
| NMA (NO)      | Simeiz        | 22       | -1600|3000|1200|3000| |

TABLE 1. EVN member telescopes including those currently under construction at Sardinia and Yebes. System Equivalent Flux Density (SEFD) values for new or refurbished telescopes/receivers (e.g. the re-surfaced Lovell 76-m) are current best estimates or as yet unknown. The table is divided into 3 parts: full, associate members and affiliated observatories.

to be detected, imaged and self-calibrated with the EVN. This advantage applies particularly to spectral line observations (both emission and absorption studies). In addition, another key advantage of the EVN is its capability to perform sustained VLBI observations at very high data rates (currently 512 Mbit/sec). Uniquely, the EVN is able to observe at these sustained data rates for 12 hours or longer.

Figure 2 shows the 1σ r.m.s. (image) noise level of a standard EVN array (excluding the DSN telescopes and Arecibo) at \( \lambda \leq 18 \) cm for typical spectral line single channel widths of 6 and 30 kHz, dual polarisation continuum bands of 16 MHz (128 Mbits/sec), 32 MHz (256 Mbits/sec) and 64 MHz...
Figure 2. The 1-σ image noise level achieved by the EVN at λ18 cm as a function of time (minutes) for typical spectral line channel widths (6 and 30 kHz), dual-polarisation continuum data rates of 128, 256 and 512 Mbit/sec. For comparison the noise levels achieved by the VLBA for a channel width of 30 kHz and its maximum sustained data rate of 128 Mbits/sec are also included. The noise level achieved by a global VLBI array operating at a sustained data rate of 128 Mbits/sec is also presented. Finally we present the anticipated performance of the eEVN – the current EVN telescopes connected together by optical fibres.

(512 Mbits/sec). As a point of reference I plot the corresponding noise levels of the VLBA at 6 kHz, and 16 MHz (the latter being equivalent to the VLBA’s maximum sustainable data rate of 128 Mbits/sec over 12 hours). In the same figure I also include an extremely sensitive Global VLBI array including the EVN, VLBA, VLA, GBT, DSN and Arecibo. Casting an eye towards the future, I have plotted the noise level that would be achieved by the EVN at λ6 cm, assuming fibre connections (eEVN) and a bandwidth of ∼ 2 GHz per polarisation (see section 4). In the latter case, the eEVN can be expected to reach impressive sub-microJy noise levels in a typical 12 hour (on-source) observing run.

2.2. UNIQUE EVN FREQUENCIES

Another important feature of the EVN is the availability of observing frequencies that are essentially unique, at least in the northern hemisphere. These include UHF band observations (∼ 800 – 1300 MHz) that have been used to search in relatively distant extra-galactic systems for (redshifted)
neutral hydrogen in absorption, and the $\lambda$5 cm receivers that have been used to infer the presence of circumstellar discs around massive stars located within star forming regions in our own galaxy (see Booth these proceedings for a summary of the latest extra-galactic HI absorption and Methanol maser results). The fact that these receivers were constructed quickly, and then rapidly deployed across a substantial fraction of the network, emphasises the EVN’s ability to respond flexibly to “bottom up”, user driven demand.

2.3. COMBINED JOINT EVN-MERLIN OBSERVATIONS

The EVN often co-observes with the UK’s MERLIN radio telescope network. Two of the MERLIN telescopes conduct both VLBI and MERLIN observations simultaneously – usually the Cambridge 32-m telescope and one of the Jodrell Bank “home” telescopes (either the Lovell 76-m or Mk2 telescope). The advantage of joint EVN-MERLIN observations is the excellent uv-coverage that can be obtained from the combined data set. MERLIN provides baselines on scales ranging from 6 to 217 km, thus providing overlap with the shortest (projected) EVN baselines (Jodrell-Cambridge and Effelsberg-Westerbork in particular). The combined data set therefore includes a range of baseline lengths, from a few to several thousand kilometers. This is of course ideal for detecting and imaging large extended sources that might otherwise be resolved-out or be extremely difficult to image accurately with the EVN alone.

Usually EVN-MERLIN observations take place during every session at one of the main EVN observing frequencies (usually $\lambda\lambda$18 or 6 cm, although joint observations at $\lambda$1 cm are also possible). The inclusion of the common Jodrell-Cambridge baseline in both the EVN and MERLIN arrays, ensures that the data sets can be combined together in a consistent fashion.

2.4. THE EVN AS PART OF THE GLOBAL VLBI NETWORK

VLBI is an international effort. The very longest baselines available via the ground require collaborations between various VLBI networks. In the northern hemisphere a particularly strong collaboration exists between the EVN and the VLBA. Both networks employ very similar recording systems (MkIV and VLBA respectively) which provide a wide range of compatible observing modes. Global VLBI observations usually involve the participation of the most sensitive VLBI telescopes in the world, including those that provide the longest baseline lengths – it’s not uncommon for up to 20 VLBI telescopes to participate in a single 12 hour observing run. In addition, many Global VLBI projects are also made together with simultaneous MERLIN observations. This high resolution, Global VLBI Network
currently provides the ultimate in terms of both sensitivity and uv-coverage (see Figure 3). Snapshot observations of a large number of sources, or of galactic sources that evolve quickly also becomes feasible with such a 20 station global array.

2.5. ON-GOING ENHANCEMENTS TO THE EVN

So far we have focussed on the areas where the EVN is strongest, viz. unmatched sensitivity and the ability to observe at several unique frequencies. There is a continuous and vigorous EVN programme of development to maintain and enhance these capabilities. General enhancements to the network (e.g. the recent upgrade to 2-head recording and 512 Mbit/sec data rates) are coordinated via the EVN Technical & Operations Group (see www.evlbi.org/tog/tog.html for more details).

Several significant events are expected to take place in the short-term, in particular the addition of two large telescopes to the EVN over the course of the next two to three years. These are the 64-m Sardinia Radio Telescope (the SRT – to be built at San Basilio, near Cagliari and operated by the IRA) and the OAN-Yebes 40-m telescope (to be built alongside the current 14-m OAN antenna at Yebes, near Madrid). In 2005 the Miyun 50-m mesh telescope (located near Beijing, China) should be complete, and this may also participate in EVN observations (up to and including $\lambda 3.6$ cm). In addition, several other major upgrades of EVN telescopes have just been completed. These include the recent upgrade of the WSRT array, and the installation of an active surface for the Noto 32-m telescope. The replacement of the existing reflecting surface of the Lovell 76-m telescope is on-going and is expected to be complete by the end of 2002. These will permit the Lovell telescope to observe usefully at frequencies up to 10 GHz – boosting its sensitivity by a factor of 5 at $\lambda 6$ cm. This major engineering development (which includes the upgrade of the drive and pointing control system) will transform the Lovell’s capability as a VLBI and MERLIN antenna. Progress with the Lovell telescope upgrade and the construction of the new 40-m telescope at Yebes (as of summer 2001) is presented in Figure 4.

It must also be noted that there are certainly areas where the performance of a heterogeneous network such as the EVN might be considered less than optimal, at least in comparison to a homogeneous, full-time network such as the VLBA. Certainly the EVN is a more difficult instrument to calibrate, and only recently have a significant number of telescopes achieved frequency flexibility. In addition, the geographical location of the majority of the antennas is also not optimal for high frequency observations ($> 20$ GHz). The EVN’s ability to react to “target-of-opportunity”
observations is also more limited than the VLBA – at least outside of network sessions. Similarly it is difficult for the EVN to adequately monitor sources with evolving radio structure, at least in comparison to the uniform temporal coverage that the VLBA can provide.

Nevertheless, progress is being made in all these areas. Automatic pipelining of EVN (and global) VLBI data (see section 3.1 and Reynolds, Paragi & Garrett 2002) now largely hides the intricacies of EVN calibration from the user. Experiments requiring fast frequency switching are beginning to become more common in network sessions, and the addition of the new 40-m Yebes and 64-m Sardinia telescopes (capable of operating at frequencies up to 115 GHz) will enhance the EVN’s sensitivity at higher frequencies. Vigorous efforts to move the EVN towards real-time operations (see section 4) will also provide increased flexibility to conduct more uniform monitoring campaigns or to respond to “target-of-opportunity” events.

![Figure 3](image-url)  
*Figure 3.* Left: The upgrade of the Lovell Telescope surface – a factor of 5 improvement in sensitivity is expected at $\lambda 6$ cm. Right: Construction continues of the 40-m telescope at Yebes – the pedestal is complete, work continues on the backing structure and reflector panels. The new 40-m telescope (inset) will operate at frequencies up to 115 GHz.

### 3. The EVN MkIV Data Processor at JIVE

The construction and development of a VLBI correlator entirely dedicated to EVN activities is one of the great achievements of the last decade. The EVN MkIV Data Processor at JIVE (Casse 1999, Schilizzi et al. 2002b) was developed as part of an international collaboration, the primary contributors being the European Consortium for VLBI and the MIT Haystack Observatory, in the USA. The EVN MkIV Data Processor is operated by JIVE and is now the main-stay of EVN data correlation (including global projects which it shares with the NRAO-VLBA).

The Data Processor is capable of handling data from 16 telescopes simultaneously (more via multiple pass correlation) and can handle MkIV, VLBA and MkIII data formats. Standard correlation of the vast majority of EVN and global VLBI continuum and spectral line experiments are
now routinely processed at JIVE. The capacity of the correlator is continually being enhanced, and new capabilities introduced (see www.jive.nl for the most up-to-date information). On-going projects include: recirculation (in order to provide superb spectral resolution in excess of 8192 channels per baseband), Pulsar Gating (to optimise Pulsar detection limits) and the PCInt (Post-correlator Integrator) that will permit high-speed read-out of the correlator at data rates of up to 160 MBytes/second).

The PCInt development is expected to see “first-light” by the end of 2002 (Parsley 2001a) – it will transform the capability of the EVN (and Global VLBI arrays) providing the possibility to image dozens of faint sub-mJy radio sources within the primary beam of the individual VLBI antennas (see Garrett these proceedings). To take advantage of the fantastic output data rates the PCInt can generate, significant off-line computing resources will be required. Off-line computing resources are likely be the main bottleneck in the new system, at least for the first few years of operation.

3.1. EVN USER SUPPORT

As well as operating the EVN Data Processor, JIVE is largely responsible for EVN user support. JIVE support scientists (and in addition other JIVE staff) are involved in providing a level of user support that was previously unknown within the EVN, and rivals or surpasses that provided by other instruments. In particular, the following services are routinely provided:

− advice regarding the technical content of proposals (e.g. cover-sheet specifications, choice of mode, observing strategy etc)
− scheduling assistance and maintenance/development of NRAO’s Sched (for specific EVN requirements)
− absentee correlation and data quality check-out
− automatic calibration of EVN and Global VLBI data correlated at JIVE (via a Pipeline process)
− direct assistance with VLBI data and image analysis.

In addition, the support scientists also contribute to monitoring the reliability and performance of the EVN (via special Network Monitoring Experiments) and also conduct network tests aimed at extending the capabilities of the network.

Financial support is available to those EVN users that wish to visit JIVE in order to avail themselves of these services (in particular scheduling and data analysis). Indeed the EVN is in receipt of a substantial award from the European Commission in Brussels (Access to Research Infrastructures), that comprehensively supports EVN users that are not affiliated to the EVN Consortium institutes but are located within the European Union or Associated States. In addition, there is also internal EVN support for users
that are directly affiliated to EVN Consortium institutes. Both programmes support not only visits to JIVE but also to other members of the EVN. For example, users frequently visit Jodrell Bank Observatory in order to take advantage of the local expertise in combining joint EVN-MERLIN data sets.

4. The Future of the EVN

Across the globe radio telescopes and interferometer arrays are involved in significant efforts to improve their overall performance and their continuum sensitivity in particular. These developments are desperately needed in order for radio astronomy to maintain its competitiveness with other next generation instruments – especially sub-mm and IR telescopes. Anticipated improvements largely rely on the possibility of observing and processing much larger continuum bandwidths than was previously possible. The use of optical fibre technology now permits the digital transport of many GHz of bandwidth over 1000’s of km. Next generation correlators are now being designed and constructed to handle the associated Gbit/sec input data rates and subsequent processing requirements. The EVLA, e-MERLIN and LOFAR telescopes will be the first radio telescopes to take advantage of these developments – permitting huge areas of sky to be mapped-out with sub-arcsecond resolution and microJy sensitivity.

The consequences for VLBI, and the EVN in particular, are crystal clear. In order to remain competitive with, and complementary to these upgraded or new radio instruments, the EVN must be able to observe and process several GHz of bandwidth too. The connection of the EVN telescopes to com-
commercial “λ-networks” (fibre data transport utilising wavelength-division multiplexing techniques) is now being vigorously explored in both Europe and the USA - the first connections and fringe tests are expected to occur within the year (Schilizzi 2002a, Whitney 2002, Parsley 2002). Perhaps all VLBI telescopes (in particular those located nearby densely populated areas) will be connected to such networks in 5-10 years time, the exact timescale depending on local circumstances. Trans-continental connections also appear feasible too. Meanwhile the new disk-based MkV (Whitney 2001) and PC-EVN (Parsley 2001b) recording systems are set to replace the current generation of tape recording systems. These disk-based PC systems can already record data at rates that are similar to current MkIV or VLBA systems. In addition, the same systems are poised to take advantage of the expected expansion in the capability of PC hardware over the next few years. While the investment in both fibre or disk-based technologies is substantial, it will provide VLBI networks such as the EVN with sensitivity levels that are similar or even better than that anticipated for either the EVLA or e-MERLIN. A natural consequence of employing observing bandwidths that span several GHz is the almost complete uv-coverage that accompanies it. Figure 5 shows the uv-coverage of a fibre connected EVN (eEVN). The transparent, real-time combination of the eEVN and e-MERLIN will also result in a significant enhancement in imaging capabilities of the combined array.

As a consequence of all these developments, a replacement for the EVN Data Processor will also be necessary. The new correlator will need to be
capable of handling a global array of $\sim 30$ telescopes (each generating 10-30 GBits/sec of data) and the phenomenal output data rates that will enable the natural field of view (then set by the primary beam of individual VLBI elements) to be imaged out in its entirety. New broad-band receivers and a new generation of VLBI data acquisition electronics will also be required at the telescopes, in order to take full advantage of the available bandwidth. There are (not surprisingly) severe implications for (“off-line”) data processing requirements too. This not only concerns raw processing power but also the development of new calibration and image algorithms. In a very real sense, the eEVN with baselines on the scales of several thousand km, “fantastic” data rates and microJy sensitivity, will be the natural test-bed to investigate some of the problems and possible limitations that might be relevant to next generation instruments such as the SKA (see Kus these proceedings).

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