

# From truck to optical fibre: the coming-of-age of eVLBI

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**Abstract.** Spurred by the advent of disk-based recording systems and the nearly explosive increase of internet bandwidth, eVLBI (Parsley et al. 2004) has undergone a remarkable development over the past two years. From ftp-based transfers of small amounts of astronomical data, through near real-time correlation (disk-buffered at the correlator), it has culminated this spring in the first three telescope real-time correlation at JIVE (Onsala, Westerbork and Jodrell Bank). In this paper we will give a review of this development and the current state of affairs. We will also address the current limitations and the way we may improve both bandwidth and reliability and finally we will discuss the opportunities a true high-bandwidth real-time VLBI correlator will provide.

## 1. Introduction

At this time, the replacement of MkIV magnetic tape recorders with Mark5 units, PC-based disk recorder systems (Whitney 2003), is in full swing. As a direct result of this development, eVLBI, connecting stations through Mark5 units via optical fibres, has become possible and may well become the successor to disk-based recording.

Fibre communication networks are ideally suited to the real-time transfer of huge amounts of data over long distances. The adoption of direct fibre connections by eMERLIN signals the progress that is being made in this area. As large networks are being deployed for the use of research in Europe, and as networks become more flexible, the introduction of a real-time VLBI system is a realistic goal to pursue.

The EVN and JIVE are actively involved in a proof-of-concept (POC) programme which aims to demonstrate the feasibility of real-time VLBI using IP routed networks. This POC is supported by GÉANT, a collaboration between European National Research and Education Networks, the European Commission, and Dante (Delivery of Advanced Network Technology to Europe). The aim is to connect at least four EVN telescopes to the correlator at JIVE, ultimately at data rates of 1 Gbps, and feed these data streams directly into the correlator.

In connecting the telescopes, local loops (the last mile connection) are a critical item. At the time of writing, the Westerbork, Onsala and Torun radio telescopes have 1 Gbps connections, while Jodrell Bank and Arecibo are connected through 155 Mbps. The upgrade of Jodrell Bank to 2.5 Gbps and the connection of Medicina at 1 Gbps are planned for the end of this year.

JIVE itself was connected to Netherlight in September 2002, and currently can make use of 6 lambda's, each capable of carrying 1 Gbps, and one direct Gbps connection to the Westerbork Synthesis Radio Telescope.

The outline of this paper is as follows. In Section 2 we discuss transport protocols and possible optimizations. Section 3 deals with tests and results, and in Section 5 we consider pos-

sible implications for the operation of the EVN. Section 5 lists the conclusions.

## 2. Tcp versus udp, tuning issues

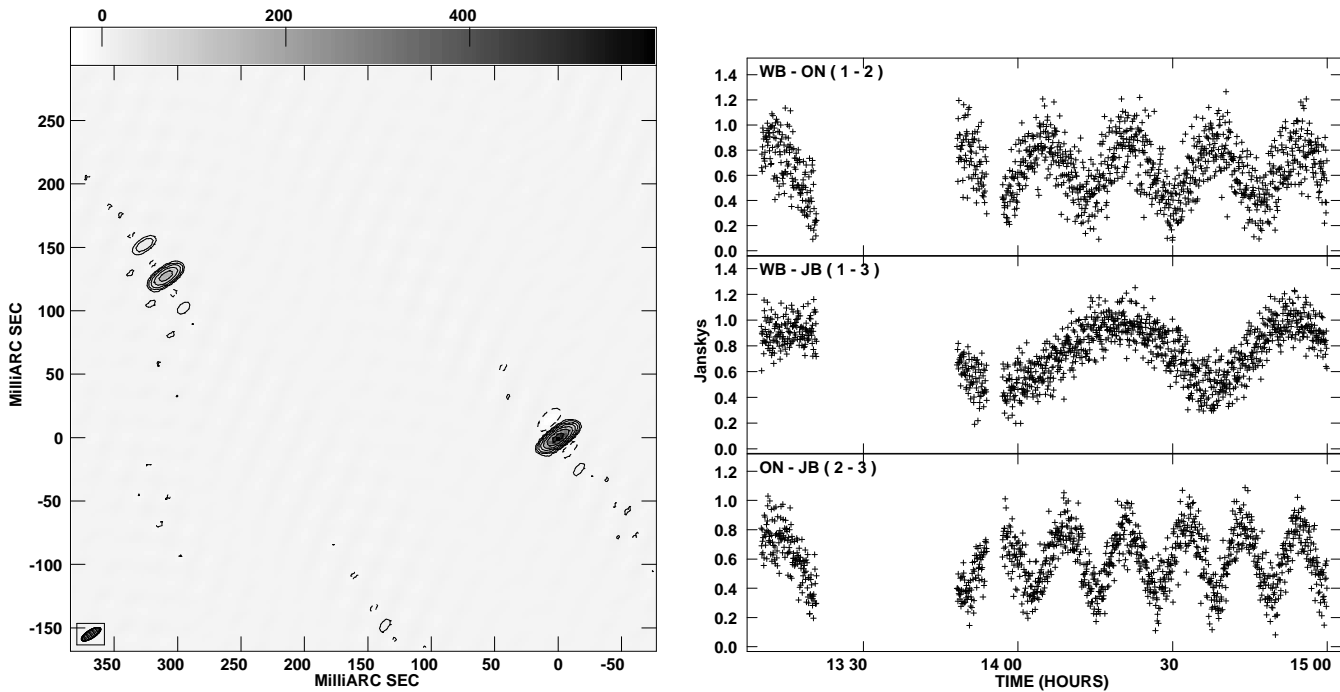
In principle, data can be transferred in many ways and forms, especially on dedicated networks. Here we exclusively consider IP based protocols using existing networks.

The most widely used internet transfer protocols are TCP and UDP. Both are based on the IP protocol, that is, both make use of IP packets, consisting of data and a header. However, while the TCP protocol tries to maximize reliability using a direct connection, through three-way handshakes, acknowledgments, backoff algorithms and re-sending of packets in the case of packet loss, UDP is connectionless and will simply send off packets without further accounting. Apart from the case of dedicated point-to-point connections, this makes UDP faster than TCP, but large amounts of data may go missing, and packets may even arrive in the wrong order. Although a certain amount of data loss is acceptable in the case of VLBI, UDP can only be used in combination with a mechanism that would count and re-order packets, replacing gaps with dummy data.

Different protocols, like Scalable and High Speed TCP, have been and are being developed, attempting to combine high speed with high reliability. For the time being, the software provided with the Mark5 units only supports TCP and UDP, although a VSI-E software module, currently under development at Haystack, will provide more flexibility (D. Lapsley, private communication).

The performance of TCP can be improved, sometimes quite dramatically, by the tuning of several parameters. In current Linux implementations many of these parameters are set to default values that are inappropriate for high-speed networks.

- TCP window or congestion window. This buffer determines how many packets can be sent (and received) at one time and is calculated as the product of the roundtrip time and the bandwidth. To enable large window sizes, the default system buffer sizes must be adjusted.



**Fig. 1.** First real-time eVLBI map of the gravitational lens system, JVAS B0218+357 (left), two images of a bright radio quasar, separated by 334mas across the sky, result in a beating correlated amplitude on all 3 baselines, the period depending on the baseline length and orientation.

- Txqueuelen–netdev\_backlog. These determine the sizes of queues between kernel network subsystems and the network interface card driver, on sending and receiving ends. Here too, default sizes must be increased.
- Selective acknowledgment (sack). The implementation of sack in current Linux releases can cause a serious delay in connection recovery after a burst of packet loss, and should be disabled.
- MTU size. The use of jumbo frames (9000 bytes instead of 1500) has a dramatic effect on throughput, but all equipment (such as switches and routers) along the path must support this. Generally this is not (yet) the case.
- Interrupt moderation/coalescence. With every TCP packet generating one interrupt, some motherboard/cpu combinations are overwhelmed by the number of interrupts during Gbps transfers. It is possible to limit the number of interrupts generated by adjusting the parameters of the network interface card driver, thereby reducing the load on the cpu. This does however increase the delay.

### 3. Tests and results

In this section we review the tests done over the past few years at JIVE and the results they have led to. These tests were conducted both on the bench, between Mark5 units connected through patch cables or via the switch at Netherlight, and between Mark5 units in Dwingeloo and at various observatories. In some cases different PCs (not Mark5s) were also used to measure throughput across international networks. We have done both memory-to-memory tests (using iperf and similar programs) and tests involving real data being read from

and to recording media. Network stress tests were also done, in which as much data as possible was sent simultaneously from several stations to JIVE.

All of the tuning parameters mentioned in the previous section influence transfer speeds to some degree, and some of them influence each other. Some of the parameters are only important at high speeds, which can only be reached in memory-to-memory tests on the bench. Transfer of real data can be influenced by yet other factors, like the load on the PCI bus of the PC or the speed of disk access. The best result we have obtained so far was the transport of real data via a patch cable at a rate of ~500 Mbps, with jumbo frames, and ~300 Mbps without. Note that memory-to-memory transfers over such a connection will easily reach speeds of ~900 Mbps, even without jumbo frames (if properly tuned).

The results of these tests are summarized in Table 1. In the following I will describe various transfer modes.

#### 3.1. ftp-based eVLBI

One of the first practical implementations of eVLBI was the transfer of astronomical data through ftp for the purpose of fringe tests. For this, small amounts of data are transferred from Mark5 diskpacks to normal Linux files and ftp'd to JIVE. At first these data were then again stored on Mark5 diskpacks and correlated in the regular way, nowadays the software correlator package developed and maintained by the Radio Astronomy Group in Kashima Space Research Center is used, leaving the hardware correlator available for production correlation. This method has greatly improved the response time of JIVE to re-

**Table 1.** Test results of TCP and UDP transfers in various setups. Listed are the maximum data rates in Mbps. Note that in many cases transfer rates were not constant over time, and moreover were not symmetrical, i.e. data rates from and to JIVE would differ.

	Mem – Mem		Disk2net – Net2disk		In2net – Net2disk	In2net – Net2out
	udp	tcp	udp	tcp	tcp	tcp
Bench via patch	930		250			256
idem, jumbo frames	960			544		512
Bench via Amsterdam	500	360				256
idem, jumbo frames			341	456		
Westerbork-Jive	867	680			256	64
idem, jumbo frames			249	378		
Bologna-Jive	670	128		307		
Jodrell-Jive	50	70			64	32
Arecibo-Jive		88				32
Torun-Jive	800	260				32
Onsala-Jive				177	256	64
Jive-Haystack	612			71		

port technical problems to the observatories and made the EVN a more reliable instrument.

As this method is based on standard ftp, the bandwidth of the connection is not a critical factor. However, the amount of data that can be transferred in this way remains limited (many stations still have poor connectivity), and the correlation itself is time consuming. Typically, a transfer (some 15 to 30 seconds worth of data, up to 1GB/station) will take of the order of minutes to hours, while the correlation itself (single baselines to one station, normally Effelsberg) takes about one hour (on an 8-node dual 2GHz Opteron Linux cluster).

### 3.2. Dual buffered eVLBI

The next step was to bypass the stage of storing data as Linux file by using the Mark5 commands `disk2net` and `net2disk`. Although not very different from regular ftp, this removes the need for extra storage and reduces the time involved. Again, bandwidth is not critical and in fact this way of operation could cut down on operating costs by eliminating the need for transporting diskpacks. The disadvantage is that during the transfer, which generally will be slower than real-time, the Mark5 units are not available for either recording or playback.

Several tests were done in this mode, testing connectivity and data integrity, using telescopes at Westerbork and Onsala and the Medicina Mark5 unit that had been hooked up to a Gbps connection at the GARR POP in Bologna.

### 3.3. Single buffered eVLBI

The last step leading up to real-time eVLBI was to stream data directly from the formatters at the stations (Mark5 command `in2net`) to diskpacks at JIVE. On January 15<sup>th</sup> 2004 this mode was tested with Westerbork, Onsala and Cambridge (via Jodrell). Due to the slower link to Jodrell, data from Cambridge were sent only at 64 Mbps, and higher rates were recorded and transferred overnight. Rates of up to 256 Mbps were tested.

Good fringes were obtained at 256 Mbps between Onsala and Cambridge, and on all baselines at 128 Mbps. The fringes were produced within half an hour of the end of the observation, the final image within 24 hours.

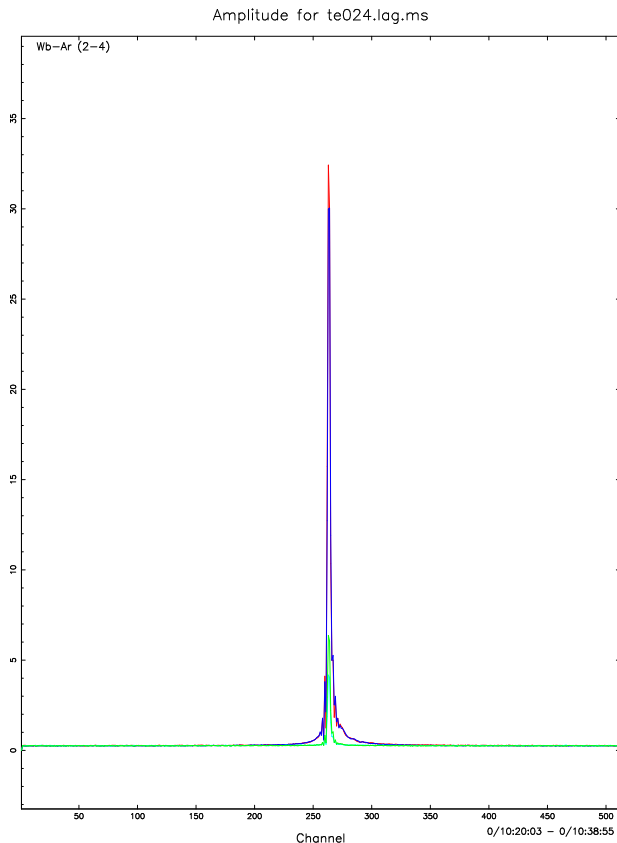
### 3.4. Real-time eVLBI

Once it became possible to servo net-streaming data in the Mark5 units, we could go ahead and implement real-time eVLBI. As telescopes are not available at all times for testing, a number of tests were done using a simulation setup. This setup consisted of three Mark5 units, one unit (acting as formatter) playing back pre-recorded data into a second unit, which sends the data across a patch cable to a third unit, which plays the data into the correlator. In this way we first of all could establish feasibility, and in the second place we could determine the highest possible transfer rate under optimal circumstances. The highest rates achieved in this way were 512 Mbps with jumbo frames, 256 Mbps without.

In normal operations the correlator clock is set to the observing time which is recorded in the observing logs. This observing time is checked against the time codes in the data stream. Software modifications to the correlator control code were needed to synchronize the correlator clock to UT (minus a few seconds). The logistics involved in connecting various telescopes were not always trivial and resulted in a large number of long-distance telephone calls. Nevertheless, at this time several successful tests have been conducted (Figure 1), with ever-increasing ease of operation.

The most recent experiment took place September 10<sup>th</sup> of this year, with telescopes in Arecibo, Westerbork, Torun and Cambridge participating, and produced fringes on all baselines (Figure 2). The first science-driven eVLBI project is scheduled for the end of September this year.

The highest rate we have reached so far in this mode is 64 Mbps (Onsala and Westerbork) but because of the lower



**Fig. 2.** Example of a transatlantic fringe on the Westerbork-Arecibo baseline of 0528+134, observed September 10<sup>th</sup> 2004 using real-time eVLBI.

connectivity to Jodrell and Arecibo only 32 Mbps experiments were carried out with these stations.

#### 4. eVLBI: towards eEVN?

The move towards eVLBI ties in closely with other projects, all having a tremendous impact on VLBI. The PCInt project currently being developed at JIVE will allow the full capacity of the correlator to be harnessed, permitting a spectral resolution of 8092 channels per baseline or integration times as short as 15 milli-seconds (van Langevelde et al., these proceedings), hugely expanding the field-of-view of VLBI. While incremental improvements in collecting area for the EVN are expected from the Yebes-OAN 40-m telescope and the IRA 64-m Sardinian Radio Telescope, a significant increase of sensitivity will result from the availability of sustained data rates of 1 Gbps and, expected on relatively short time-scales, data rates well in excess of this. Also in the area of improved receiver technology, both cm and mm-VLBI are likely to see significant progress (Garrett 2004).

What will eVLBI mean for the EVN? Although we still are in a development phase it is clear that the technique works and that with additional effort the data rates can and will be cranked up. And considering the current pace of development, both of internet bandwidth and optical technology, one can imagine a lambda switched EVN, a network in which telescopes are

connected to the correlator through point-to-point dedicated connections.

A few advantages:

- No consumables. Removing the need for recording media, and its transport, will constitute a considerable saving of money and effort for the EVN. This will of course have to balance the price-tag of a (semi) dedicated network.
- Fast turn-around. A real-time connected-element EVN will deliver data products to the users in a matter of days. This will reduce the long delay between conception of a project and actual research, and make the EVN a more exciting instrument to use.
- Reliability. Network performance will be monitored continuously, feedback in the case of problems will be nearly immediate. To optimise this, a flexible, more centralised form of control may be needed. With guaranteed reliability, it will be easier for the EVN to react to targets of opportunity such as GRB after-glow.
- Future bandwidth needs. The use of standard off-the-shelf hardware components ensures that eVLBI will be able to take full advantage of commercially driven technological improvements. It should be noted that bandwidths beyond 1 Gbps will require a new correlator, which may well take a distributed form.

eVLBI will also change the current operating model of the EVN. In the new model, the correlator will be an integral part of the network, with monitoring information being exchanged nearly continuously between correlator and telescopes. As a result the EVN will become one instrument, with highly increased coherence and reliability. Moving to eVLBI will enable us to combine eEVN with eMERLIN, thereby creating the most sensitive VLBI network in the world. Further in the future, the combination of eEVN with radio telescopes such as ALMA and SKA is a real and exciting possibility.

#### 5. Conclusions

At this point, real-time eVLBI is about to come of age and to become, albeit on a limited scale, an EVN mode of operation in its own right. With additional effort and investments higher data rates with more telescopes are well within reach. In the near future, technological developments are bound to result in an explosive growth of available bandwidth, making 1 Gbps real-time correlation a realistic goal. Availability of bandwidth will no doubt create demands for yet more bandwidth, and we should look forward to multi-Gbps correlation. The move towards eEVN is a logical next step, and will put the EVN on the forefront of future developments.

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