eEVN: a Pan-European radio telescope

Huib Jan van Langevelde[a], Mike Garrett[a], Steve Parsley[a], Arpad Szomoru[a], Harro Verkouter[a], Cormac Reynolds[a], Friso Olnon[a], Andy Biggs[a], Bauke Kramer[a], Zsolt Paragi[a], Sergei Pogrebenko[a]

[a]Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, the Netherlands

ABSTRACT

Technological advances are changing the nature of VLBI. Disk based recording has already led to substantial increases in sensitivity and with the advent of new telescopes and data acquisition systems VLBI will start penetrating the micro-Jansky sky. With the employment of fibre based communication networks as the basis for production, real-time VLBI networks will become a reality. This changes the way VLBI is done and removes bottlenecks in operation and scientific exploration. At the output side, fantastic new correlator output data rates and the ability to deal with these via powerful PC clusters promises to expand the typical VLBI field-of-view to scales previously reserved for connected, short baseline interferometers. These developments require new algorithms for user processing, as well as new interfaces to present the product to the users.

Keywords: Radio Astronomy, VLBI, Optical Fibres, Field-of-View, Interferometry, High Data-rates

1. INTRODUCTION

The European VLBI Network (EVN, (EVN, see `www.evlbi.org`) is a collaboration of radio telescope institutes in Europe, China and South Africa. The EVN is constantly improving its performance by upgrading all elements in the data path. Many of the current upgrades are enabled by the rapid development of commercial off-the-shelf (COTS) PC-based products. These new developments include: flexible digital signal processing, disk-based data recording, data transfer via transnational, broad-band, internet communication networks and powerful (off-line) computing resources via (Linux) PC clusters.

Phase referencing techniques have already improved the limiting brightness of sources that can be accessed with the EVN over the last decade. The technical advances, combined with the introduction of new, sensitive antennas, will dramatically increase the number of sources that can be studied with VLBI by enhancing the sensitivity.

Moreover, the way VLBI is done by its users, the astronomers, will change too. The new recording and data transport methods will shorten the feedback loop considerably. Together with investments in calibration techniques this will allow automatic processing, at least for preliminary results in experiments that use standard set-ups. The EVN correlator will start operating in wide field mode for all observations, building up an archive that will contain a vast number of faint sources. After a proprietary period this archive will be open to the astronomical community and images will be accessible through the internet.

2. VLBI SENSITIVITY

In VLBI (and radio interferometry in general) the image and baseline sensitivity are dependent on several different parameters. Two of these are specific to the antenna: the effective collecting area and the antenna system noise. In addition, sensitivity to broadband continuum radio emission is determined by the total bandwidth of the observing band and the total integration time. In VLBI coherence of the received signal over time (and bandwidth) is limited and calibration has to be performed regularly in order to take full advantage of the total integration time. Within the coherence time (typically minutes) a detection needs to be made, which allows (self-)calibration of atmospheric parameters, to allow longer integration.

It is clear from these factors that improvements in sensitivity can be obtained via four independent parameters: (i) increased collecting area, (ii) lower noise receiver systems, (iii) longer coherence times & (iv) larger total observing bandwidths.

langevelde@jive.nl

2.1. Antennas & Receivers

Probably the most important factor in the sensitivity is collecting area. Incremental improvements for the EVN are expected from the Yebes-OAN 40-m telescope and the IRA 64-m Sardinian Radio Telescope. A significant increase in collecting area for cm-VLBI will have to await the construction of the next generation cm-wave radio telescope – SKA (see Schilizzi this volume). Meanwhile, significant progress in the area of receiver technology is possible.

Rapid frequency switching is important for spectral index mapping studies but also increases the robustness and reliability of VLBI operations. Many of the telescopes in the EVN are now frequency flexible. Furthermore, polarization purity is another topic that is increasingly important in VLBI receiver design. This is an area in which a homogeneous array such as the VLBA has a significant advantage. The current aim of the EVN is to produce $< 2\%$ cross-talk between left and right hand circular polarization channels. Otherwise polarization issues limit the dynamic range of total intensity images of even moderately bright radio sources. For polarization studies, the level of impurity must be good enough that second order calibration corrections can safely be neglected.

The effects of Radio Frequency Interference (RFI) will also become increasingly important as VLBI systems become more sensitive and observe larger bandwidths. Although RFI does not usually correlate on baselines > 10 km, local interfering signals are often so strong that they can easily saturate receivers, and dominate the antenna system noise. In addition, as a noise source, RFI is often extremely variable on time scales of a few seconds or less — tracking the telescopes calibration under such conditions is usually impossible.

Advances in these areas allow the robust detection of weaker sources or the fast detection of nearby calibrators. Well calibrated telescopes can be used successfully in phase referencing, allowing to use longer integration times than the normal coherence time. The advance of modern correlators, which run with very accurate models obtained by the geodetic community, has introduced phase-referencing as a standard technique.[1] In this mode rapid switching to a nearby calibrator to calibrate instrumentation and atmosphere at each site, allows to map sources too weak for self-calibration. This permits the routine detection of relatively faint (sub-mJy) radio sources[2] at wavelengths up to $\lambda \approx 1$ cm. These phase-reference images are often dynamic range limited at the level of 20:1, in-beam phase-referencing removes such limitations.

2.2. Data acquisition

Access to much broader bandwidths is expected to increase at a rapid rate in the next couple of years. The consequences for both mm and cm-VLBI are significant. The longer term aim must be to attain data rates of several Gb/s, reaching tens of Gb/s by the end of the decade. This can be utilized not just for bandwidth but also in order to employ multi-bit signal representation required by RFI mitigation algorithms.

The maximum total bandwidth used with tape-based recording systems is ≈ 64 MHz (in each of 2 polarizations), corresponding to a total data rate of 512 Mb/s (2-bit signal representation and Nyquist Sampling). In 2003 the maximum data rate that could be sustained in the EVN was 256 Mb/s, set by the availability of the so-called thin-tapes required for high capacity recording. Recently, sustained data rates of 1 Gb/s on disks was advertised. This will lead to a factor of two better sensitivity for both mm and cm-VLBI networks. The replacement of the current generation of magnetic tape recorders, with PC-based disk recorder systems is in full swing. By employing commercial PC hardware, the VLBI community takes advantage of the rapid technological development in this area. In principle, a doubling of the data capacity of PC-based recorders might be expected every few years. Since the Mk5A[3] system can already record at 1 Gb/s (see Figure 1), data rates in excess of this are likely to be possible on relatively short time-scales. In addition, the cost of disks will continue to decrease, at least in real terms (i.e. for a given storage capacity).

An alternative (or perhaps successor) to disk-based recorder systems is the connection of VLBI networks via optical fibres (Figure 1). Fibre communication networks can accommodate the real-time transfer of huge amounts of data over long distances. The adoption of direct fibre connections by *e*-MERLIN (see Garrington this volume) signals the progress that is being made in this area. As the costs of these networks continue to fall, and as commercial networks become more flexible, the introduction of a real-time VLBI system is a reasonable goal to pursue.

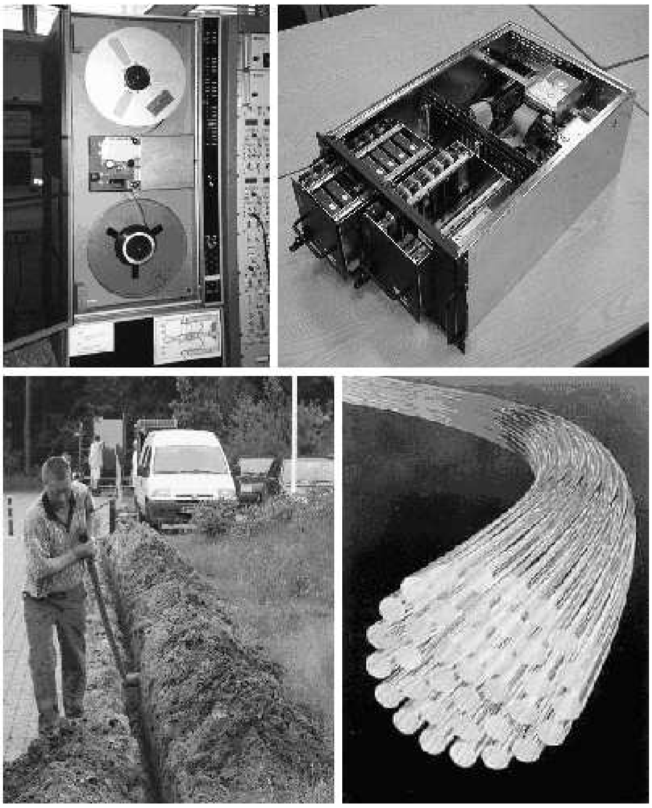

Figure 1. Magnetic tape technology (top left) is now being replaced by PC disk-based (Mk5) recording systems (top right). Real-time VLBI using optical fibre networks must be the long-term goal (bottom right). The EVN correlator at JIVE is already connected by a fibre network that currently provide Gb/s data rates but will be easily upgraded to permit even larger data rates to be employed.

In the EVN we are conducting a project to demonstrate the feasibility of real-time VLBI using shared IP routed networks. A proof-of-concept test programme (to be conducted over the next 1-2 years), aims to connect together directly at least 4 European telescopes to the EVN correlator at JIVE.[4] Each telescope will generate up to 1 Gb/s data streams, and these will feed into the EVN correlator at JIVE. The idea is to correlate the data with minimal buffering at either end of the fibres. The provision of local loops (last mile connections) to the telescopes and correlator is often the critical item. Local loops are in place at Dwingeloo (JIVE), Torun, Onsala and Westerbork. Negotiations are on-going at other EVN sites, in particular Jodrell Bank, Effelsberg, Medicina and Metsahovi.

Several advances have been made in the exploration of eVLBI. We have successfully transferred data at a rate of 300 Mb/s on the international network links. These tests can be conducted in many ways. In order to measure network speeds disk to disk transfers between remote Mk5A units have been made. Similarly so called ftp-VLBI has been explored with short data sets to verify the proper functioning of the VLBI elements before user experiments. These tests can nowadays be performed without interrupting production correlation on the EVN MkIV data processor. Instead a software correlator is used that runs on a cluster computer that can process several baselines in a reasonable time for diagnostics.

However, the goal of eVLBI is to accomplish real-time correlation without buffering. A major milestone was passed on April 28; the first ever real-time European eVLBI image was produced at JIVE. Signals from three radio telescopes of the European VLBI Network (EVN) were sent directly via fibre networks into the Data Processor at JIVE and correlated, without the data at any time having been stored on disk. The array consisted of radio telescopes located in Onsala (Sweden), Jodrell Bank (UK) and a single antenna of the Westerbork Synthesis Radio Telescope (the Netherlands). To transfer the data we used National Research and Education Networks (NRENs) and GÉANT. The NRENs used were: SURFnet, SUNET, NORDUnet and UKERNA. In this experiment a single, dual polarized 4-MHz band, at a frequency of 5.0 GHz was observed with 2-bit sampling,

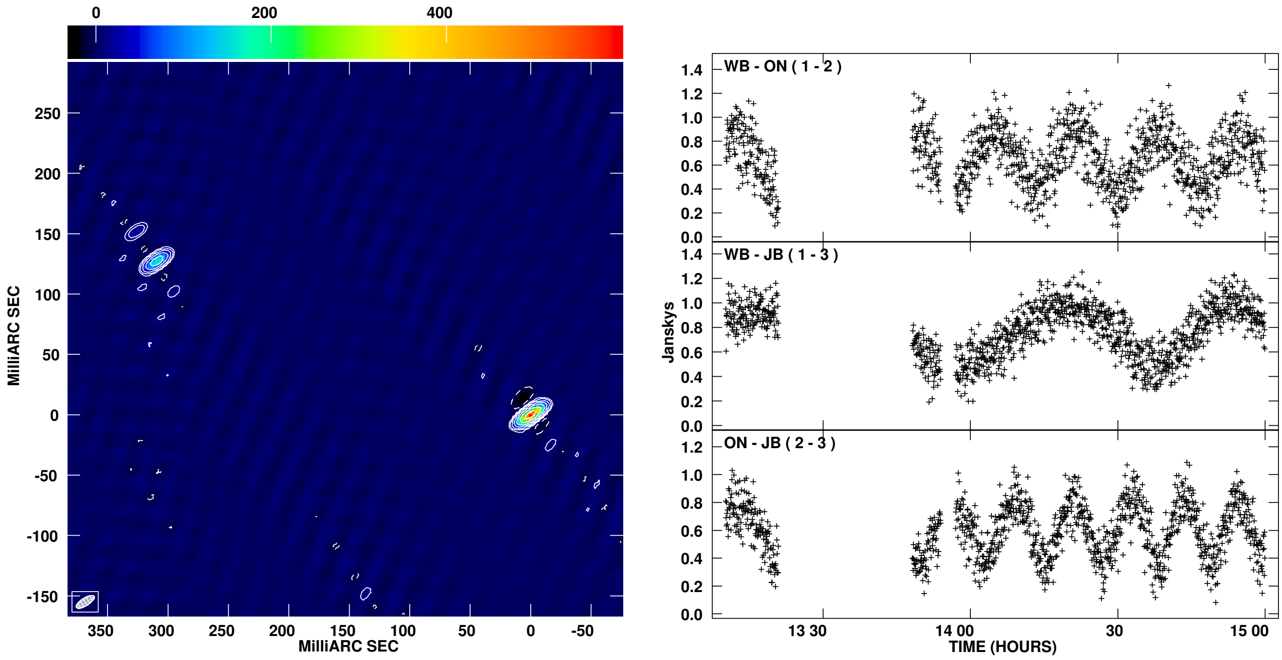

Figure 2. First real time eVLBI map of the gravitational lens system, JVAS B0218+357 (left), two images of a bright radio quasar, separated by 334mas across the sky, result in a beating correlated amplitude on all 3 baselines, the period depending on the baseline length and orientation. Data was digitized at the telescopes and correlated in real-time at JIVE.

resulting in a modest data rate of 32 Mb/s.

Both fibre and PC-based VLBI networks will permit routine Gb/s VLBI observations to be made in the course of the next few years. Developments beyond this requires (in many cases) a replacement of the current VLBI data acquisition system. Correlation capacity is currently limited to 1 or 2 Gb/s per station. For example, the EVN MkIV correlator at JIVE can currently handle 16 telescopes at 1 Gb/s or (potentially) 8 telescopes at 2 Gb/s. Data rates in excess of this would require a new, more capable correlator. It is clear that to take full advantage of the increasing capacity of both disk and fibre-based systems, considerable efforts must begin, in terms of new receiver systems, new data acquisition racks and future VLBI correlator developments.

For continuum cm-VLBI a total gain in sensitivity of at least 5 seems plausible over the next few years. In principle, noise levels at μJy and even sub-μJy levels should be attainable by global VLBI arrays. An important provision is that all VLBI telescopes adopt the same fully compatible, next generation (disk-based) data acquisition systems.

So far we have neglected to mention that any increase in observed bandwidth will also (assuming the data remains unaveraged in frequency) result in an improvement in uv-coverage and thus image fidelity. This is particularly the case for cm-VLBI where the fractional bandwidth should soon approach unity and Multi Frequency Synthesis techniques can be employed to take full advantage of this. An important development in recent times, has been the construction of front-end receivers that can be instantaneously tuned over a wide-range of sky frequency.

3. CORRELATOR DATA PRODUCTS

A peculiarity of VLBI is that the sampled signals are transported in digital form and the shape (resolution) of the data product is defined later in the correlator. In fact, often a set of recordings is processed in more than one pass, for example to get full resolution on different sub-bands in the recording or for optimal response for a different source in the beam of the observations. In the correlator process there are usually two factors that

Figure 3. The EVN correlator at JIVE has been operational since the end of 1999. This picture shows the setup with all 16 station inputs from tape units. Currently half the inputs are disk based recorders. The PCInt project will enable the EVN correlator to generate and handle output data rates as high as 160 MB/s or 13 TB/day. This will permit the full capacity of the correlator to be harnessed.

determine the capabilities of the correlator, the first is the total capacity, the total number of spectral points that the correlator can deliver. The second is set by the output bandwidth, which determines how accurately the VLBI response (visibility) can be sampled and subsequently stored.

In the EVN MkIV data processor at JIVE (Figure 3) the total number of 1024 correlator chips and 16 inputs sets the maximum resolution to 512 spectral points for each baseline in a 16 station experiment. When the number of stations drops below 8, the available number of channels increases to 2048. Currently we are implementing recirculation in the correlator, which will multiply this capacity when the data does not come in at the maximum sample rate of 32 MHz. This feature is mostly applicable for spectral line modes, where modest bandwidths are often used.

The correlator hardware can sample the visibilities with a minimum of 15ms integration time. However, to dump all baseline products at such fine resolution requires considerable bandwidth often exceeding bus and disk access characteristics. We have made considerable advantages in this area.

3.1. Increasing output data rates

For a connected element array, the field-of-view is often set by the primary beam size of the individual telescope elements. For VLBI this is hardly ever the case. In VLBI, a more demanding limitation is set by the fine spectral resolution and short integration times that must be employed in order to circumvent both bandwidth smearing and time averaging effects.[6] Since preserving the field-of-view scales (computationally) with baseline length squared, wide-field VLBI analysis places enormous pressure on off-line computer resources (processing speed *and* disk space). These are many orders of magnitude greater than for short-baseline, connected arrays.

In the same vein, a VLBI field-of-view that is comparable with the primary beam of the individual telescopes, places demands on the correlator output data rate that are nothing short of "fantastic". Pushed to their limits, current VLBI correlators are just about capable of providing sufficient resolution in both time and frequency (e.g. 0.5 s integration time and 1024×62.5 kHz channels) to permit the inner 3 arcmin the telescope primary beam to be imaged out with full sensitivity at 1.4 GHz. This corresponds to a correlator output data rate (≈ 1 MB/s)

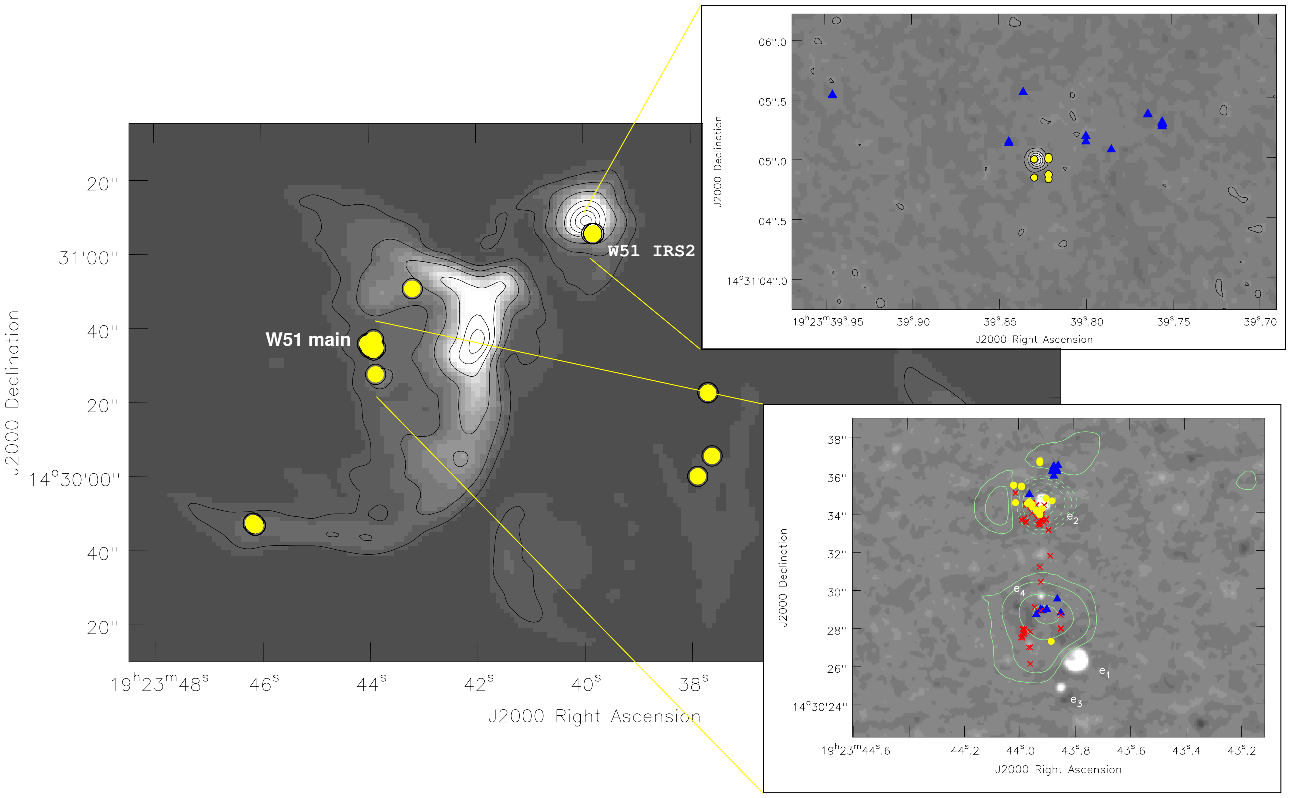

Figure 4. The methanol masers in the massive star formation complex W51 spans arc-minutes on the sky. Imaging these accurately over the primary beam of the contributing telescopes requires high spectral and temporal resolution. The high resolution data can be compared with other tracers of star formation with milli-arcsecond accuracy.[7]

- well short of what is required to map out the full (half-power point) primary beam of a 100m, never-mind the much larger field-of-view associated with 25 or 32m class telescopes.

Much finer spectral resolution is not only required to expand the field-of-view, but is also important for spectral-line studies. Often spectral-line projects have to trade spectral resolution for the number of telescopes, polarization products etc. Many projects also require multiple-pass correlation because more than one spectral feature is present (and the correlator provides just enough resolution for one line in any given pass). The capabilities of the PCInt will also be indispensable when the correlator is upgraded to use recirculation. In this mode the correlator capacity is time-shared for modes that do not require the full sampling rate.

The PCInt project currently being developed at JIVE will enable the EVN correlator to generate and handle output data rates as high as 160 MB/s or 13 TB/day.[5] This will permit the full capacity of the correlator to be harnessed, yielding a spectral resolution of 8092 channels per baseline or integration times as short as 15ms. PCInt will hugely expand the field-of-view of VLBI quite generally (not just the EVN), and will provide the capability to simultaneously map-out large swathes of the radio sky with milliarcsecond resolution.

The first stage in this project has been implemented by upgrading the correlator with 8 Single Board Computers (SBC), which handle the data and have 100 Mb/s Ethernet to flush the data. In the final PCInt configuration the data will be read from DSP powered serial ports. A total of 8×1 GB/s Ethernet connections are then available to flush out the data. The software is set up in such a way that the data can be handled in parallel by a set of workstations that write the data to an array of disks with fast access. This is necessary to overcome another possible bottleneck: disk access.

There are several astronomical applications that require larger fields of view. Galactic masers may extend over rather large areas, especially in star formation complexes (Figure 4). Gravitational lenses are another case

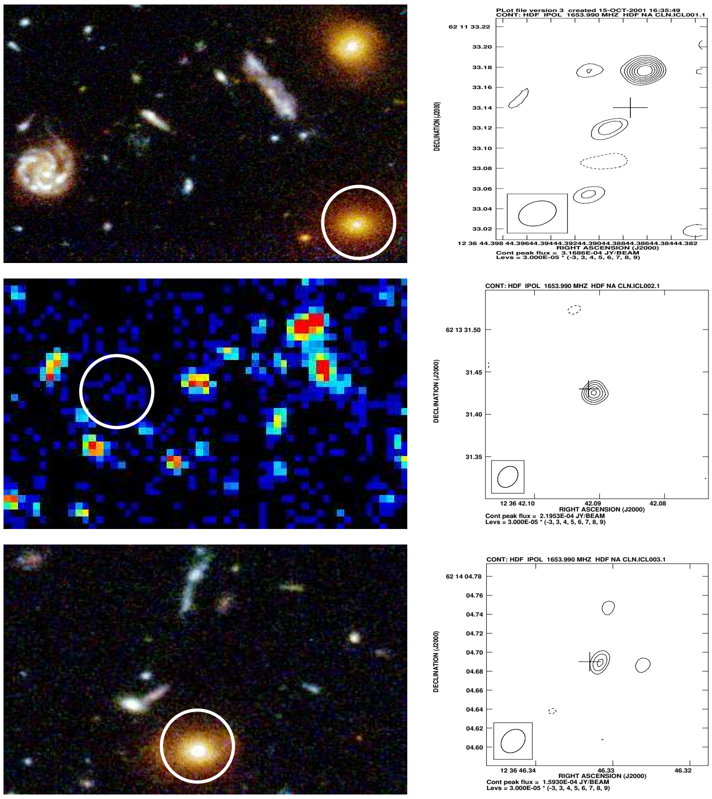

Figure 5. EVN detections in the HDF: the distant z=1.01 FRI (top), the z=4.4 dusty obscured starburst hosting a hidden AGN (middle) and the faint 180 μJy, z=0.96 AGN (bottom). Crosses represent the MERLIN-VLA positions for these sources.[2]

where VLBI sources may extend over a large field of view. Moreover, studies of the faint radio source population may be done more efficiently when a large instantaneous field of view is available. A long integration at the full recording bandwidth can then be employed to study many weak sources simultaneously.

As an example we consider the high resolution observations of radio sources in the Hubble Deep Field (HDF). It contains many radio-sources at low flux level over a large (by VLBI standards) field. Long integrations with the most sensitive telescopes are required to investigate their nature with VLBI. The Effelsberg beam encompasses an area much larger than the HDF and so in principle a single observation can be used to study the nature of each source with VLBI. This technique was explored with the EVN at 1.6 GHz and the VLBA correlator.[2] Even at this moderate resolution the field of view barely covers the HDF. VLBI detections for 3 sources were made at 150-350 μJy (Figure 5). Such studies will benefit greatly from the upgrades ongoing in the EVN, both in recording and correlator capacity.

In addition to sensitivity and image fidelity issues (see previous section), there is another astronomical motivation for instantaneous access to large swathes of bandwidth: Serendipitous VLBI spectral line surveys (e.g. HI in absorption). Already such surveys are being conducted by connected element arrays[8] and as the field-of-view of VLBI observations increases, VLBI can easily follow suit.

3.2. User products

Over the last 10 years the VLBA has the set the standard in terms of generating accurate and homogeneous VLBI calibration data. The next step is to provide images via both manual and automatic analysis paths. The EVN is making progress in this area, continuous system temperature data is now available, both as a function of time and frequency. The calibration of the telescopes is considerably improved, with lots of essential new features. In addition, the EVN is now able to compare the pointing position of the telescope and the direction of the target source i.e. it is now possible to generate "flag files" that can be used to identify non-valid telescope data. Furthermore, the data is now made available in an on-line archive. (http://www.jive.nl/archive/scripts/listarch.php). Initially the data is password protected while the PI has the proprietary rights. At the same place JIVE is providing preliminary calibration for every dataset, through pipeline processing. The EVN pipeline[9] produces a set of AIPS calibration tables (a-priori calibration, fringe-fitting and self-calibration) and various standard plots. As well as reducing the effort required on behalf of the astronomer, we also gain a much better understanding of the performance of the network. The astronomer who proposed the project can opt to initially restrict the pipelining to calibrators. However, after the proprietary period of one year the preliminary images will be available through internet access. This way all astronomers can take advantage of the EVN pipeline - irrespective of their experience, affiliation or geographical location.

With PCInt the data streams will increase. It is anticipated that all correlation will one day run at full resolution in order to build up an archive which may be accessed for other scientific studies than the original proposal. However, data quality evaluation and internal calibration must still be performed promptly. While the output data will be at full resolution, the PI may receive the data at a coarser resolution, one that is optimal for the scientific goal of his study. In a similar way the interface to the archive will allow users to make a selection and create a dataset at a lower resolution, possibly by averaging for a new target position. This operation will be ported to a parallel processing environment, in order to make such products available in an almost interactive manner. It is possible that wide field of view VLBI images will be made as an integral part of the data processor product. Such a solution would fit in with the Virtual Observatory paradigm.

The above activity is part of an EC funded activity within the RadioNet consortium called ALBUS. It also involves work on new calibration tools for ionospheric and tropospheric calibration. These will allow for example more robust phase referencing. In the same project there is attention for implementing both wide-field and wide-band imaging processing on cluster computers. Such tools are required to allow the user to take full advantage of the very sensitive, very massive data of the eEVN.

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