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Scientific Applications of e-VLBI

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The advantages of e-VLBI over traditional media-recorded VLBI are briefly discussed. These advantages lie in two broad areas, those which reduce the operational burden of VLBI and those which enable wholly new kinds of observations to be made. In the first category, e-VLBI contributes to increases in reliability, to a more convenient way to use the instrument, reduced manpower effort and an easing of scheduling constraints. It also allows us to more easily expand bandwidth without building new recording equipment. In the second area the obvious advantage is in the increased speed of results from e-VLBI, which allows rapidly evolving sources to be observed and the next observations planned. A less appreciated, and yet to be fully realised e-VLBI advantage, especially when married to real time software correlation, is that of automation. Automated media-less operations will allow new types of long duration survey VLBI observations to be made lasting weeks to months. Potentially such a system could be used to create an always-on few telescope VLBI network which would follow up all suitable transient detections for accurate radio position and structure determination. An important and continuing benefit of the e-VLBI developments of recent years has been the closer integration and merging of connected element and long baseline interferometry via the e-MERLIN and e-LOFAR projects. The long term prospects for this synergy and the implications for long baseline centimetre wavelength interferometry in the era of the SKA are briefly mentioned.

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1. Introduction

Would we ever, if we didn't have to, build a radio interferometer which was *not* a real time instrument? That is to say would we choose to build an interferometer which relied on recorded media, unless forced to by technical difficulty/cost? The answer is surely no, nobody has ever seriously considered basing say ALMA or the EVLA on recorded data. While recording antenna electric field data has some small specialist advantages (such that the data can be re-correlated) this is more than outweighed by its many disadvantages. These disadvantages include (1) Non-real time operation, limiting reliability of VLBI, disallowing some types of rapid-response science, and providing a barrier to the use of the technique to new users who are more used to faster response times. (2) The large infrastructure required to transport, store and catalogue the media. This effort is very labour intensive and hence costly. The limits on physical media and manpower give an inflexible system where the rate of recording is fixed. Additionally since every upgrade in bandwidth has historically required an upgrade to the recording equipment, such upgrades have been expensive and time consuming.

Despite the obvious advantages of real-time operation many of us 'old-hands' have become resigned to doing long baseline interferometry in the slow and traditional way via recorded media; simply because there was no alternative. We are no longer in that situation, the recent world wide community effort in developing the e-VLBI technique and especially the great success of the EU funded EXPReS project has changed this situation. In this paper I discuss the specific advantages of the e-VLBI technique (concentrating on astronomy and having inevitably a somewhat European-centric view). I believe these lie in two broad areas, first in operational advantages (see Section 2) where the same observations we traditionally did can now be done using e-VLBI but with increased reliability, convenience and reduced effort. The second class of advantages (see Section 3) lie in enabling new science applications of the VLBI technique which are qualitatively different from what could be done before. In the final sections of this paper I discuss one final aspect of the e-VLBI revolution namely the synergy with real-time instruments (such as LOFAR and e-MERLIN) and look forward to the future of e-VLBI centimetre wavelength astronomy in the SKA era.

2. Operational Advantages

2.1 Reliability

The Achilles heel of traditional media based VLBI has been that one was efffectively observing blind, meaning faults were often not found until the data was correlated months later. This has historically been an especially significant problem for the EVN which is a part-time array where the telescopes also have other uses. The use of e-VLBI allows end-to-end tests of the system allowing faults to be detected and corrective action to be taken. One way to do such testing is to transmit small amounts of data in selected experiments while the rest is recorded; this operation model is now standard in EVN disk sessions. Such real time fringe testing has contributed to the EVN's strong improvement in reliability in recent years. Furthermore in full e-VLBI experiments the real-time feedback on telescope performance is always present which has contributed to these experiments having a very high record of reliability.

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2.2 Faster results

As discussed below in Section 3 the speed of results of e-VLBI can result in a qualitative difference in the type of science that can be done. In addition however this speed can be highly desirable even when the science could otherwise, with patience, still be done. Arguably the often months long delay between observations and availability of media recorded data is an aspect of media based EVN observations that acts as a barrier to new users. While perhaps more tolerable to old users this may not be true for potential new younger users. It is worth noting that delays of several months are a significant fraction of PhD timescales in many countries. Perhaps an even more annoying aspect is the uncertainty of knowing exactly when one will get the data which adds uncertainty to the planning of research work. When using real-time e-VLBI these problems are eliminated and the observer knows in advance exactly when the data will be available. Having such immediate results will be especially attractive when dealing with joint e-MERLIN - EVN observations where the e-MERLIN part of the data is produced in real time.

2.3 Reduced Effort and Cost

The manpower involved in handling media (often requiring telescope operator staff on duty), and other manpower to pack/condition/unpack and catalogue media is a significant cost in personnel time spread over the network. In addition there are direct shipping costs for the media. These costs are avoided using e-VLBI (although of course there are other costs involved with procuring and renting e-VLBI links).

2.4 Scheduling flexibility and Scalability

In recorded VLBI the size of the media pool and its geographical location is an important factor in addition to telescope and correlator time that must be taken into account when organising observations, a factor which is avoided using e-VLBI. This increased flexibility can allow the rate of observations to be more easily increased in response to demand, rather than being limited by the size of the media pool and how fast it can be cycled through the correlator. Likewise it may be the case that future advances in bitrate are easier to realise with an e-VLBI system than with a media based system since a new recording system does not need to be developed (although this advantage is mitigated against to the extent that future media recording is done on general computer storage devices).

3. New types of Science Applications

3.1 Transients

The obvious advantage of e-VLBI is its speed. It has been pointed out that this is primarily an advantage in the 'speed of results', which should be distinguished from the 'speed of response' - which is the time it takes to set up and obtain VLBI data after a triggering event. The first of these speeds is directly affected by moving from media to e-VLBI. In contrast the speed of response depends on many factors including telescope availability, proposal review and scheduling policies etc. However even in this area there are significant advantages to using real time e-VLBI: the scheduling is less constrained by the availability of media at the stations or the need to ship it to the stations, and quickly set-up observations are more reliable if done in real-time than done blind using recording.

The primary e-VLBI advantage of speed of results means that next observations on a rapidly evolving source can be quickly planned, so that maximum scientific impact can be extracted from the monitoring campaign. These new observations could be using VLBI at the same or different frequency, on a new radio instrument or at a different waveband. Because VLBI has the highest spatial resolution of any direct imaging technique it should ideally be applied at the start of a flaring event, and its results used to plan observations on other instruments. Despite this, until the advent of e-VLBI results on long baselines were often produced only after the whole observing campaign was over or well advanced.

There are many examples given in this conference of e-VLBI applied to transients and it is clearly an area that it is well-tailored for. The dimension of time variability is one of the last frontiers of astronomy to be systematically explored and right now is undergoing a huge expansion in capability. High energy satellites such as Fermi and the metre wavelength LOFAR wide-field of view telescope are or will be discovering transients regularly. Follow-on long baseline centimetre wavelength observations will be needed to obtain accurate positions, high resolution internal structures and radio spectral energy distributions.

One aspect of transient research that is not always fully appreciated is that because individual source types often only occur rarely there is a high scientific priority on collecting as much information as possible on each event. It follows that as well as 'speed of results' it is also highly desirable to have data from as many antennas, on the longest baselines, with as high a bandwidth as possible. While e-VLBI achieves fast results using it may mean leaving out antennas that are not e-VLBI equipped and therefore significantly impacting on achieving these other desirable goals, especially that of getting the highest angular resolution. This problem can be avoided by using 'record and transmit' modes in which those antennas which are e-VLBI equipped at high bandwidth simultaneously transmit in real time to the correlator via e-VLBI and also make a local recording. Those stations without such a connection simply record data. This mode allows for a real-time correlation of a subset of the antennas giving the chance for a 'quick-look' at the data to plan future observations. Later on there can be a correlation of all the antennas using the recorded data, which is either physically shipped to the correlator or 'electronically shipped' over low capacity data connections. This mixed record-transmit mode has been successfully tested on the EVN; in the future it might be deployed to allow global array transient observations in experiments where the EVN portion gives immediate results while the whole global data set is correlated later.

3.2 Automation

While the most obvious impact of e-VLBI is on speed, another potentially far reaching impact is that of the automation that it allows. This is especially the case if e-VLBI is combined with real-time software correlation. Traditional media based VLBI is very manpower intensive and this human factor sets practical limits to the type of experiments that can be planned and executed. Amongst the manpower needed operators are needed to man the telescope and swap media modules. Additional effort at stations are needed to unpack, condition, pack and ship media and at the correlator manpower is needed to unpack, store and mount the media. In contrast for e-VLBI all these manpower steps required to deal with media are eliminated. Combining e-VLBI data transfer

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with software correlators gives additional automation advantages. The old hardware correlators were designed in the tape era and lack flexibility. Such hardware correlators are also needed for their core job of correlating large telescope arrays from the media sessions and large but infrequent many station e-VLBI observations. In contrast a software correlator can be dedicated to serving a small real-time e-VLBI array. Such software correlators can also be more easily integrated into the array scheduling and data reduction pipelines and more easily programmed to deal with interrupts like automatically generated requests to look at new transient sources etc.

With an operational real-time eVLBI/software correlation system one could for instance have two or three antennas conducting survey type observations lasting a month or more at a stretch throughout the year. Possible applications would be maser monitoring, intra-day continuum variables, astrometry and transient follow-up. For spectral line only surveys the bandwidth requirements would be modest, however bandwidths approaching 1 Gbit/s would be desirable for studying continuum transients and for astrometry observations using quasars as references. Such a group of antennas could be used to observe all suitable transients that occur to obtain accurate positions and first structural information. One could imagine given enough committed antennas that at least two e-VLBI connected telescopes could be active all the time at a common frequency in order to do VLBI follow-up on all transients that occur, while meanwhile carrying out survey observations. It goes without saying that in order to fully realise the above dream ideally all aspects of operations from schedule generation to distribution and pipeline reduction of data should also be automated. Work is already well advanced on many of the aspects of automation that will be needed but more is needed in order to implement an operational system.

4. Unifying connected-element and long baseline instruments

A final important area where e-VLBI and EXPReS has had a major impact is the blurring of the divisions between VLBI and connected element interferometry. While members of the VLBI tribe were previously easily recognised by their attachment to tape recorders, this technical difference is no longer so acute. For instance the transmission of data over public networks pioneered by the e-VLBI community is now used to implement the long international baselines on the e-LOFAR telescope. This is an array that was planned from the start to be a connected element real-time interferometer. At several sites of international LOFAR stations the contacts made with academic network providers and the local connections put in place for e-VLBI have greatly aided and speeded up the process of establishing international LOFAR stations. International LOFAR within Europe would not be nearly as advanced as it is today if it were not for work done over the last five years in e-VLBI. Another important aspect of this synergy which we still have to look forward to is the operational one, in which the wide-field of view LOFAR will act as trigger for many new transients which can then be followed up by e-VLBI at centimetre wavelengths.

The other obvious area of synergy between e-VLBI and a connected element instrument is e-MERLIN, which is a unique resource situated in Europe which amongst other things can supply extremely high sensitivity short baselines. To get reliable e-MERLIN+EVN imaging it is essential to get cross fringes from a least some of the e-MERLIN telescopes to the EVN telescopes. Such a seamless interoperation of e-MERLIN and EVN is an important goal to strive for and progress has been achieved within EXPReS towards the goals of getting multiple 1Gbit/s streams out from

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e-MERLIN to be sent to the JIVE correlator and 4Gbit/s streams from an external station (tested from Onsala) into the e-MERLIN correlator. The technical specifications of e-MERLIN in terms of station bandwidth and bitrate are extremely challenging to achieve over public nettworks but are a possible intermediate timescale goal to aim for in future developments within the e-EVN on the way to the goals of the EVN2015 plan.

5. Future Outlook

A final payoff of the work being doing on e-VLBI is that it prepares technology and techniques for the future, which will be vital for implementing SKA. Exactly how the bandwidths required for SKA on continental baselines will be implemented is of course not yet clear, what can be built may in the end depend on costs. Even in the SKA era however there is a bright future for e-VLBI in the Northern hemisphere especially if it can be expanded to reach all of the existing or planned large collecting areas. The Northern hemisphere has advantages over the South in terms of its larger landmass and population. The first advantage means that only in the North are 10000 km baseline arrays available with good uv coverage over a wide range of declinations. The second advantage of high population and large communications capacity means that large bandwidths on such baselines can be practical and economic. A complementary higher resolution radio interferometer to SKA in the Northern hemisphere (probably also extending to higher frequency than SKA, see EVN2015 planning document) would be extremely valuable to have in the SKA-era, however to be an attractive instrument it should ideally like SKA also be a real-time telescope, implemented via e-VLBI techniques.