eVLBI Scientific Benefits

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1 Introduction

The sensitivity of observations of weak radio sources depends on the size of the telescopes, the total observing time and the observing bandwidth. To improve the sensitivity, and so the ability to detect and image weaker radio sources, any or all of these factors needs to increased. Signficantely increasing the observing time is impractical and increasing the collecting area prohibitively expensive. For continuum sources increasing the observing bandwidth is the simplest way of improving the sensitivity of a a wide range of observation.

Recent networking developments within Australia will make large amounts of networking bandwidth available for scientific research at costs much lower than normal commercial rates. These wide bandwidth links (>=10 Gbps) will allow real time correlation at bandwidths much wider than is currently available and have many advantagues over trying to record on and ship a vast array of hard disk drives.

In this document the scientific benefits of installing wide-bandwidth networks to all LBA observatories is discussed. The benefits have been divided into the science which will benefit from improved sensitivity, advantages of using baseband recording and a software correlator, the benefit of real-time correlation and SKA links.

In the first instance only 3 ATNF antennas will be linked (Tidbinbilla may follow fairly quickly), the *uv* coverage will be fairly poor. There are however many scientifically interesting projects which can tolerant moderate image quality and depend critically on sensitivity.

2 Achievable Sensitivity

VLBI by nature has sparse *u*-*v* cover and an inhomogeneous array of antennas. This means image sensitivities depend critically on Tsys and *u*-*v* based weighting. In the following tables, a simple "optimal" weighting has been assumed, which will give maximum sensitivity but higher sidelobe level. Loss of sensitivity due to more sensible weighting techniques will have the same fractional effect regardless of recording data rate. (However if using multi-frequency synthesis, wide bandwidth recording potentially has better *u*-*v* coverage which will reduce the dirty beam sidelode level.)

Table 1: Assumed SEFD values (Jy) for the VLBI antenna. Future receivers may have significantly better Tsys values for some antennas for specific frequencies.

	Frequency (GHz)				
Antenna	1.4	2.4	5.0	8.4	20
Parkes	40	40	110	42	812
Tidbinbilla	22	25		25	60
ATCA	339	470	345	427	865
Phased ATCA[1]	76	105	77	95	193
Mopra	339	400	345	427	900
Hobart	480	650	630	550	2000
Ceduna		380	480	650	2500

[1] Effective SEFD with 5 antennas phased together

Table 2: Images RMS noise (μJy/beam) expected after a 12 hr observation. Natural weighting, with no correction for antenna Tsys has been assumed.

		Frequency (GHz)				
Data rate		1.4	2.4	5.0	8.4	20
128 Mbps	(2×16 MHz)	27	29	80	30	105
1 Gbps	(2×128 MHz)	9.4	10	28	10	37
4 Gbps	(2×512 MHz)	4.7	5.1	14	5.2	19
8 Gbps	(2×1 GHz)		3.6	10	3.7	13
16 Gbps	(2×2 GHz)			7.1	2.6	9.3

Table 3: 3-σ Brightness temperature sensitivities at 8 GHz.

		Frequency (GHz)
Data rate		3-σ Brightness Temperatue Sensitivity (K)
128 Mbps	(2×16 MHz)	8e4
1 Gbps	(2×128 MHz)	3e4
4 Gbps	(2×512 MHz)	1e4
8 Gbps	(2×1 GHz)	9e3
16 Gbps	(2×2 GHz)	7e3

3 Radio Galaxy Populations

The speed and cost of modern computing means that it is now feasible to make VLBI images across a large fraction of the primary beam of the largest radio telescopes. Coupled with high sensitivity, this makes VLBI a powerful probe for studying populations of faint radio galaxies in the early universe. We would expect to be able to detect ∼250 sources within the Parkes primary beam (Jackson, 2004) (assuming a detection limit of 10 μJy in 12 hr at 1.4 GHz).

We do not know the star formation history of the Universe, or when the first stars and galaxies turned on. To address these issues it is necessary to find and study the most distance, and so faintest, objects in the Universe. Experiments such as the Hubble and Chandra deep fields have been made for this reason.

Radio observations have two advantages over optical observations. They are not affected by dust, and so can detect very dusty starburst galaxies which are hidden from optical and infrared observations (around 15% of the μJy radio sources in the Hubble Deep Field are too faint be seen optically). Secondly, VLBI has a much higher spatial resolution than other techniques, allowing the individual galaxies to be resolved. Specifically, VLBI observations of these faint sources can distinguish AGN with their characteristic double lobe structure from star burst galaxies, which dominate the sky at the sensitivities which will are expected to be achieved with this upgrade.

The SCUBA detector on JCMT has detected many individual galaxies which are thought to have star formation rates of $\sim$300 $M_{\odot}$/yr. However, identification has been difficult because of their limited positional accuracy and confusion in the images. Sensitive, high resolution, radio observations offer the best route to identify sum-mm galaxies discovered by SCUBA, APEX and, in the future, ALMA.

4 Faint Radio Sources

The study of a variety of faint radio sources will benefit from the increased sensitivity of this upgrade. The wide field techniques discussed previously will form a vital part of the improve benefit (such as studying SNR in nearby galaxies). Specific potential targets include:

- Sensitive VLBI observations of local group galaxies will be able to detect and resolve specific radio sources, such as supernova remnants and HII regions. As well as improving our understanding of the object populations, the spatial resolution of VLBI will enable proper motion studies to be made which can be used (for example) to track the expansion of SNRs or accurately measure the galactic rotation.

- Micro-quasars are Galactic analogues of AGN but with times-scales much smaller. This makes them ideal laboratories for studying extreme environment astrophysics. Wide band, real-time VLBI is the best way of studying these objects as they are very weak and change rapidly (both in brightness and spatially) on very short time scales (days). The improved sensitivity of the array should also allow study of micro-quasars in nearby galaxies.

- Gravitational lenses are a powerful tool for studying many aspects of cosmology. The improved sensitive will allow a much larger population of lenses and lens candidates to be imaged at high enough resolution study the lens characteristics and allow more accurate modelling of the distribution of both the lensing and lensed galaxy.

5 Pulsars

VLBI observations of Pulsars are important to determine the position and proper motion of pulsar (Dodson et al, 2003). Current bandwidths are enough to measure the brightest sources. Improved sensitivity would allow much weaker sources to be observed and strongest sources to be observed at higher frequencies, where the higher resolution will allow more accurate positions to be determined and the effects of the ionosphere and scintillation due to the ISM. Two specific projects which would greatly benefit from the improved sensitivity are:

- The Pulsar Timing Array is using pulsar timing to search for gravitational wave (Manchester, XXXX). The range of wavelengths the experiment is sensitive to can be increased if the position, parallax and proper motion of the pulsars can be measured independently from the timing data. High sensitivity and the highest practical observing frequency are required to get the most accurate positions. Accurate VLBI positions of a set of pulsars spread across the sky will also allow the Barycentric and ICRF reference frames to be accurately aligned.
- Chandra can be used to directly observe the spin axis for a significant number of pulsars (e.g. Pavlov et al 2000). Comparing the spin axis to the pulsar proper motion gives a unique insight into the initial processes in the SN explosion (Ng & Romani, 2004, Dodson et. al. 2004). Many of the pulsars for which this comparison is possible are quite weak; for these more sensitive VLBI observations are needed to measure the proper motion.

VLBI interferometry can be used to study the scintillation nature of pulsars (Gwinn etal 1998, Gwinn, 2001). Wider bandwidth VLBI systems will allow the pulsar dynamic spectra to be measured over a much wider bandwidth and so more accurate determine the nature of the scintillation.

6 Phase referencing

To obtain accurate positions using VLBI or detect very weak sources, phase referencing is required. To be able to transfer the phase corrections to the target source, the calibrator must be as close as possible, typically no more than a few degrees offset. As the atmospheric coherence time is a few minutes the calibrator must be strong enough to self-calibrate the phase with an integration time of the order of 1 minute. It is often difficult finding a calibrator strong enough and close enough to the target. By increasing the bandwidth (and so the baseline sensitivity) weaker phase calibrators can be used, significantly increasing the chance of finding a near by calibrator. With enough sensitivity (GHz bandwidth) the chance of finding an in beam phase reference source approaches a unity. The ability to use much weaker phase reference calibrators is a benefit for both continuum and spectral line targets. In fact in beam phase referencing will probably be most practical with strong masers (and pulsars) using the “reverse phase referencing” technique, there the target sources is used to self calibrate the data and the phase corrections applied to the rest of the data which is then imaged over the full primary beam to serendipitously detect background radio sources to use as reference positions for proper motion studies.

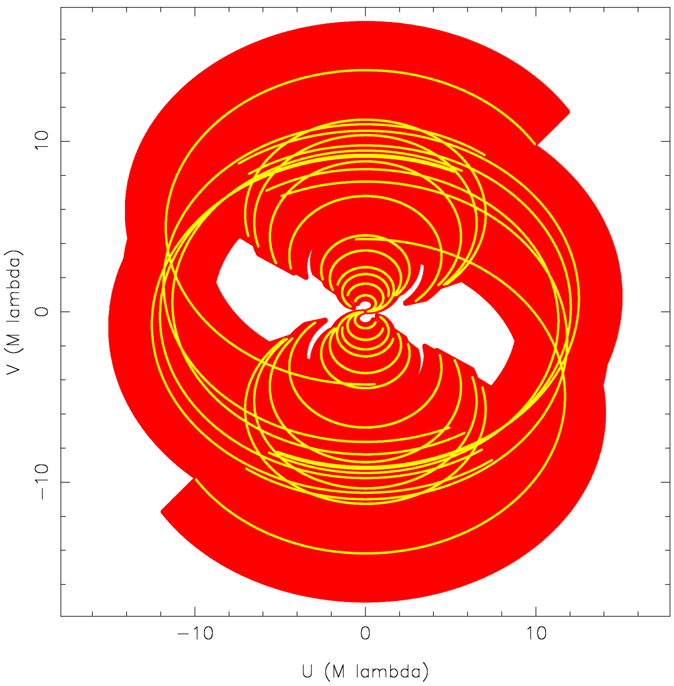

Figure 1: The restored *u*-*v* coverage of the LBA using a 1 GHz bandwidth with a sky frequency of 2–3 GHz. The lines show the normal coverage at 2.5 GHz with a narrow frequency range.

7 Multi-Frequency Synthesis

The LBA suffers because of a limited number of telescopes and so poor *uv* coverage. Multi frequency synthesis can be used to improve the *uv* coverage through the different wavelengths across a wide-band observation. A 500 MHz observing bandwidth at 1 GHz wavelength or 2 GHz at 5 GHz is enough to fill most of the holes in the *u*-*v* coverage. Figure 1 shows the expected *u*-*v* coverage for a 1 GHz bandwidth at a sky frequency of 2-3 GHz. The reduced "holes" in the *u*-*v* coverage will result in reduce side-lobe levels in the dirty beam. This will allow higher quality imaging with increased dynamic range.

8 Masers

Observations of Galactic and extra-galactic water masers currently suffer due to the liited velocity range available with current bandwidths. A 16 MHz bandwidth gives a 200 km/s velocity range at 22 GHz, which is not enough for some Galactic water masers (with velocity ranges in excess of 250 km/s). For water megamasers the velocity widths are even higher ($\sim$2000km/s). Depending on the source either multiple bands across the velocity range, or the entire range would be needed to observe the emission.

The continuum emission associated with jets at the heart of active galaxies which show OH and water megamasers emission is usually too weak detect with current VLBI arrays. The increased LBA sensitivity would allow detection of the center of the galaxies. These could then be used to study the maser/jet interaction, or the continuum emission could use used as a phase reference source to allow imaging of masers with a peak flux much lower than can currently be detected within the coherence time. As an example, the continuum emission from an Arp220 type galaxy could be detected to a redshift of $\sim$3-5.

9 Realtime Single-Baseline Observations

The Parkes-Tidbinbilla (PTI), operating in realtime, was a scientifically very successful instrument. With the LBA antennas networked linked, single baseline PTI type experiments could be easily performed. A Parkes-Mopra baseline with 1 Gbps bandwidth would be slightly more sensitive than the original PTI (Parkes-phased ATCA or Parkes-Tidbinbilla would be significantly more sensitive). Logistically such a system would be very flexible. When Tidbinbilla time becomes available within a shorter time scale than normal ATNF/LBA scheduling, single baseline experiments could be scheduled between available telescopes (Hobart, Mopra in summer, CA06 during compact configurations etc). During the summer a significant amount of time for Mopra-CA06 may be available. Specific science applications which would benefit from single baseline observations include:

- flux density monitoring of compact sources for scintillation studies
- sensitive surveys looking for compact sources
- calibrator surveys. As well as benefiting southern hemisphere VLBI, this would benefit the ATCA and possibly ALMA.
- pulsar proper motion experiments.

10 Other Applications

Wide-bandwidth, realtime links will make the LBA available to service external users for other purposes outside the normal operation of the LBA.

- Three mm VLBI could currently be done between the ATCA and Mopra. It is possible that the Tidbinbilla 34m beam-waveguide antenna could be installed with a 3mm receiver. Due to the high system temperatures and low flux densities of mm continuum sources, wide bandwidths are required to detect all but the brightest targets.
- The geodetic community is currently a leader in the eVLBI field. They wish to process geodetic observations in realtime to make the EOP (Earth Orientation Parameters) values available as quickly as possible. This upgrade will allow telescopes such as Tidbinbilla and Parkes to participate in these experiments. Wider bandwidth observations will eventually increase the accuracy of the geodetic measurements.

- The planned Japanese next generation space VLBI mission, VSOP2, will have data rates of up to 2 Gbps. This upgrade will enable the LBA to again be an important contributor to on-going space VLBI.
- NASA has started using the VLBA for spacecraft astrometry to more accurately determine the orbital parameters of their probes. eVLBI has the potential to make the LBA much more useful as it could provide close to realtime feed back compared to the normal tape record and ship model of VLBI. This would mesh well with the proposed NASA funded 7-mm receivers for the ATCA, allowing spacecraft astrometry at 7-mm, real time transfer of tracking data direct to Tidbinbilla and the incentive for NASA to also fund a 7-mm receiver for Mopra for astrometry.

11 Network links and (near) real-time correlation

Wide bandwidth links will allow data to be correlated in real-time or near real-time. This will have a number of operational as well as scientific benefits.

- With data currently correlated weeks to months after observing, many setup problems at the observatories are not detected until after the observations. Real-time correlation will significantly improve the reliability of the array.
- Currently the network is scheduled in 1 week blocks for logistical reason. This is unsatisfactory for some types of experiments, specifically proper motion observations which may require regular observations much more frequently than the current time between sessions. With a networked array it will be easier to schedule special experiments out of the normal VLBI blocks.
- VLBI observations of transient events such as X-ray and Gamma ray bursts are important in understanding the detailed structure of these events. With eVLBI it will be logistically simpler to respond quickly to such events. More importantly the possibility to correlate the data real-time and process the data almost immediately will be of great benefit. As the time evolution of such sources, in both flux density and morphology, cannot be predicted ahead of time, rapid assessment of the data is needed to know the best way to observe the events.

12 Baseband recording and software correlation

Baseband recording using commodity hardware combined with correlation of the data in software on a cluster of low cost PCs has the advantage of much more flexibility. Potential benefits of this include:

- Ultra high spectral resolution for masers and satellite Doppler tracking.
- Pulsar de-dispersion within the correlation process.
- Baseband recorders can be used for single dish observations as well, allowing a large range of potential specialised single dish observations, such as RFI mitigation and pulsar binning autocorrelation.

13 SKA benefits

The eVLBI expansion will have numerous direct and indirect benefits to the SKA science and engineering effort.

- The two main scientific benefits of SKA will be for high sensitivity, high resolution imaging as well as high sensitivity, low brightness temperature. Low brightness temperature observations will need to "calibrate out" bright unresolved point sources. A high sensitivity LBA will encourage Australian astronomers to study a range of science projects (as outlined already) which will become the "bread and butter" of SKA.
- Many VLBI calibration and processing techniques (such as phase referencing and wide field imaging) will be directly related to high resolution SKA observations.
- The distributed nature of SKA will resemble the current eVLBI project in many ways. This project will enable us to learn how to use the long haul networks effectively as well as build working relationships with potential industry partners.
- While the central core of SKA will be situated in a radio quiet zone, many of the long baseline antennas will have to contend with bad RFI. This array will allow us to directly experiment with various RFI mitigation techniques such as multi-bit sampling for RFI robustness. The advantage of using VLBI for this as opposed to single instruments such as the ATCA or Parkes is that each antenna in the network will see significantly different RFI (as the SKA will).