eVLBI requirements for the CABB
ATNF eVLBI Memo #2
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1 Introduction

The Compact Array Broadband Backend (CABB) is currently being developed for the ATCA and will increase the processed bandwidth to 2 GHz on each of two separate, dual polarisation IFs.

There is interest in using the CABB for realtime VLBI using broadband network links. This document discusses the technical and scientific requirements that the CABB would need to meet to be useful for eVLBI purposes.

2 CABB Overview

The CABB is based on reconfigurable Field Programmable Gate Arrays (FPGA). The basic design of the system is to have two dual polarisation IFs each with a bandwidth of 2 GHz and sample the data with 8 bit precision. The first stage of processing is a digital polyphase filter bank which will channelise the data. The spectral channels are then individually correlated with the corresponding channels from other antennas using a set of simple “continuum” type cross-correlators. Note that the correlator does not perform any further channelisation of the data (i.e. there is no second FFT etc), it simply multiples and accumulates the digitally filtered data.

3 Strawman eVLBI

Using the CABB for eVLBI we would like to be able to process, in realtime, data from at least 8 VLBI stations (including the ATCA) with bandwidths of up to 2 GHz. Some observations would be observed with lower bandwidth in exchange for higher spectral resolution. Correlation of more than 8 stations may be required. For this a mode which traded off total bandwidth for a greater number of input stations would be acceptable.

As the CABB is an 8 station correlator, there may be up to two spare filterbanks. It may be desirable to have them availability for single dish use for Tidbinbilla and UTas antenna simultaneous with normal ATCA usage.

There are two ways the system could be put together.

3.1 Digital Filtering at the ATCA

At the observatories the IF could simply be sampled and then the digitised data sent directly to Narrabri, where it is then fed into the existing polyphase filterbanks for channelisation, fringe rotation etc. This has the advantage that it requires the least amount of equipment at the observatories. However to transport a full dual pol 2 GHz IF with 8 bit sampling would require sending 64 Gbps of user data per station (so at least 320 Gbps data coming into Narrabri). This data rate could be reduced either by reducing the bandwidth or the number of bits of sampling, with an associated reduction in sensitivity. The filterbanks would have to be designed so that they can input < 8 bit data and a total bandwidth < 2 GHz.

3.2 Digital filtering at the Observatory

Polyphase filterbanks could be installed at the observatories and the channelised data sent to the CABB. The main advantage of this is that if the network bandwidth was limited, then instead of transporting, say, a single 256 MHz band of data, two 128 MHz bands at the top and bottom frequency range could be selected. This would be beneficial for multi-frequency-synthesis, needed to help improve the *u*-*v* coverage. Other advantages of having the filterbanks installed at the observatories include:

- they could potentially be used as a DAS for international VLBI experiments where the data are to be sent to a correlator other than the CABB.
- they could be used for single dish spectroscopy.

Geometric delay (and clock) composition wrt the Centre of Earth (COE) would have to be done at the observatory, as the precision to which delay corrections can be made to the filtered data is reduced. (Delay can only be corrected to ± 1 sample, and the filtered data has significantly reduced bandwidth, so sampling interval).

It should be noted that filtering (channelising) the data at the observatory does not fundamentally affect the data rate sent to the correlator After filtering the data could be quantised to 2 bits.

4 Data Transport

Networks are designed in a layered manner with different protocols sitting on top of each other. Normal Internet traffic use the IP protocol, however it sits on top on a number of lower level protocols. A decision will have to be made whether to try and use a high level protocol (i.e. IP) or access the fibres at a lower lever (the SONET layer).

Low level access has a number of advantages:

- Minimal data overhead and fewer computers to delay and impend data flow.
- Capable of accessing full physical bandwidth of network.
- Less equipment on-route to add to jitter, latency etc

- Can be customised to VLBI requirements (tolerate parity errors etc)

However it needs custom designed equipment which may increase cost and manpower.

Alternatively access to the network could be using a high level protocol such as IP. The advantages and disadvantages of this would be:

- Utilise industry standard switching equipment
- Only way to use shared network bandwidth.
- The VSI-e standard (for international eVLBI) is based on IP.
- IP does not guarantee all data will arrive (at all or in order).
- Higher latency and jitter.
- Complicates interface with CABB.
- Restricts the potential data rate with current generation computers.

5 Delay and Fringe Rates

VLBI requires higher geometric delay and delay rate compensation by the correlator than the ATCA will need. For ground based VLBI, the geometric delay would be expected to vary $\pm$25msec from the COE. The data transport latency would be expected to be significantly larger than this. The maximum delay rate for ground based experiments would be 2usec/sec. This gives at fringe rate of 200 kHz for a 100 GHz observing frequency on international baselines. Clock errors would be expected to be up to 50μsec and typical clock rates of a few μsec/sec (up to a 10's of μsec/sec).

If the CABB is ever used for processing space VLBI, then the required delay and fringe rates would need to be significantly larger. The geometric delay would be of the order of $\pm$120msec, however there would also be significant delays to download the data from the spacecraft. The fringe rate would be up to *XXXX*.

There would also be residual delay and fringe rates due to errors in orbit determination. However, these would be significantly less than the geometric delay so should have no impact on the design.

5.1 Spacecraft Tracking

The LBA may be used for space craft tracking. Issues that may rise are rapid changes in effective (Ra,Dec) of the spacecraft (so some sort of ephemeris needed) and solar-system objects are in the near field of the antennas.

6 ATCA specific requirements

The ATCA will have a number of specific requirements for VLBI usage.

6.1 Simultaneous Operation

Observers may wish to use data collected by the ATCA simultaneously with the VLBI. The CABB must be able to simultaneously correlate data from all 6 ATCA antenna with the VLBI data stream. The bandwidth, spectral and time resolution requirements of the ATCA data will generally be different from the VLBI data. (As much bandwidth as possible, with modest frequency and time resolution requirements). This could be achieved by using on of the two ATCA frequencies for filtering and correlating ATCA antenna data, and the other for VLBI data.

6.2 Tied Array

The ATCA is normally used as a phased array for VLBI experiments. This means a tied array unit is needed which can add the signal from multiple antennas. Because the tied array has a limited field of view, some experiments (e.g. wide field imaging) may require the array to be phased with multiple positions within the primary beam. Each of these pencil beams would have to be correlated with all other VLBI antenna. The total number of phased array beams would never be more than 5 (at this point it would be simpler to simply correlate each antenna separately). It would be acceptable to trade off bandwidth for extra tied array beams.

6.3 Split array

For some experiments (e.g. if the ATCA took part in observations with VERA) it would be beneficial to have two tracking points (source/calibrator pair) which are further apart that the single dish primary beam size. The best solution for this is to run the array in a split array mode where some of the antennas are pointing towards (and phased up on) one source and the rest are pointing towards another source.

7 Wide Field Imaging

Imaging a large field with VLBI (anything $>$than a few 10's of arcsec) requires narrow channel bandwidths and short integration times. This is because phase response of a source changes away from the correlation phase centre. The phase rate increases linearly as a source is moved away from the phase centre, as does its phase variation with frequency. To avoid decorrelation effects (so SNR loss) and imaging artifacts (so called time and frequency smearing) the spectral resolution and integration time needs to be “small enough”. What small enough means depends on the frequency, baseline length, required field-of-view (and how much decorrelation the astronomer will tolerate).

To estimate required integration times and spectral resolutions, an aips++ program has been used to calculate decorrelation effects for a sample array. A description of this program is given in and a summary of required integration times for various field-of-views, observing frequencies and arrays are given in an Appendix.

In summary, for the current LBA, integration times of 50 msec and spectral resolutions of up to 5 kHz would be required. Including baselines to South Africa increases these requirements to 13 msec and 1 kHz. This is assuming a maximum decorrelation of 5% on any baseline. Relaxing this requirement allows longer integration times and coarser spectral resolutions (see Appendix)

Given that the potential observing bandwidth is very large compared to observing frequency (for example observing from 1–3 GHz), the required frequency resolution etc changes significantly, as does the FOV. The numbers calculated in the appendix are calculated at specific frequencies, rather than for a, say, 2 GHz band from 1–3 GHz. For a experiment with a 1–3 GHz, the FOV at 3 GHz is 3 times smaller that at 1 GHz. Presumably most observers would use the FOV at highest frequencies. The reduction in required frequency resolution is roughly linear (i.e. roughly 3 times lower for this example).

The LBA is a mixture of large number of different sized antenna (22m, 26m, 30m, 64m, 70m plus the phased ATCA). As such, "Full-primary beam" imaging depends a lot on the compromise the astronomer is willing to accept. The phased ATCA may also be in extended arrays (750m is common), which reduces its FOV considerably. In the Appendix the requirements for a fictional 100m and 25m antenna have been calculated to give indications of the correlation specifications needed.

If the full 2 GHz bandwidth is correlated for widefields, very high correlator output data rates will be required (up to 85 GB/sec in the Appendix). This is equivalent to the input data rate into correlator. Such rates seem unrealistic within the lifetime of the correlator. It is probably realistic to want output data rates up to $\sim$ 100 MB/sec (this is roughly the raw data rate of current disk-based VLBI experiments).

8 International Compatibility

It is important that the LBA is able to continue to observe with other non-LBA observatories. Compatibility with these international partners is important. This includes compatible recording and formatting modes. For example the current standard observing mode is multiples of 16 MHz bands, with channelisation done at the correlator. This data would either have to be recorded at the observatory, or sent to another correlator via the network.

The CABB may be used as the correlator for international telescopes, which may not have digital filterbanks. In this case the ATCA filter banks would have to be used to channelise the data. It is likely that the data from international telescopes would be already processed into numerous bands (e.g 16-128 MHz) and using IP network transport layer.

9 Miscellaneous Requirements

9.1 Circular Polarisations

VLBI requires circular polarisations as the parallactic angle at each telescope will be different. Traditionally, quarter wave hybrids are used to convert linears into circulars at the telescope before recording. Given the large fractional bandwidths (particularly at the lower frequencies), it is unlikely a normal hybrid will be work.

The best solution is probably to use the filter banks to do the linear to circular conversion with a frequency dependence. A technique to calibrate the appropriate phase differences between linear polarisations will need to be developed. It is possible this may need to either be (semi)-continuous (e.g. using the scheduled calibration sources) or repeated at least every few hours.

Given the hybrid nature of the LBA, some flexibility may need to be incorporated into this design (e.g. to allow for receivers which produce circular polarisation). It would be desirable to also use this system for nominally circular receivers to improve the on axis polarisation purity (by applying an appropriate complex gain to the two polarisations).

9.2 Tsys

The receiver Tsys will change significantly across the bandwidth. Some ability to measure Tsys as a function of frequency will be needed. If 8 bit sampling is used, receiver gain as a function of frequency needs to be determined (once per frequency band per observing session). If 2 bit sampling is used, then frequency dependent Tsys will need to be computed.

9.3 Simultaneous Continuum and Spectral Line

For some experiments (such as water masers) the astronomer will wish to observe a relatively narrow band (few 10's MHz to 100 MHz) with as much simultaneous wideband as possible (with relatively low spectral resolution).

Some phase-referenced spectral line experiments may wish to observe the phase reference source with lower spectral resolution (and larger bandwidth) than the program source. This would require rapid ($<$5 sec) mode change for the filter banks and correlator.

9.4 Pulsars

The CABB will need to support VLBI observations of pulsars (i.e. pulsar binning or gating). The existing requirements (for the ATCA) for pulsar observing will be satisfactory.

9.5 Limited Bandwidth

Some stations may have lower bandwidth network connectivity than other stations. This means the number of bits or total sky bandwidth recorded by various stations may differ. The system will need to be flexible enough to cope with this situation.

9.6 Non-connected antenna

It is possible that some antenna which the LBA wishes to co-observe with are not connected to wide bandwidth network links. If this is the case then it will be necessary for all LBA antennas to have a disk based recording system and a way for the CABB to interface with the disk based system for correlation after recording. Availability of the CABB for offline correlation may be a problem, but presumably there will occasionally be times (such as during array reconfigurations) when the correlator could be used.

10 Sample Science Requirements

The following are a few sample science cases and required correlation configuration.

10.1 Wide Field Imaging

Widefield imaging, up to the primary beam will require spectral and time resolutions as discussed in the Appendix. For continuum work as much bandwidth as possible will be required (and still give narrow enough frequency resolution).

For observations when a limited number of objects are in the antenna field-of-view (e.g. in beam phase referencing), a mode where the data is averaged in time and frequencies at multiple phase centres would be beneficial if it reduces the output data rate. A common wide-field observing mode may involve producing many tens of subfields.

10.2 Continuum Imaging

Normal continuum imaging requires maximum correlated bandwidth, but the required FOV (field-of-view) is small (few arcsec). A spectral resolution of 1 MHz is sufficient for Australian baselines.

10.3 RFI affected observations

Large bandwidths at low frequencies will be contaminated by RFI. Many of these observations are likely to require higher number of bits (ie 8 rather than 2) in exchange for lower total bandwidth. RFI affected data would benefit from being processed with higher spectral resolution (for better RFI removal).

10.4 Extra-galactic Water Maser

Extra-galactic water masers often have a large velocity spread across the source ($>$ 2000 km/s). As the individual maser components are narrow ($<$1 km/s) they also require relatively narrow spectral resolution. The maser emissions may also be in a number of distinct velocity groupings. Two main observing modes will be required:

- Single band of up to 200 MHz with a spectral resolution of 35 kHz (5700 channels).
- 2-3 bands of $\sim$30 MHz spread over 200 MHz, also with a spectral resolution of 35 kHz.

10.5 Multi-transition Galactic Masers

OH masers have transitions at 1612, 1665, 1667 and 1720 MHz. It would be desirable to be able to observe all lines simultaneously. Each band would need at least 1 MHz bandwidth and $\sim$2048 frequency channels per band. SiO has lines at 42.8 & 43.1 GHz. It would be desirable to also observe both transitions simultaneously with at least 16 MHz bandwidth and 1024 frequency channels.

10.6 Multi-frequency synthesis

Experiments relying on multi-frequency synthesis to improve the $u - v$ coverage would require 2-4 bands across the full 2 GHz band.

11 Other Considerations

11.1 VLBI without ATCA

Some VLBI experiments may not include the ATCA (e.g. a 4 station experiment with Mopra, Tidbinbilla, Ceduna and Hobart). It would be desirable to be able to run in a mode in with one CABB frequency is dedicated to the ATCA and the other for VLBI.

11.2 Appendix

To calculate decorrelation effects for widefield imaging a aips++ Glish script was written which calculates the maximum phase and delay rates for a given FOV and other observing parameters (sky frequency, position of antennas, position of source etc).

To make the decorrelation calculations the delay and delay rates we calculated using the formula:

$$\dot{\phi} = cos(\delta)\Delta\alpha\dot{u} + \Delta\delta\dot{v}$$
$$\phi = cos(\delta)\Delta\alpha u + \Delta\delta v$$

Where $\Delta\alpha$ and $\Delta\delta$ is the offset of a point source from the phase centre and u & v are the visibility coordinates.

Three array configurations were used. One using the 6 current LBA antenna (Parkes, ATCA, Mopra, Tidbinbilla, Ceduna and Hobart), one including a fictional antenna in Western Australia and the third array also including the Hartebeesthoek antenna in South Africa. Calculations were then made for 5 sky frequencies (1.4, 2.4, 4.8, 8.6 and 20 GHz) and for a 2 arcminute FOV as well as the FOV FWHM of a 100 m and 25 m antennas (chosen arbitrarily given the range of antennas diameters within the LBA).

For the full combination of arrays, frequencies and FOV's three different decorrelation tolerances were used allowing a maximum decorrelation (on any baseline of 5%, 10% and 50%. It has been assumed that image smearing effects of visibilities with up to 50% decorrelation can be corrected for when imaging (Cornwell, private communication). It is worth remembering that most baselines have less decorrelation than this maximum and for the most affected baseline the average decorrelation will be less.

The technique used to come up with the required frequency and time resolution was to first calculate the required frequency resolution assuming a 10 msec integration time and decorrelation of 45%, 9% and 4%. The calculated frequency resolution was then used to calculate the maximum integration time which would give a maximum decorrelation of 50%, 10% and 5%.

The following 2 tables give the required frequency then time resolutions, while the third table gives corresponding correlator output data rate. The values were calculated for a source with a declination of -20 and a total observing time of 16 hours (depending on source elevation). The required time and frequency resolutions would be less for sources further from the equator.

Required frequency resolution (kHz) for 3 sample VLBI arrays, for a range of frequency, field of view and maximum decorrelation.

Decorrelation[a]	**FOV**[b]	**L**[c]	**S**[c]	**C**[c]	**X**[c]	**K**[c]
	LBA (At, Mp, Pk, Ti, Ho, Cd)					
50%	2’	357.1	357.1	357.1		
	100m	83.3	142.9	285.7	500.0	1111.1
	25m	20.9	35.7	71.4	128.2	294.1
10%	2’	153.8	153.8	153.8		
	100m	35.0	59.9	119.0	212.8	500.0
	25m	8.7	15.0	29.9	53.5	123.5
5%	2’	102.0	102.0	102.0		
	100m	23.1	39.7	79.4	140.8	322.6
	25m	5.8	9.9	19.8	35.5	82.0
	LBA + WA					
50%	2’	208.3	208.3	208.3		
	100m	47.2	80.6	161.3	285.7	666.7
	25m	11.8	20.2	40.3	72.5	166.7
10%	2’	87.0	87.0	87.0		
	100m	19.8	33.8	67.6	120.5	277.8
	25m	4.9	8.4	16.9	30.2	69.9
5%	2’	57.5	57.5	57.5		
	100m	13.1	22.4	44.6	80.0	185.2
	25m	3.2	5.6	11.1	19.9	46.3
	LBA + Hartebeesthoek & WA					
50%	2’	67.1	67.1	67.1		
	100m	15.2	26.0	52.1	92.6	212.8
	25m	3.8	6.5	13.0	23.3	54.1
10%	2’	28.1	28.1	28.1		
	100m	6.4	10.9	21.8	39.1	90.1
	25m	1.5	2.6	5.3	9.5	22.0
5%	2’	18.6	18.6	18.6		
	100m	4.2	7.2	14.4	25.8	59.9
	25m	1.0	1.6	3.3	5.9	13.7

Notes:

(a) Maximum decorrelation on any baseline at any time

(b) Field of view. 2’ is a fixed 2 arminute, 100m is the FWHM of a 100m antenna at the corresponding frequency (8.8’, 5.2’, 2.6’, 1.4’ & 0.6’) & 25m is the FWHM of a 25m antenna at the corresponding frequency (35.3’, 20.6’, 10.3, 5.8’ & 2.5’).

(c) 1.4 GHz, 2.4 GHz, 4.8 GHz, 8.6 GHz & 20.0 GHz

Required time resolution (sec) for 3 sample VLBI arrays, for a range of frequency, field of view and maximum decorrelation.

Decorrelation[a]	**FOV**[b]	**L**[c]	**S**[c]	**C**[c]	**X**[c]	**K**[c]
	LBA (At, Mp, Pk, Ti, Ho, Cd)					
50%	2’	3.446	2.010	1.005		
	100m	0.717	0.706	0.741	0.735	0.868
	25m	0.176	0.178	0.179	0.180	0.189
10%	2’	1.208	0.705	0.352		
	100m	0.257	0.258	0.273	0.266	0.256
	25m	0.066	0.064	0.065	0.065	0.067
5%	2’	0.918	0.535	0.268		
	100m	0.205	0.204	0.204	0.211	0.212
	25m	0.051	0.051	0.051	0.051	0.052
		LBA + WA				
50%	2’	2.027	1.182	0.591		
	100m	0.454	0.457	0.455	0.464	0.457
	25m	0.114	0.114	0.114	0.113	0.114
10%	2’	0.782	0.456	0.228		
	100m	0.172	0.176	0.176	0.179	0.180
	25m	0.045	0.045	0.044	0.045	0.045
5%	2’	0.572	0.334	0.167		
	100m	0.129	0.129	0.130	0.130	0.130
	25m	0.033	0.032	0.032	0.032	0.032
	LBA + Hartebeesthoek & WA					
50%	2’	0.714	0.416	0.208		
	100m	0.159	0.160	0.159	0.162	0.167
	25m	0.040	0.040	0.040	0.040	0.040
10%	2’	0.247	0.144	0.072		
	100m	0.053	0.056	0.056	0.056	0.059
	25m	0.017	0.016	0.016	0.016	0.016
5%	2’	0.207	0.121	0.060		
	100m	0.047	0.047	0.047	0.047	0.047
	25m	0.013	0.014	0.013	0.014	0.014

Notes:

(a) Maximum decorrelation on any baseline at any time

(b) Field of view. 2’ is a fixed 2 arcminute, 100m is the FWHM of a 100m antenna at the corresponding frequency (8.8’, 5.2’, 2.6’, 1.4’ & 0.6’) & 25m is the FWHM of a 25m antenna at the corresponding frequency (35.3’, 20.6’, 10.3, 5.8’ & 2.5’).

(c) 1.4 GHz, 2.4 GHz, 4.8 GHz, 8.6 GHz & 20.0 GHz

Correlator output data rate, assuming the previous time and spectral resolution. The data rate has been calculated assuming 8 stations, a 2 GHz bandwidth, cross polarisations, 4 byte complex visibilities and autocorrelations. The required data rate will scale if less antennas, bandwidth etc are used in a specific experiment.

Decorrelation[a]	**FOV**[b]	**L**[c]	**S**[c]	**C**[c]	**X**[c]	**K**[c]
			LBA (At, Mp, Pk, Ti, Ho, Cd)			
50%	2’	1 MB/s	2 MB/s	3 MB/s		
	100m	19 MB/s	11 MB/s	5 MB/s	3 MB/s	1 MB/s
	25m	306 MB/s	177 MB/s	88 MB/s	49 MB/s	20 MB/s
10%	2’	6 MB/s	10 MB/s	21 MB/s		
	100m	125 MB/s	73 MB/s	35 MB/s	20 MB/s	9 MB/s
	25m	1.9 GB/s	1.1 GB/s	579 MB/s	324 MB/s	136 MB/s
5%	2’	12 MB/s	21 MB/s	41 MB/s		
	100m	238 MB/s	139 MB/s	69 MB/s	38 MB/s	16 MB/s
	25m	3.7 GB/s	2.2 GB/s	1.1 GB/s	621 MB/s	264 MB/s
			LBA + WA			
50%	2’	3 MB/s	5 MB/s	9 MB/s		
	100m	52 MB/s	31 MB/s	15 MB/s	8 MB/s	4 MB/s
	25m	836 MB/s	489 MB/s	245 MB/s	137 MB/s	59 MB/s
10%	2’	17 MB/s	28 MB/s	57 MB/s		
	100m	330 MB/s	189 MB/s	95 MB/s	52 MB/s	22 MB/s
	25m	5.0 GB/s	2.9 GB/s	1.5 GB/s	828 MB/s	358 MB/s
5%	2’	34 MB/s	59 MB/s	117 MB/s		
	100m	666 MB/s	389 MB/s	194 MB/s	108 MB/s	47 MB/s
	25m	10.4 GB/s	6.1 GB/s	3.1 GB/s	1.7 GB/s	759 MB/s
			LBA + Hartebeesthoek & WA			
50%	2’	23 MB/s	40 MB/s	81 MB/s		
	100m	465 MB/s	270 MB/s	136 MB/s	75 MB/s	32 MB/s
	25m	7.2 GB/s	4.2 GB/s	2.1 GB/s	1.2 GB/s	520 MB/s
10%	2’	162 MB/s	278 MB/s	556 MB/s		
	100m	3.2 GB/s	1.8 GB/s	922 MB/s	514 MB/s	212 MB/s
	25m	43.1 GB/s	26.4 GB/s	13.0 GB/s	7.2 GB/s	3.1 GB/s
5%	2’	292 MB/s	500 MB/s	1.0 GB/s		
	100m	5.6 GB/s	3.2 GB/s	1.6 GB/s	928 MB/s	400 MB/s
	25m	84.5 GB/s	49.0 GB/s	25.6 GB/s	13.3 GB/s	5.7 GB/s

Notes:

(a) Maximum decorrelation on any baseline at any time

(b) Field of view. 2’ is a fixed 2 arcminute, 100m is the FWHM of a 100m antenna at the corresponding frequency (8.8’, 5.2’, 2.6’, 1.4’ & 0.6’) & 25m is the FWHM of a 25m antenna at the corresponding frequency (35.3’, 20.6’, 10.3, 5.8’ & 2.5’).

(c) 1.4 GHz, 2.4 GHz, 4.8 GHz, 8.6 GHz & 20.0 GHz