EVLA Memo 64
Wide-Field Imaging with the EVLA: WIDAR Correlator Modes and Output Data Rates

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Abstract

Of all the anticipated imaging problems to be undertaken by the EVLA, the most demanding, both in terms of data rate, data storage and post-processing, will likely be that of wide-band, wide-field imaging – imaging the entire antenna primary beam with the full bandwidth. In this memo, I summarize the correlator requirements for various observing scenarios with the EVLA: distortion-free imaging of the entire primary beam with, and without high levels of RFI; and targeted imaging within the primary beam, with and without high levels of RFI. The capabilities of the WIDAR correlator are described, and the modes which best match the observing requirements are identified. In general, the correlator is an excellent fit for wide-band, wide-field imaging in the VLA's standard configurations. However, for the full EVLA which incorporates the New Mexico Array, the WIDAR correlator will not in general be capable of simultaneously providing full band coverage and full beam imaging without accepting significant image degradation. The shortfall is particularly noted at the lower frequencies.

1 Introduction

The scientific goals set for the EVLA require imaging to the thermal noise for all Stokes parameters. As the imaging characteristics of the EVLA are not perfect, sidelobe responses to off-axis background sources will in many situations limit the sensitivity in the region containing the source of interest. To obtain thermal noise-limited performance, these sidelobes must therefore be accurately removed.

The interferometer response to such off-axis objects is affected by many variables – antenna pointing, primary beam gain and phase, atmospheric phase perturbations, system bandwidth, correlator integration time, and many others. All must be accounted for to some degree for in order to achieve the stated imaging goal.

In this memo, I discuss the practical ramifications of two of these sources of aberration – system bandwidth and time averaging. Both cause well-understood aberrations which can be addressed in a number of ways. The simplest of these – reducing the bandwidth and time averaging to values so small as to reduce the aberrations to negligible values – has an obvious major impact on computing if the total bandwidth is to be retained. The advantage of this approach is that the imaging for all sources within the primary beam will be essentially perfect (except for other aberrations!), and so the full scientific content of the field will be preserved.

An alternate approach is to accept a certain degree of image degradation, and to employ extra post-processing to reduce or remove the sidelobe disturbances of the degraded background objects. Additional processing will generally be required, as the degree of aberration varies with distance from the imaging center, so deconvolution cannot assume a spatially invariant point-source response. Providing that such methods can be shown to be effective in removing the unwanted sidelobes, this approach should be very attractive, as the data rate, and hence the costs of data transfer and storage will be greatly reduced. This approach will likely be taken when the background objects are not of scientific interest. A critical question is how much image degradation can be tolerated while still retaining the goal of noise-limited imaging for the region of interest. Until this question is answered, it is difficult to accurately estimate the required data storage and processing requirements.

Intimately connected with these issues are the capabilities of the correlator. If the correlator cannot provide the required frequency channelization over the full available bandwidth, then full-sensitivity, aberration-free imaging will not be possible, and some loss in either sensitivity of imaging will be inevitable. The EVLA's 'WIDAR' correlator has been designed with the ability to provide the short time-averaging and narrow channelwidths to permit nearly aberration-free imaging throughout the full field of view for the VLA's standard configurations at most frequencies. This correlator provides a very wide range of operational modes, and the identification of the most appropriate correlator mode for a given scientific application will be in general a non-trivial process. One of the goals of this memo is to show how correlator modes are selected for the wide-field imaging application. Note, however, that I do not guarantee that the modes recommended are optimal!

2 Wide-Field Imaging Fundamentals

The most demanding application of the EVLA correlator, both in terms of data rate and in post-processing, will most likely be in wide-field imaging, roughly defined as the observing mode which seeks to map all objects within the solid angle defined by the antenna primary beam[1] For the purpose of permitting estimation of the data storage requirements and processing, I define two specific wide-field imaging modes:

- **Distortion-Free Imaging** This mode seeks to minimize the distortions due to finite bandwidth and time averaging throughout the entire primary beam. The primary scientific application would be for surveys, where accurate flux density and image structure are required throughout the solid angle defined by the primary beam.

- **Targeted Imaging** This mode permits significant imaging degradation for off-axis background objects, provided that the sidelobes of the degraded images can still be removed so that the full sensitivity and imaging fidelity for the sources of scientific interest are retained. This mode would be used when the region of scientific interest is much smaller than the antenna primary beam.

The primary aberrations which blur or distort off-axis images are due to finite bandwidth and time averaging. I discuss each in the following sections, and define criteria for each of the two imaging modes.

2.1 Chromatic Aberration (Bandwidth Broadening)

A unit point source located at radial distance θ from the image coordinate center has a complex visibility given by: $V = \exp(2\pi i B\nu\theta/c)$ – a function of frequency. When observed by an interferometer of projected baseline B and square bandwidth $\Delta\nu$ about central frequency ν_0, the observed visibility amplitude is reduced by a factor

$$R_{\Delta\nu} = \mathrm{sinc}\left(\frac{B}{\lambda}\cdot\frac{\Delta\nu}{\nu}\cdot\theta\right) \tag{1}$$

from the visibility amplitude at the central frequency: $V_0 = \exp(2\pi i B\nu_0\theta/c)$. Here, $\mathrm{sinc}(x) \equiv \sin(\pi x)/(\pi x)$.

For distortion-free imaging within the primary beam, it is necessary to minimize this amplitude loss. A rather stringent condition is that the loss be by less than 10% on the longest baseline at the radial distance of the first null of the primary beam. This null is located at an angle $\theta \sim \lambda/D$, where D is the antenna diameter. The proposed condition leads to a maximum tolerable bandwidth of

$$\Delta\nu = \frac{\nu D}{4B} \tag{2}$$

which sets the bandwidth limit for 'Distortion-Free Imaging'.

For 'targeted imaging', some significant amplitude loss can be tolerated, and a much more relaxed condition can be set. As shown by Bridle and Schwab [1], the effect of chromatic aberration on a synthesis image is to radially convolve the true brightness with a distortion function $D(\theta)$ whose shape is that of the bandpass and whose width is proportional to the angular offset, θ_0, of the source from the phase center. For a square bandpass,

$$D(\theta) = \frac{\nu}{\Delta\nu\theta_0}\sqcap\left(\frac{\nu}{\Delta\nu}\cdot\frac{\theta}{\theta_0}\right), \tag{3}$$

where $\sqcap(x)$ is the rectangle function of unit height and width. This convolution radially stretches the angular extent by an amount $\theta_0\Delta\nu/\nu$, and preserves the total flux. The 'dirty' image is then the convolution of this 'stretched' source with the point-spread function. The net effect is to radially convolve the true structure with

[1] The only significant challenger for this distinction will be in RFI removal – but this application can be rightfully considered as the ultimate wide-field imaging application!

a position-dependent dirty beam which is itself the radial convolution of the center point-spread function with the distortion function. The (degraded) image of a source at any offset could be deconvolved in one of two ways: with the central (undegraded) beam, in which case the 'clean components' will preserve the radial stretching, or with a locally derived beam which includes the radial stretching, in which case the radial aberration will be removed[2]. Both procedures should remove the unwanted sidelobes. The choice of which procedure to follow would presumably be made on practical considerations.

It would appear from this argument that the effects of an arbitrary amount of chromatic aberration can be removed through simple deconvolution of the image, but in fact there will be a limit based on how identical the actual bandpasses are, the structure of the source, and on other practical considerations. When the bandpass shapes are defined by a digital correlator like WIDAR, they should be very stable, and the ability to deconvolve even highly stretched sources should be very accurate. The actual limit on stretching, beyond which the sidelobes cannot be sufficiently removed, is unknown.

For the purposes of this memo, I adopt a fairly conservative criterion for 'targeted imaging' – the radial stretching of a point source at the antenna first null is equal to the synthesized beam's width[3]. This case corresponds to a maximum bandwidth (or channel frequency width) of

$$\Delta\nu = \frac{\nu D}{B}, \tag{4}$$

which thus allows a four-fold increase in channelwidth over the 'distortion-free' case. This defines the limiting bandwidth for the 'Targeted Imaging' mode.

One further factor needs to be incorporated. The EVLA will often be observing in a high-RFI environment. A sharp spectral 'line' caused by narrow-band RFI will be propagated to many (perhaps many tens of) frequency channels by the phenomenon often called Gibbs' ringing. This is caused by the sharp cutoff in the lag function, and can be largely offset by tapering the lag function, or smoothing the output spectrum[4]. Either way, the result is to degrade the spectral resolution by a factor up to two. In order to obtain the desired spectral resolution needed to minimize chromatic aberration, it will thus be necessary to generate the original spectrum with up to twice the spectral resolution. In this situation, the required channel frequency width is reduced by a factor of two, to:

$$\Delta\nu = \frac{\nu D}{8B} \tag{5}$$

for 'Distortion-Free Imaging' in the presence of strong RFI, and

$$\Delta\nu = \frac{\nu D}{2B} \tag{6}$$

for 'Targeted Imaging' in the presence of strong RFI.

Table 1 shows the maximum fractional bandwidth, $\Delta\nu/\nu$ for the four combinations.

Required Fractional Bandwidth, $\Delta\nu/\nu$, for EVLA Wide-Field Imaging							
Imaging Goal	RFI	All values have been multiplied by 10^5					
	Condition	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	High RFI	.89	8.9	28	89	280	890
Imaging	Low RFI	1.8	18	56	180	560	1800
Targeted	High RFI	3.6	36	113	360	1130	3600
Imaging	Low RFI	7.2	72	226	720	2260	7200

Table 1: The required fractional bandwidth, $\Delta\nu/\nu$, required for wide-field imaging. The upper half of the table ('Distortion-Free Imaging') applies when precise imaging of the entire primary beam is desired, the lower half ('Targeted Imaging') applies when only the central object is of scientific interest, but good sidelobe removal of background objects is needed. The 'High RFI' cases apply when in-band RFI is expected, and spectral smoothing will be required to minimize Gibbs' ringing. The 'Low RFI' sampling condition applies when RFI is not expected to be a limiting factor.

[2]However, this will not restore the lost resolution.

[3]This condition has been suggested by both F. Owen and T. Cornwell. It is the author's view that the tolerable stretching will be considerably greater.

[4]Note that in this case, the distortion function $D(\theta)$ takes the form of the smoothed spectral response.

The halving of the spectral resolution, and hence doubling the correlator data production rate, will not affect the data record rate, as the spectral smoothing will be done in the CBE (Correlator BackEnd) prior to archiving. However, due to practical considerations of the WIDAR correlator (explained below), observers will need to be aware of the choice, and to make a decision based on both the expected RFI spectrum and the capabilities of the correlator.

For estimation of the data rate, the relevent number is not the channel width, but the number of channels. This is given by

$$N_c = \frac{\nu_u - \nu_l}{\Delta\nu} = K(BWR - 1)\frac{B}{D} \tag{7}$$

where BWR is the bandwidth ratio: $BWR = \nu_u/\nu_l$, and the coefficient K takes the value of 8, 4, 2, or 1, depending on the RFI condition and field-of-view requirement. The value $K = 8$ applies for distortion-free imaging with expected RFI, the value $K = 4$ applies for distortion-free imaging without RFI, $K = 2$ applies for targeted imaging in the presence of RFI, and $K = 1$ is for targeted imaging without RFI.

The number of required channels, per polarization product, for the EVLA's bands and configurations, is shown in Table 2 when $K = 8$.

Wide-Field Imaging Channelization			
	Band		
Config.	L, S, C	X, U, K, A	Q
NMArray	112000	56000	28000
A	11200	5600	2800
B	3542	1770	885
C	1120	560	280
D	354	177	89
E	112	56	28
BWR	2.0	1.5	1.25

Table 2: The number of spectral channels, per polarization product, needed to accurately preserve the astronomical information within the entire primary beam, for the full bandwidth, in the presence of RFI. If no RFI is expected, the numbers can be cut in half. If the goal is to enable good sidelobe removal without perfect preservation of the background source structures, numbers can be divided by four (when RFI is expected), or by eight (when RFI is not expected). Note that these are the number of channels desired. The number actually obtained will depend on the capabilities of the correlator.

2.2 Time-Averaging Loss

The reduction in amplitude of the complex visibility due to time-averaging is by a factor:

$$R_t = \mathrm{sinc}(ft) \tag{8}$$

where f is the fringe frequency in Hz, and t is the time averaging duration in seconds. For an observation where an object is at an angular distance θ ($<< 1$ rad) from the delay center, the *maximum* fringe frequency is

$$f_{max} = \frac{B\omega\theta}{\lambda} \quad \text{Hz} \tag{9}$$

where B is the baseline length, and $\omega = 7.27 \times 10^{-5}$ rad/sec is the angular rotation rate of the earth.

If the same stringent condition for distortion-free imaging is applied as before – loss on the longest baseline of less than 10% at the first null of the antenna pattern, the maximum fringe frequency for an object at the first null is found to be simply

$$f_{max} = \frac{B\omega}{D} \quad \text{Hz.} \tag{10}$$

This loss condition occurs when $ft = 0.25$, from which the integration time to found to be

$$t_{min} = \frac{1}{4f} = \frac{D}{4\omega B} \quad \text{sec.} \tag{11}$$

For the EVLA, this corresponds to 0.25, 2.5, 8, 25, 80, and 250 seconds for the NMArray, A, B, C, D, and E configurations, respectively.

The effect of time-averaging on an image is much more complicated than that of chromatic aberration, as the time averaging is dependent on the three-dimensionial coordinates of the baseline, and not on the two-dimensional projection of that baseline, as for chromatic aberration. Thus, there is no effective convolving function dependent on the projected baseline components which can be used to permit deconvolution in the image plane. However, it is possible to calculate the effective local point-spread function, utilizing the known distribution of baselines and fringe rates which contribute to the image. One can imagine an imaging procedure where the wide-field image is subdivided into many smaller images, each of which has an associated point-spread function which includes both the effects of finite bandwidth and finite time averaging. This approach is naturally attractive, as the current methodology for wide-field imaging requires sub-division of the image into many sub-fields in order to counteract the so-called '3-d effect', and to enable angle-dependent phase calibration.

There are likely better approaches to handling the deconvolution problem when the data are significantly affected by bandwidth and time averaging, but a discussion of these lies beyond the scope of this memo. For the purposes of estimating the approximate data rate, I will adopt the same pair of conditions that were used for bandwidth broadening – a stringent condition sufficient to permit wide-field imaging with minimal loss of image quality ('Distortion-Free Imaging') with the minimum averaging time given above, and a more relaxed condition, ('Targeted Imaging'), where the averaging is lengthed by a factor of four, hence $t_{avg} = D/(\omega B)$.

3 Relations for Data Production

The WIDAR correlator will generate cross-power and autocorrelation spectra for the 27 antennas currently comprising the VLA. Presuming completion of Phase II, the correlator will be expanded to 40 stations, providing real-time correlation for the 37 antennas of the full EVLA.

Estimation of the output data rate for such a correlator is straightforwards: For N_a antennas, there will be $N_a(N_a + 1)/2$ products (presuming autocorrelations as well as cross-correlations) for each of N_p polarizations. Each of these polarization products will comprise N_c spectral channels, and each complex visibility for each of these channels will be stored as two 4-byte numbers. The assemblage of products will be output at a rate of $1/t_d$ per second, where t_d is usually identified as the integration time. Presuming a 20% overhead for 'meta-data', the output data rate from the correlator can be expressed as:

$$\dot{\mathcal{D}} = \frac{5N_pN_cN_a(N_a + 1)}{t_d} \quad \text{Bytes/sec} \tag{12}$$

Note that the product N_pN_c is often identified with the total number of spectral channels produced by a correlator.

In the following sections, I estimate some values for large-scale experiments.

3.1 Maximum Data Rate

The maximum nominal data rate (presuming the spectral smoothing and resampling is done within the CBE), summing over all four correlations, is then:

$$\dot{\mathcal{D}} = 17.6 \left(\frac{B}{D}\right)^2 (BWR - 1) \quad \text{Bytes/sec for the 27-antenna EVLA27} \tag{13}$$

and

$$\dot{\mathcal{D}} = 32.7 \left(\frac{B}{D}\right)^2 (BWR - 1) \quad \text{Bytes/sec for the 37-antenna EVLA} \tag{14}$$

For the VLA, the rate works out to 35, 11, 3.5, 1.1, and 0.35 MB/sec for the A, B, C, D, and E configurations for $BWR = 2$. For the 37-antenna EVLA, the rate becomes 6.4 GB/sec. It must be emphasized that these are maximum theoretical rates – they presume a correlator which can process the entire 2:1 BWR in all four polarizations.

These rates assume the distortion-free imaging condition. They are reduced by a factor of four if bandwidth broadening at the first null equal to the array resolution is considered tolerable, and by a factor of 16 if both this bandwidth broadening, and a similar degree of time-average loss are accepted. Further reductions by a factor of a few may also be realized if it can be demonstrated that greater bandwidth broadening can be accommodated.

Other significant reductions in data rate and volume can be gained if the frequency and time resolutions were made baseline-dependent. Were both to be employed, reductions by a factor of a few for standard VLA configurations and by at least an order of magnitude for the full EVLA would be obtained.

For all these data-volume reduction schemes, there will be an additional cost in increased data processing needs and complexity. Discussion of the advantages and disadvantages of these is outside the scope of this memo. However, given the potential large reductions in data volume (perhaps more than a factor of 100 for some situations), it will be important to understand these potential savings, and the resulting computational costs.

4 WIDAR Correlator Capabilities

Application of equation 12 requires knowledge of the number of spectral channels produced by the correlator. This in turn depends both on the requirements of the experiment and on the capability of the correlator to meet those requirements. In this section, I give a top-level, necessarily incomplete, summary of the WIDAR correlator's capabilities. For a much more comprehensive description, refer to Chapter 8 of the EVLA Project Book (www.aoc.nrao.edu/evla/admin/projbook/chap8.pdf).

The WIDAR correlator accepts four pairs of inputs, with each pair normally comprising two oppositely polarized signals of up to 2048 MHz bandwidth. Each of these eight inputs is then digitally filtered to produce 16 sub-bands, each with bandwidth of $128/2^n$ MHz, where n can be 0 to 12 – corresponding to a range from 128 MHz to 31.25 kHz. The generated sub-bands for any one input band are not constrained to have the same bandwidth. Sub-bands with 128 MHz bandwidth must be centered on one of 16 defined frequencies, evenly spaced to span the 2048 MHz baseband bandwidth. Sub-bands with narrower bandwidths can be arbitrarily placed within any of the 16 defined 128-MHz wide slots.

The correlator actually consists of 16 sub-band correlators, each of which processes the data from one sub-band for all eight inputs. The sub-band correlator can produce, for each input pair of its sub-band, one, two, or four spectra, corresponding to one parallel-hand polarization (e.g. RR or LL), two parallel-hand polarizations (e.g. RR and LL), or four polarizations (e.g. RR, RL, LR, and LL) respectively. Each sub-band correlator calculates a total of 1024 spectral channels in its standard (non-recirculating) mode.

The correlator has great flexibility in allocating its resources. The 1024 spectral channels from a sub-band correlator can be assigned to one, two, or all four input pairs of signals. Thus, for example, the 1024 channels can be assigned to a single polarization correlation from a single input signal. Or they can be given to the four polarization products from a single input pair. Similarly, the capabilities of an entire sub-band correlator can be assigned to another sub-band correlator. So for example, the 8192 channels from eight of the sub-band correlators can be assigned to the other eight sub-band correlators, thus doubling the spectral resolution. Or the resources of 15 of the 16 sub-band correlators can be given to the remaining sub-band correlator, resulting in 16384 channels for that single sub-band correlator. In the most extreme example, all 16384 spectral channels could be given to a single sub-band correlator to process a single polarization. These 16384 channels would then span the requested sub-band bandwidth, which can be one of 128, or 64, or 32, ..., .03125 MHz, thus providing spectral resolution as fine as 1.91 Hz.

The correlator has two internal modes which directly affect the number of generated spectral channels. The numbers above (based on 1024 channels per sub-band correlator) are appropriate when the correlator is in its '4-bit' mode. If high spectral dynamic range is desired, a '7-bit' mode can be invoked, resulting in a reduction in the number of channels by a factor of four – to 256 per sub-band correlator. When in this mode, the maximum sub-band channel width is reduced to 64 MHz. Furthermore, if the 7-bit mode is utilized, only one IF pair can be correlated with full polarization, or two IF pairs with dual polarization. The choice of 7-bit or 4-bit correlation can be assigned by specific sub-band correlator and input IF pair. Hence, within a single input IF pair, the use of 7-bits or 4-bits can be individually selected for each of the 16 sub-bands. Furthermore, the use of 7-bit correlation for a sub-band correlation of a single input IF pair does not require 7-bits for the other input IF pair processed by that sub-band correlator. The 7-bit mode is appropriate when high RFI is expected within a sub-band. If the worst RFI is localized to a few specific frequencies, the sub-bands which cover these can operate in the 7-bit mode, and one other IF pair can operate, with full polarization, at 4 bits. This 'mixed-bit-mode' application will preserve correlator resources and maximize the total bandwidth.

The correlator can also provide recirculation on one or two of its input pairs. Recirculation provides twice the number of channels for each factor of two reduction in bandwidth. Thus for example, if a sub-band filter is set to 64 MHz, recirculation can be invoked to double the number of available channels. Another factor of two reduction in sub-band bandwidth enables a further factor of two increase in the number of channels, etc. Recirculation cannot be invoked indefinitely – there are eight available stages of recirculation, thus enabling a factor of $2^8 = 256$ increase in the number of channels. The maximum number of spectral channels available per sub-band correlation is then $1024 \times 256 = 262144$, which would be available at a sub-band bandwidth of 500 kHz if only a single input pair of signals is processed. For sub-band bandwidths narrower than 500 kHz, the number of available channels remains the same. Thus, if all channels are assigned to a single input polarization, the limiting spectral resolution is $31250/262144 = 0.119$ Hz. The maximum number of output spectral channels is $16 \times 262144 = 4194304$. Recirculation is available on any or all sub-bands for two input pairs when operating in 4-bit mode (and the numbers of channels given above assume this mode), but on only one input pair when in 7-bit mode.

4.1 WIDAR and Wide-Field Imaging with the EVLA

The preceding sections assumed that the full bandwidth can be divided into channels whose widths are exactly right for the frequency of observation. This will rarely – probably never – be the case. A real correlator has its own limitations, which must be factored in when attempting to estimate how specific experiments will be set up, and what the data transport, storage, and post-processing needs will be.

The WIDAR correlator is a highly flexible machine which will be able to provide most of the required channelization for wide-field imaging. The correlator configuration used for each band and array configuration depends on many factors – there appears to be no simple rule to be applied. In the following sections, I give what appears to be the optimal setup which will provide the required channel resolution, and maximizes the provided bandwidth coverage, for some of the EVLA's bands. The available setups for both 4-bit and 7-bit resampling are provided for both 2-polarization and 4-polarization applications. It is presumed that a 1-polarization setup is of no interest in wide-field imaging.

5 Suggested WIDAR Modes and Resulting Data Rates

In this section I identify specific recommended WIDAR correlator modes for each configuration and band. In this section, the label 'NMArray' refers to the full, 37-antenna EVLA.

5.1 L-Band (1 – 2 GHz Band)

The total bandwidth is nominally 1 GHz in each polarization, although it is doubtful the frequencies below 1.2 GHz will be used for wide-field imaging, as the sensitivity rapidly degrades below this frequency. At this band, only one input IF pair is required, as it can accommodate the entire bandwidth, and can receive the full correlator resources. Table 3 gives the minimum required channelwidth for this band, based on the low-end frequency of 1.0 GHz.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at L-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free Imaging	Strong	9	89	280	890	2800	8900
	Weak	18	180	560	1800	5600	18000
Targeted Imaging	Strong	36	360	1130	3600	11300	36000
	Weak	72	720	2260	7200	22600	72000

Table 3: The minimum channelwidth in kHz required for wide-field imaging at L-band, for each of the EVLA configurations. Two imaging conditions are considered – distortion-free imaging, where minimal image degradation over the full primary beam is the goal, and targeted imaging, where limited distortions of background objects are acceptable. For each, the required frequency resolution corresponding to a strong RFI case (where frequency oversampling is required) and weak RFI, are given. For this band, I anticipate the strong-RFI case.

Table 4 gives some of the correlator options available for this appliction. The mode to be selected will generally be that which provides both the required channel resolution and the maximum bandwidth, for the number of polarizations and re-quantizer level (either 4 bits or 7 bits) desired. There are many more modes which utilize narrower sub-band bandwidths – however it is clear that these are not of interest for this wide-band application.

WIDAR Correlator Modes for Wide-Field Imaging at L-Band								
	BW	SubBW	4-bit mode (low RFI)			7-bit mode (high RFI)		
Recirc.				2pol	4pol		2pol	4pol
Factor	MHz	MHz	Nchan	kHz	kHz	Nchan	kHz	kHz
0	1024	64	16384	125	250	4096	500	1000
1	1024	64	32768	62‡	125	8192	250	500
	512	32	"	31	62‡	"	125	250
2	512	32	65536	16⋆	31	16384	62	125
	256	16	"	8	16⋆	"	31†	62
3	256	16	131072	4	8	32768	16	31†
	128	8	"	2	4	"	8∗	16
4	128	8	262144	1	2	65536	4	8∗

Table 4: A table to show relevent correlator modes applicable to wide-field, wide-band imaging at L-band. There are many other modes not shown. Note that the 2nd column shows the input bandwidth *per polarization*, while the 4th and 7th columns show the *total* number of spectral channels produced. The best mode choices for imaging with the full EVLA (VLA+NMArray) are marked by the symbols: ∗ identifies recommended modes for distortion-free imaging in the presence of RFI; ⋆ for distortion-free imaging without RFI; † for targeted imaging with RFI; and ‡ for targeted imaging with no RFI.

Within this table, I have identified with four symbols those modes which provide the necessary spectral resolution, while maximizing the total processed bandwidth, for the full EVLA (VLA + NMArray) requirements, for the four conditions:

- Distortion-free imaging correlator modes with spectral oversampling to constrain the effects of RFI are identified with an asterisk (∗). For this case, the required resolution is 9 kHz, while the correlator can provide 8 kHz – a good match.
- Distortion-free imaging correlator modes with no spectral oversampling are identified with a star (⋆). The required resolution is 18 kHz, the correlator provides 16 kHz.
- Imaging with moderate bandwidth broadening, with spectral oversampling, are identified with a dagger (†). The requirement is 36 kHz, the correlator provides 31 kHz.
- Imaging with moderate bandwidth broadening, with no spectral oversampling, are identified with a double dagger (‡). The requirement is 72 kHz, the correlator can provide 62 kHz.

The recommended modes and the net output data rates for distortion-free imaging are given in Table 5, and for targeted imaging are given in Table 6.

In these tables, I have selected, for each configuration, the correlator setup modes which match the loss requirements for four different situations: 4-bit mode with critical spectral sampling for two and four polarizations, and 7-bit mode with spectral oversampling for two and four polarizations. Given the expected RFI environment at this band, the 7-bit modes are likely to be required. Mixed 4-bit and 7-bit modes are possible – as discussed in the next section.

From these tables, I can conclude that the WIDAR correlator will enable full-bandwidth, full-polarization distortion-free imaging, in a low-RFI environment, for all standard VLA configurations. For a high-RFI environment, the full-bandwidth can be processed only for the short (C, D and E) configurations, while for B-configuration, the full bandwidth can be processed if only the parallel-hand correlations are desired. For the full EVLA, very significant bandwidth reductions will be required – to as low as 128 MHz total if the 7-bit mode with spectral oversampling is required for all sub-bands.

The situation is much better for targeted imaging, where the full bandwidth can be processed for the A-configuration, and even for the full EVLA with dual polarization if the low-RFI condition can be applied to these long baselines (a likely possibility for most of the WIDAR sub-bands).

Observing Modes and Data Rates for Distortion-Free Imaging at L-Band													
Config.	Δt	NPol	High RFI (7-bits + oversamp.)					Low RFI (4-bits + crit.samp)					
			CW	BW	Nch	Nch	$\mathcal{D}$	CW	BW	Nch	Nch	$\mathcal{D}$
	sec		kHz	MHz	corr	record	MB/s	kHz	MHz	corr	record	MB/s
NM	.25	2	8	128	32768	16384	460	16	512	65536	65536	1840
Array		4	8	128	65536	32768	920	16	256	65536	65536	1840
A	2.5	2	31	512	16384	8192	12.4	125	1024	16384	16384	25
		4	31	256	16384	8192	12.4	125	1024	32768	32768	50
B	8	2	250	1024	8192	4096	2.0	500	1024	16384	4096	1.9
		4	250	512	8192	4096	2.0	500	1024	16384	8192	3.9

Table 5: The optimal WIDAR correlator modes and output data rates for distortion-free wide-field imaging in the 1–2 GHz band. The examples shown are for the RFI-strong case (requiring 7-bit correlation and factor-of-two spectral oversampling), and the RFI-weak case (4-bit correlation and no spectral oversampling). In this band, the high RFI case is likely to apply in most sub-bands. The first three columns are, in order: (1) Configuration, (2) averaging time, (3) number of polarization products. The next five columns apply to the 'high-RFI' 7-bit correlation mode, and are in order: (4) the channelwidth in kHz, (5) the single-correlation bandwidth in MHz, (6) the total number of channels produced, (7) the total number of channels recorded, and (8) the archive data rate. The final five columns are the same as columns 4 – 8, but pertain to the low-RFI, 4-bit mode. Values for the C, D, and E configurations are not shown – for these, the full input bandwidth can be processed, and the output data rate is less than $\sim$ 1 MB/sec.

Observing Modes and Data Rates for Targeted Imaging at L-Band													
Config.	Δt	NPol	High RFI (7-bits + oversamp.)					Low RFI (4-bits + crit.samp)					
			CW	BW	Nch	Nch	$\mathcal{D}$	CW	BW	Nch	Nch	$\mathcal{D}$
	sec		kHz	MHz	corr	record	MB/s	kHz	MHz	corr	record	MB/s
NM	.25	2	31	256	16384	8192	230	62	1024	32768	32768	920
Array		4	31	256	32768	16384	460	62	512	32768	32768	920
A	2.5	2	250	1024	8192	4096	6.3	500	1024	16384	4096	6.3
		4	250	512	8192	4096	6.3	500	1024	16384	8192	12.5

Table 6: The optimal WIDAR correlator modes and output data rates for targeted wide-field imaging in the 1–2 GHz band, for high-RFI and low-RFI environments. Refer to Table 5 for a fuller description of the entries. Entries for B through E configurations are not shown – for these the full input bandwidth can be processed, and the data archive rates are less than 2 MB/sec.

5.2 S-Band (2 – 4 GHz Band)

The total bandwidth at this band is 2 GHz in each polarization. The use of 7-bit or 4-bit correlation will depend on the RFI environment. If 7-bits is required, only one IF pair will be utilized when full polarization is desired, or when recirculation is required. Otherwise, two IF pairs will be employed, with the input bandwidth split between them[5].

As discussed in Section 4, mixed 4-bit and 7-bit modes are available, and will be used if the RFI within a sub-band is not so high to require 7-bit correlation. But if 7-bits is utilized for one sub-band correlator, then the maximum sub-band width will be 64 MHz, and that sub-band correlator cannot process any other input IF pair if full polarization is desired. If only two polarizations are desired, one other input IF pair can be processed – at 7-bits with 2 polarizations, or 4-bits with full polarization.

Table 7 gives the minimum required channelwidth for this band, based on the low-end frequency of 2.0 GHz.

Table 8 gives some of the range of correlator options available for this appliction.

The net output data rates for the most extreme case (distortion-free imaging) are given in Table 9 for various modes. In this table, I have selected, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations.

Table 10 shows the preferred modes and data record rates for Targeted Imaging at S-Band.

The situation is similar to L-band – the full bandwidth can be processed in the low-RFI distortion-free case for

[5]With no recirculation, and 4-bit correlation, one input pair could be utilized. However, there is no advantage is doing so

Channelwidth in kHz Required for EVLA Wide-Field Imaging at S-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	18	180	560	1800	5600	18000
Imaging	Weak	36	360	1110	3600	11100	36000
Targeted	Strong	72	720	2250	7200	22500	72000
Imaging	Weak	145	1450	4500	14500	45000	144000

Table 7: The minimum channelwidth in kHz required for wide-field imaging at S-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

WIDAR Correlator Modes for Wide-Field Imaging at S-Band												
	4-bit mode (Low RFI Case)						7-bit mode (High RFI Case)					
Rcrc	N_{ifp}	Bandwidth		N_{ch}	Channelwidth		N_{ifp}	Bandwidth		N_{ch}	Channelwidth	
Fctr		Total	sbnd		2pol	4pol		Total	sbnd		2pol	4pol
		MHz	MHz		kHz	kHz		MHz	MHz		kHz	kHz
0	2	2048	64	16384	250	500	2∗	2048∗	64	4096	1000	1000
	2	1024	32	"	125	250	2∗	1024∗	32	"	500	500
1	2	2048	64	32768	125	250	1	1024	64	8192	250	500
	2	1024	32	"	62	125	1	512	32	"	125	250
2	2	1024	32	65536	31	62	1	512	32	16384	62	125
	2	512	16	"	16	31	1	256	16	"	31	62
3	2	512	16	131072	8	16	1	256	16	32768	16	31
	2	256	8	"	4	8	1	128	8	"	8	16
1	2	3	4	5	6	7	8	9	10	11	12	13

Table 8: A table to show the correlator modes applicable to wide-field wide-band imaging at S-band. The table comprises two halves, the left for the 4-bit correlation mode, and the right for the 7-bit mode. Column 1 (the bottom line gives the column numbers) gives the recirculation factor. Columns 2 and 8 give the number of input IF pairs, columns 3 and 9 the total input bandwidth, per polarization, columns 4 and 10 give the sub-band bandwidth, columns 5 and 11 the total number of channels produced, columns 6 and 12 the channel resolution for the two-polarization mode (RR and LL), and columns 7 and 13 the channel resolution for four-polarization products (RR, RL, LR, and LL). Note that for the 7-bit full polarization mode with no recirculation, only one IF pair is available. The entries marked with an asterisk (∗) are to be divided by two for full (four) polarization mode.

Observing Modes and Data Rates for Distortion-Free Imaging at S-Band									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW	Nch	Nch	$\mathcal{D}$	BW	Nch	Nch	$\mathcal{D}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	256	32768	16384	460	1024	65536	65536	1840
$\Delta t = .25$	4	128	32768	16384	460	512	65536	65536	1840
A	2	512	8192	4096	6.2	2048	16384	16384	25
$\Delta t = 2.5$	4	512	16384	8192	12.4	2048	32768	32768	50
B	2	1024	4096	2048	1.0	2048	16384	4096	1.9
$\Delta t = 8$	4	1024	8192	4096	2.0	2048	16384	8192	3.9

Table 9: The optimal WIDAR correlator modes and output data rates for distortion-free wide-field imaging at S-band. Refer to the caption to Table 5 for a more complete description.

the standard VLA configurations. High RFI conditions, or the full EVLA, will necessitate significant reductions in bandwidth. For targeted imaging, available bandwidths are at least doubled, and if the weak-RFI condition applies, nearly the entire bandwidth can be accommodated, even for the full EVLA.

Observing Modes and Data Rates for Targeted Imaging at S-Band									
Config.	NPol	Strong RFI				Weak RFI			
		BW	Nch	Nch	$\mathcal{D}$	BW	Nch	Nch	$\mathcal{D}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	512	16384	8192	230	2048	32768	32768	920
$\Delta t = .25$	4	256	16384	8192	230	1024	32768	32768	920
A	2	1024	4096	2048	3.1	2048	16384	4096	6.3
$\Delta t = 2.5$	4	1024	8192	4096	6.2	2048	16384	8192	12.5

Table 10: The optimal WIDAR modes and output data rates for targeted wide-field imaging, for high-RFI and low-RFI environments. See Table 5 for further explanation. Values for the B, C, D, and E configurations are not shown – for these, the full input bandwidth can always be processed, (except for 7-bit mode with full polarization, where half the bandwidth can be processed), and the output data rates are less than ~ 2 MB/sec.

5.3 C-Band (4 – 8 GHz Band)

The bandwidth of 4 GHz per polarization will require the correlator to utilize two input pairs, each of 2 GHz width. Recirculation is available on both for 4-bit mode, but on only one for 7-bit mode.

Table 11 gives the minimum required channelwidth for this band, based on the low-end frequency of 4.0 GHz.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at C-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	36	360	1120	3600	11200	36000
Imaging	Weak	72	720	2220	7200	22200	72000
Targeted	Strong	145	1450	4500	14500	45000	145000
Imaging	Weak	290	2900	9000	29000	90000	290000

Table 11: The minimum channelwidth in kHz required for wide-field imaging at C-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

Table 12 gives some of the correlator options available for this appliction.

WIDAR Correlator Modes for Wide-Field Imaging at C and X Bands												
	4-bit mode (Low RFI Case)						7-bit mode (High RFI Case)					
Rcrc	N_{ifp}	Bandwidth		N_{ch}	Channelwidth		N_{ifp}	Bandwidth		N_{ch}	Channelwidth	
Fctr		Total	sbnd		2pol	4pol		Total	sbnd		2pol	4pol
		MHz	MHz		kHz	kHz		MHz	MHz		kHz	kHz
0	2	4096	128	16384	500	1000	2*	2048*	64	4096	1000	1000
	2	2048	64	"	250	500	2*	1024*	32	"	500	500
1	2	2048	64	32768	125	250	1	1024	64	8192	250	500
	2	1024	32	"	62	125	1	512	32	"	125	250
2	2	1024	32	65536	31	62	1	512	32	16384	62	125
	2	512	16	"	16	31	1	256	16	"	31	62
3	2	512	16	131072	8	16	1	256	16	32768	16	31
1	2	3	4	5	6	7	8	9	10	11	12	13

Table 12: A table to show the correlator modes applicable to wide-field wide-band imaging at C- and X-bands. Refer to the caption for Table 8 for a complete description. Items marked with an asterisk (*) are to be divided by two for 4-polarization mode.

The net output data rates for the most extreme case (distortion-free imaging) are given in Table 13 for various modes. In this table, I have selected, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations.

Observing Modes and Data Rates for Distortion-Free Imaging at C-Band									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW	Nch	Nch	$\dot{\mathcal{D}}$	BW	Nch	Nch	$\dot{\mathcal{D}}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	256	16384	8192	230	1024	32768	32768	920
$\Delta t = .25$	4	256	32768	16384	460	1024	65536	65536	1840
A	2	1024	8192	4096	6.2	4096	16384	16384	25
$\Delta t = 2.5$	4	512	8192	4096	6.2	2048	16384	16384	25
B	2	2048	4096	2048	1.0	4096	16384	4096	1.9
$\Delta t = 8$	4	1024	4096	2048	1.0	4096	16384	8192	3.9

Table 13: The optimal WIDAR correlator modes and output data rates for distortion-free wide-field imaging at S-band. Refer to the caption to Table 5 for a full description.

Table 14 shows the preferred modes and subsequent data production and record rates for Targeted Imaging at C-Band.

Observing Modes and Data Rates for Targeted Imaging at C-Band									
Config.	NPol	Strong RFI				Weak RFI			
		BW	Nch	Nch	$\dot{\mathcal{D}}$	BW	Nch	Nch	$\dot{\mathcal{D}}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	512	8192	4096	115	2048	16384	16384	460
$\Delta t = .25$	4	512	16384	8192	230	2048	32768	32768	920
A	2	2048	4096	2048	3.1	4096	16384	4096	6.3
$\Delta t = 2.5$	4	1024	4096	2048	3.1	4096	16384	8192	12.5

Table 14: The optimal WIDAR modes and output data rates for moderate-distortion wide-field imaging at C-band, for high-RFI and low-RFI environments. See Table 6 for further explanation.

The situation is again similar to L and S-bands – as anticipated, as all three bands have 2:1 BWR, thus requiring the same number of frequency channels.

5.4 X-Band (8 – 12 GHz Band)

As the bandwidth is the same as at C-band, the correlator setups are the same. Because the primary-beam-limited field of view is smaller, the tolerable channelwidths are increased, as shown in table 15, based on the low-end frequency of 8.0 GHz.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at X-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	71	710	2250	7100	22500	71000
Imaging	Weak	142	1420	4500	14200	45000	142000
Targeted	Strong	285	2850	9000	28500	90000	290000
Imaging	Weak	570	5700	18000	57000	180000	580000

Table 15: The minimum channelwidth in kHz required for wide-field imaging at X-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

The correlator options are the same as at C-band, as shown in Table 12.

The net output data rates for the most extreme case (distortion-free imaging) are given in Table 16 for various modes. In this table, I have selected, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations.

The suggested modes and data rates for targeted imaging at X-band are given in Table 17.

The BWR for this band is 1.5:1, so a greater fraction of the band can be expected to be made available for wide-field imaging than the lower frequency bands with 2:1 BR. RFI is not a major concern in this band, and it

Observing Modes and Data Rates for Distortion-Free Imaging at X-Band									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW	Nch	Nch	$\dot{\mathcal{D}}$	BW	Nch	Nch	$\dot{\mathcal{D}}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	512	16384	8192	230	2048	32768	32768	920
$\Delta t = .25$	4	256	16384	8192	230	1024	32768	32768	920
A	2	1024	4096	2048	3.1	4096	16384	8192	12.5
$\Delta t = 2.5$	4	1024	8192	4096	6.2	4096	16384	16384	25
B	2	2048	4096	2048	1.0	4096	16384	2048	1.0
$\Delta t = 8$	4	1024	4096	2048	1.0	4096	16384	4096	2.0

Table 16: A table to show the correlator modes applicable to distortion-free wide-field imaging at X-band. Refer to the caption for Table 5 for a complete description.

Observing Modes and Data Rates for Targeted Imaging at X-Band									
Config.	NPol	Strong RFI				Weak RFI			
		BW	Nch	Nch	$\dot{\mathcal{D}}$	BW	Nch	Nch	$\dot{\mathcal{D}}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	1024	8192	4096	115	4096	16384	16384	460
$\Delta t = .25$	4	512	8192	4096	115	2048	16384	16384	460
A	2	2048	4096	2048	3.1	4096	16384	2048	3.1
$\Delta t = 2.5$	4	1024	4096	2048	3.1	4096	16384	4096	6.3

Table 17: The optimal WIDAR modes and output data rates for targeted object imaging at X-band. See Table 5 for further explanation.

is anticipated that the 4-bit modes will likely be sufficient for most of the sub-bands.

5.5 U-Band (12 – 18 GHz Band)

At this band, the full bandwidth is 6 GHz, thus requiring three input IF pairs to the correlator. The desired channel widths are given in Table 18, based on a lower frequency limit of 12 GHz.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at U-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	110	1070	3400	10700	34000	107000
Imaging	Weak	210	2140	6750	21400	67500	214000
Targeted	Strong	430	4300	13500	43000	135000	430000
Imaging	Weak	850	8500	27000	85000	280000	850000

Table 18: The minimum channelwidth in kHz required for wide-field imaging at U-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

The appropriate setup is to utilize 3 input pairs, each of 2 GHz. In the non-recirculating mode with 4-bits, half the correlator resources will be assigned to the first two input pairs, the other half to the remaining input pair. As this pair will then produce spectra with twice the needed resolution, the CBE will smooth and resample them at the appropriate resolution. With 7-bits, however, only two IF pairs can be processed, limiting the BW to 2048 MHz. With recirculation, we run into significant WIDAR limitations: in 4-bit mode, only two of the input pairs can provide recirculation; in 7-bit mode, only one pair. These restrictions cause significant loss in bandwidth for the highest resolution imaging applications. The applicable correlation setups are shown in Table 19.

The rececommended correlator modes and net output data rates for the most extreme case (distortion-free imaging) are given in Table 20 for various modes. In this table are shown, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations. In this table, I have 'cheated' a little, using the 125 kHz resolution mode when the requirements

WIDAR Correlator Modes for Wide-Field Imaging at U-Band												
	4-bit mode (Low RFI Case)						7-bit mode (High RFI Case)					
Rcrc Fctr	N_{ifp}	Bandwidth		N_{ch}	Channelwidth		N_{ifp}	Bandwidth		N_{ch}	Channelwidth	
		Total MHz	sbnd MHz		2pol kHz	4pol kHz		Total MHz	sbnd MHz		2pol kHz	4pol kHz
0	3	6144	128	12288	1000	2000	2*	2048*	64	4096	1000	2000
	2	4096	128	16384	500	1000	2*	1024*	32	"	500	1000
	2	2048	64	"	250	500	2*	512*	16	"	250	500
1	2	2048	64	32768	125	250	1	1024	64	8192	250	500
	2	1024	32	"	62	125	1	512	32	"	125	250
2	2	1024	32	65536	31	62	1	512	32	16384	62	125
	2	512	16	"	16	31	1	256	16	"	31	62
1	2	3	4	5	6	7	8	9	10	11	12	13

Table 19: A table to show the correlator modes applicable to wide-field wide-band imaging at U-band. Refer to the caption for Table 8 for a complete description. Entries with an asterisk (*) are to be divided by two for 4-polarization mode.

call for 110 kHz (and similarly for the other modes) for the full EVLA. The error from this adjustment will likely be unnoticeable.

Correlator Modes and Data Rates for Distortion-Free Imaging at U-Band									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW MHz	Nch corr	Nch record	$\mathcal{D}$ MB/sec	BW MHz	Nch corr	Nch record	$\mathcal{D}$ MB/sec
NMArray	2	512	8192	4096	115	2048	16384	16384	460
$\Delta t = .25$	4	512	16384	8192	230	2048	32768	32768	920
A	2	2048	4096	2048	3.1	6144	12288	6144	9.3
$\Delta t = 2.5$	4	1024	4096	2048	3.1	6144	12288	12288	18.6

Table 20: A table to show the correlator modes applicable to distortion-free wide-field imaging at U-band. Refer to the caption for Table 5 for a complete description.

Table 21 shows the preferred correlator modes and subsequent data rates for Targeted Imaging at U-Band.

Observing Modes and Data Rates for Targeted Imaging at U-Band									
Config.	NPol	Strong RFI				Weak RFI			
		BW MHz	Nch corr	Nch record	$\mathcal{D}$ MB/sec	BW MHz	Nch corr	Nch record	$\mathcal{D}$ MB/sec
NMArray	2	1024	4096	2048	58	6144	12288	12288	345
$\Delta t = .25$	4	1024	8192	4096	115	4096	16384	16384	460
A	2	2048	4096	1024	1.6	6144	12288	1536	2.4
$\Delta t = 2.5$	4	1024	4096	1024	1.6	6144	12288	3072	4.8

Table 21: The optimal WIDAR modes and output data rates for targeted object imaging at U-band. See Table 5 for further explanation.

The correlator gives quite acceptable full-band performance for all configurations, including the full EVLA, for targeted imaging, providing the weak-RFI 4-bit correlation mode can be applied. We expect this will be the case for most of the 96 sub-bands required to span the band.

5.6 K-Band (18 – 28 GHz Band)

At this band, the full bandwidth is 8 GHz, thus requiring four input IF pairs to the correlator. The desired channel widths are given in Table 22, based on a lower frequency limit of 18 GHz.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at K-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	160	1600	5000	16000	50000	160000
Imaging	Weak	320	3200	10000	32000	100000	320000
Targeted	Strong	640	6400	20000	64000	200000	640000
Imaging	Weak	1280	12800	40000	128000	400000	1280000

Table 22: The minimum channelwidth in kHz required for wide-beam imaging at K-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

The appropriate setup is to utilize 4 input pairs, each of 2 GHz. With 7-bits, however, only two IF pairs can be processed, limiting the BW to 2048 MHz. With recirculation, we run into significant WIDAR limitations: in 4-bit mode, only two of the input pairs can provide recirculation; in 7-bit mode, only one pair. These restrictions cause significant loss in bandwidth for the highest resolution imaging applications. The applicable correlation setups are shown in Table 23.

WIDAR Correlator Modes for K, A, and Q Band Wide-Field Imaging												
	4-bit mode (Low RFI Case)						7-bit mode (High RFI Case)					
Rcrc	N_{ifp}	Bandwidth		N_{ch}	Channelwidth		N_{ifp}	Bandwidth		N_{ch}	Channelwidth	
Fctr		Total	sbnd		2pol	4pol		Total	sbnd		2pol	4pol
		MHz	MHz		kHz	kHz		MHz	MHz		kHz	kHz
0	4	8192	128	16384	1000	2000	2*	2048*	64	4096	1000	1000
	4	4098	64	"	500	1000	2*	1024*	32	"	500	500
	4	2048	32	"	250	500	2*	512*	16	"	250	250
1	2	2048	64	32768	125	250	1	1024	64	8192	250	500
	2	1024	32	"	62	125	1	512	32	"	125	250
2	2	1024	32	65536	31	62	1	512	32	16384	62	125
1	2	3	4	5	6	7	8	9	10	11	12	13

Table 23: A table to show the correlator modes applicable to wide-field wide-band imaging at K, A, and Q bands. Refer to the caption for Table 8 for a complete description. Entries with an asterisk (*) are to be divided by two for 4-polarization mode.

The net output data rates for the most extreme case (distortion-free imaging) are given in Table 24 for various modes. In this table, I have selected, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations.

Observing Modes and Data Rates for Distortion-Free Imaging at K Band									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW	Nch	Nch	$\mathcal{D}$	BW	Nch	Nch	$\mathcal{D}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	512	8192	4096	115	2048	16384	16384	450
$\Delta t = .25$	4	512	16384	8192	230	2048	32768	32768	920
A	2	2048	4096	2048	3.1	8192	16384	8192	12.5
$\Delta t = 2.5$	4	1024	4096	2048	3.1	8192	16384	16384	25

Table 24: A table to show the correlator modes applicable to distortion-free wide-field imaging at K band. Refer to the caption for Table 5 for a complete description.

Table 25 shows the preferred correlator modes and resulting data rates for Targeted Imaging at K-band.

As this band's BWR is 1.5, the overall bandwidth coverage for wide-field imaging is similar to U and X-Band. At this band, little significant RFI is expected. In addition, the very high fringe rates at this band will provide significant RFI isolation. I thus anticipate that nearly all applications can utilize the 'low-RFI' mode. For Targeted Imaging applications (which I expect would be much the majority), the full bandwidth can be processed, even for the full EVLA in dual polarization mode.

Observing Modes and Data Rates for Targeted Imaging at K Band									
Config.	NPol	Strong RFI				Weak RFI			
		BW MHz	Nch corr	Nch record	$\dot{\mathcal{D}}$ MB/sec	BW MHz	Nch corr	Nch record	$\dot{\mathcal{D}}$ MB/sec
NMArray	2	1024	4096	2048	57	8192	16384	16384	450
$\Delta t = .25$	4	1024	8192	4096	115	4096	16384	16384	450
A	2	2048	4096	512	0.8	8192	16384	2048	3.2
$\Delta t = 2.5$	4	2048	4096	1024	1.6	8192	16384	4096	6.3

Table 25: The optimal WIDAR modes and output data rates for targeted object imaging at K band. See Table 5 for further explanation.

5.7 A-Band (28 – 40 GHz) and Q-Band (40 – 50 GHz)

For both these bands, the full 8 GHz/polarization input will be split into four 2 GHz input pairs. The desired channel widths are given in Tables 26 and 27.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at A-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	250	2500	7900	25000	79000	250000
Imaging	Weak	500	5000	15800	50000	158000	500000
Targeted	Strong	1000	10000	31600	100000	316000	1000000
Imaging	Weak	2000	20000	63200	200000	632000	2000000

Table 26: The minimum channelwidth in kHz required for wide-beam imaging at A-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

Channelwidth in kHz Required for EVLA Wide-Field Imaging at Q-Band							
Goal	RFI	NMArray	A-Config	B-Config	C-Config	D-Config	E-Config
Distortion-Free	Strong	350	3500	11000	35000	110000	350000
Imaging	Weak	700	7000	22000	70000	220000	700000
Targeted	Strong	1400	14000	44000	140000	440000	1400000
Imaging	Weak	2800	28000	88000	280000	880000	2800000

Table 27: The minimum channelwidth in kHz required for wide-field imaging at Q-band, for each of the EVLA configurations. Refer to Table 3 for a fuller description.

The appropriate setup is to utilize 4 input pairs, each of 2 GHz, for the 4-bit non-recirculating modes. In 7-bit non-recirculating modes, only two input pairs are available. In recirculating modes, two input pairs are available for 4-bit multiplication, and one input mode for 7-bit multiplication. The available correlator setups are shown in Table 23.

The net output data rates for the most extreme case (distortion-free imaging) are given in Table 28 for various modes. In this table, I have selected, for each configuration, the correlator setup modes which match the bandwidth loss requirements for four different situations: 7-bit mode, with spectral oversampling, for two and four polarizations, and 4-bit mode, with no spectral oversampling, with two and four polarizations.

Table 29 shows the recommended correlator modes and resulting data rates for Targeted Imaging at A- and Q-Bands.

For these highest-frequency bands, full bandwidth, full polarization observing can be provided for the distortion-free low-RFI case. For the reasons discussed for K-band, this case is expected to apply for the great majority of observing. Those few sub-bands with RFI so high that natural fringe-winding is insufficient at the long baselines to reduce the amplitude to tolerable levels can apply the 7-bit mode, with relative little effect on the full bandwidth.

Observing Modes and Data Rates for Distortion-Free Imaging at A and Q Bands									
Config.	NPol	High RFI (7-bit,oversmpl)				Low RFI (4-bit, crit.smpl)			
		BW	Nch	Nch	$\mathcal{D}$	BW	Nch	Nch	$\mathcal{D}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	1024	8192	4096	115	4096	16384	16384	450
$\Delta t = .25$	4	512	8192	4096	115	2048	16384	16384	450
A	2	2048	4096	2048	1.6	8192	16384	4096	6.2
$\Delta t = 2.5$	4	1024	4096	2048	1.6	8192	16384	8192	12.5

Table 28: A table to show the correlator modes applicable to distortion-free wide-field imaging at A and Q bands. Refer to the caption for Table 5 for a complete description.

Observing Modes and Data Rates for Targeted Imaging at A and Q Bands									
Config.	NPol	Strong RFI				Weak RFI			
		BW	Nch	Nch	$\mathcal{D}$	BW	Nch	Nch	$\mathcal{D}$
		MHz	corr	record	MB/sec	MHz	corr	record	MB/sec
NMArray	2	2048	4096	2048	57	8192	16384	8192	225
$\Delta t = .25$	4	1024	4096	2048	57	8192	16384	16384	450
A	2	2048	4096	256	0.4	8192	16384	1024	1.6
$\Delta t = 2.5$	4	1024	4096	256	0.4	8192	16384	2048	3.2

Table 29: The optimal WIDAR modes and output data rates for targeted object imaging at A and Q bands. See Table 5 for further explanation.

6 Summary

Summary tables below show the total bandwidth for each band, for the two-polarization (RR and LL) and four-polarization (RR, RL, LR, LL) cases, for the two imaging scenarios (Distortion-Free, and Targeted), and the two RFI scenarios (strong and weak), are presented for each configuration. Table 30 is for the full EVLA, table 31 is for the EVLA27's A-Configuration, table 32 is for the B-configuration, and table 33 is for the three shortest configurations. In each table, the boldface numbers indicate that the entire input bandwidth can be processed.

Bandwidth in MHz for the Full EVLA								
	Distortion-Free				Targeted			
	High RFI		Low RFI		High RFI		Low RFI	
Band	2pol	4pol	2pol	4pol	2pol	4pol	2pol	4pol
L	128	128	512	256	256	256	**1024**	512
S	256	128	1024	512	512	256	**2048**	1024
C	256	256	1024	1024	512	512	2048	2048
X	512	256	2048	1024	1024	512	**4096**	2048
U	512	512	2048	2048	1024	1024	**6144**	4096
K	512	512	2048	2048	1024	1024	**8192**	4096
A,Q	1024	512	4096	2048	2048	1024	**8192**	**8192**

Table 30: The total bandwidth, per input polarization, in MHz, for the full EVLA, for the conditions listed. The boldface values indicate those for which the full available input bandwidth can be correlated.

In general, these tables show that for the low-RFI applications, the WIDAR correlator will accommodate both the stringent Distortion-Free imaging, and the Targeted Imaging applications with full polarization for the standard VLA configurations. The correlator's 7-bit mode provides very high linearity for high-RFI applications – the cost in applying this mode is a four-fold loss in total bandwidth – particularly evident at the high-frequency bands. However, it is not anticipated that this mode will be much required at these bands, as for these the RFI environment is much more benign, and the rapid fringe rates provide much natural isolation. Thus, this bandwidth restriction is not likely to be important. At low frequencies, where the RFI environment is severe, and the fringe-winding isolation not as effective, the loss of bandwidth is not critical. And, for the shorter

Bandwidth in MHz for the A-Configuration								
	Distortion-Free				Targeted			
	High RFI		Low RFI		High RFI		Low RFI	
Band	2pol	4pol	2pol	4pol	2pol	4pol	2pol	4pol
L	512	256	**1024**	**1024**	**1024**	512	**1024**	**1024**
S	512	512	**2048**	**2048**	1024	1024	**2048**	**2048**
C	1024	512	**4096**	2048	2048	1024	**4096**	**4096**
X	1024	1024	**4096**	**4096**	2048	1024	**4096**	**4096**
U	2048	1024	**6144**	**6144**	2048	1024	**6144**	**6144**
K	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**
A,Q	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**

Table 31: The total bandwidth, per input polarization, in MHz, for the A-Configuration, for the conditions listed. The boldface values indicate those for which the full available input bandwidth can be correlated.

Bandwidth in MHz for the B-Configuration								
	Distortion-Free				Targeted			
	High RFI		Low RFI		High RFI		Low RFI	
Band	2pol	4pol	2pol	4pol	2pol	4pol	2pol	4pol
L	**1024**	512	**1024**	**1024**	**1024**	**1024**	**1024**	**1024**
S	1024	1024	**2048**	**2048**	**2048**	1024	**2048**	**2048**
C	2048	1024	**4096**	**4096**	2048	1024	**4096**	**4096**
X	2048	1024	**4096**	**4096**	2048	1024	**4096**	**4096**
U	2048	1024	**6144**	**6144**	2048	1024	**6144**	**6144**
K	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**
A,Q	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**

Table 32: The total bandwidth, per input polarization, in MHz, for the B-Configuration, for the conditions listed. The boldface values indicate those for which the full available input bandwidth can be correlated.

Bandwidth in MHz for the C,D,E-Configurations								
	Distortion-Free				Targeted			
	High RFI		Low RFI		High RFI		Low RFI	
Band	2pol	4pol	2pol	4pol	2pol	4pol	2pol	4pol
L	**1024**	**1024**	**1024**	**1024**	**1024**	**1024**	**1024**	**1024**
S	**2048**	1024	**2048**	**2048**	**2048**	1024	**2048**	**2048**
C	2048	1024	**4096**	**4096**	2048	1024	**4096**	**4096**
X	2048	1024	**4096**	**4096**	2048	1024	**4096**	**4096**
U	2048	1024	**6144**	**6144**	2048	1024	**6144**	**6144**
K	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**
A,Q	2048	1024	**8192**	**8192**	2048	1024	**8192**	**8192**

Table 33: The total bandwidth, per input polarization, in MHz, for the C, D, and E-Configurations, for the conditions listed. The boldface values indicate those for which the full available input bandwidth can be correlated.

configurations where fringe-winding is negligible, the correlator has the capacity to process the entire input bandwidth, with full polarization, for both imaging scenarios.

The ten-fold increase in baseline length for the full EVLA, which results in a 100-fold increase in data production requirements, generate data processing requirements which do indeed exceed the WIDAR correlator's capabilities for the imaging scenarios considered here. However, for the low-RFI, targeted imaging scenario, the correlator can provide full bandwidth for dual polarization, and, with a slight extra degradation in image quality, 4-polarizations as well. Because of the very high fringe rates encountered in this configuration, I expect RFI contamination – even at the lower frequency bands – to be a minor consideration, so that noise-limited imaging with nearly the full bandwidth and full polarization, will be possible at all bands. For distortion-free applications (the image processing required to attain this will be truly stupendous!), it seems likely that no more than half the available bandwidth can be processed at any one time.

In order to simplify data archiving and processing requirements, the output data rate of the CBE will be limited to ~25MB/sec from 2009 to approximately 2012, when it will be increased approximately ten-fold. Comparison to the estimated data output rates given in Tables 5 through 29 show that this rate will accommodate the correlator modes appropriate for distortion-free imaging for all standard (A through E) configurations in the 4-bit correlation mode, with the exception of the 4-polarization modes at L and S bands. (The reduced bandwidth in the 7-bit high-RFI modes results in a reduction in output data requirements by a factor of four, so this scenario will not strain the data recording capacity). The ten-fold increase in planned capacity in ~2012 will not be sufficient to handle the full EVLA data rate for either 'distortion-free' or 'targeted' wide-field imaging, although for the latter case, a slightly relaxed broadening condition, or baseline-dependent averaging, will allow data rates to drop below the 250 MB/sec limit.

All in all, the WIDAR correlator's capabilities are an excellent match to the imaging goals of the EVLA.

7 Acknowledgement

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References

[1] Bridle, A.H. and Schwab, F.R. 'Bandwidth and Time-Average Smearing', in 'Synthesis Imaging in Radio Astronomy II', ASP Conference Series, Vol 180, Chapter 18, 1999. Taylor, Carilli, and Perley (eds.)