Astronomical Requirements for the New VLA Correlator

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Abstract

The new VLA correlator must be sufficiently powerful and sufficiently flexible to allow the astronomer to use all the new capabilities of the upgraded VLA. Astronomical considerations place stringent requirements on this correlator. It must be capable of correlating the signals from 36 antennas over bandwidths of at least 2-4, and preferably 10, GHz per polarization (bandwidth times polarization products should be at least 8-16, and preferably 40, GHz). This should be split amongst at least 4, and preferably 8, independently-tunable IF pairs. Over this bandwidth at least 4000, and preferably 8000, channels must be produced, with full polarization products for every channel. Integration times as short as 1 second are mandatory, giving a required sustainable data rate of order 10^6, and preferably 10^7, visibilities per second. Closure errors and polarization purity must be sufficient to allow dynamic ranges of $10^6 - 10^7 : 1$, while the spectral dynamic range must be at least $10^5 : 1$. The most important outstanding question is that of radio frequency interference (RFI), which will be present at very high levels throughout many of the lower-frequency bands. The requirements placed by RFI on on-line detection and excision, spectral dynamic range, and gating in time and/or frequency have yet to be worked out.

The astronomical specifications of the new VLA correlator are remarkably similar to those of the Millimeter Array correlator, suggesting the possibility of some savings through a simultaneous design and (possibly) construction. The main distinction between the two currently appears to be their RFI environments, with the upgraded VLA subject to significantly more and worse interference.

1 Introduction

One of the most important parts of the proposed VLA upgrade is the new correlator. It must be capable of handling the wide (multi-GHz) bandwidths proposed for improved continuum sensitivity, have sufficiently many channels to allow high spectral resolution over fairly wide bands, and have enough individually-tunable IFs to allow flexibility in imaging multiple lines and in measuring both line and continuum fluxes simultaneously. Further, the time resolution must be sufficient both to allow monitoring rapidly-varying sources, and to avoid time-averaging losses in imaging the full primary beam of the expanded array. The purpose of this memorandum is to quantify these vague statements, and to set forth the specifications for a correlator which will meet these astronomical requirements.

2 A Note on Nomenclature

Naming conventions for bandwidth and channel requirements can be rather confusing. If we want 2000 independent chunks of frequency, each with full polarization products, is that 2000 or 8000 channels? If we ask for 8 IFs, does that mean two frequency ranges measured with full Stokes parameters, or eight? This memorandum uses the following conventions:

- **Channel:** refers to a single resolution element of frequency. A channel may be have associated single, dual (RR+LL, or XX+YY), or full (all Stokes) polarization correlation products. I have tried to be careful to state specifically which is required in each instance: *e.g.*, 4000 channels dual polarization, which means 4000 frequency elements with two polarization products each. Other authors sometimes refer to this as "8000 channels"; here 8000 channels always means 8000 chunks which do not overlap in frequency.
  In this notation, the total number of complex correlator products is the number of channels times the number of Stokes parameters required for each channel (4000 channels dual polarization corresponds to 8000 complex correlator products).

- **IF:** abbreviation for "intermediate frequency"; used here to refer to an independently-tunable[1] band of frequency. As with a channel, an IF may have associated single, dual, or full polarization correlation products, and this will be made explicit wherever the requirement is for more than a single polarization. In this parlance the VLA currently has two IFs with full polarization information available in continuum mode.
  I also use the term **IF pair** sometimes, to imply (or to emphasize) that both polarizations (RCP+LCP, or X+Y) must be available.

- **Total bandwidth:** in this memo, the total bandwidth is the total frequency coverage, *NOT* the total frequency coverage times the number of correlator products. Again the required number of polarization products will usually be stated explicitly; for instance, an observation covering 3-5 GHz with all four Stokes parameters recorded simultaneously will be referred to as "2 GHz full polarization."

3 Astronomical Constraints on the Correlator

This section summarizes the requirements placed on the correlator by a variety of astronomical observations, taken primarily from *The VLA Development Plan* (1995). For each experiment, I give a brief description and a reference to the relevant section of the *Development Plan*, followed by the total bandwidth, number of independently tunable IFs, number of channels, spectral resolution, and any miscellaneous abilities the correlator must have to carry it out. For most

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[1] "Independently tunable" here means, "capable of being tuned to different frequencies, with reasonable flexibility." There could be some restrictions on which exact frequencies are possible, as in the current LO system; and the LO chains for the two IFs need not be totally independent (e.g. they might share a first LO or some such). For the correlator this doesn't matter, and discussion of the LO system, tuning capabilities, and the like, is outside the scope of this document.

experiments some of these parameters are irrelevant, either because they are unimportant for that particular observation, or because they do not particularly stretch the correlator's capabilities, compared to other projected experiments. In such cases those parameters are omitted. On the other hand, certain observations define the outer limits of what the correlator must be able to do; such demanding[2] parameters are indicated in **boldface**.

3.1 Radio Continuum Imaging

Although discussed in the *Development Plan* primarily in the extragalactic context (§4.2.7), continuum imaging is here given a separate subsection, to emphasize that virtually every area of astronomy will require these capabilities for some experiments.

1. High sensitivity measurements: (§4.2.7) Examples include deep imaging of regions like the Hubble Deep Field, and thermal imaging of the more distant planets, asteroids, and possibly Kuiper Belt objects. The prime mover here is the desire for the utmost in sensitivity, which requires the widest possible bandwidths.

    - *Total bandwidth:* **$\geq$2-4 GHz (prefer 10 GHz at high frequencies) (full pol'n).** See Table 1 for a list of the bands at the VLA and the desired maximum bandwidths within those bands.
    - *Dynamic range:* **$\geq 10^6 : 1$.** Set by any number of experiments, but most obviously by wishing to achieve thermal noise (of order 1μ Jy) when observing 1 Jy sources. A less familiar example is planetary radar, where the received signal is known to vary from 100 to 0.001 (or less) Jy/beam across the source. This is discussed further in §3.
    - *Misc.:* must allow RFI excision at the lower frequencies; see the section on RFI, below

2. Imaging the primary beam: (§4.2.7). Examples include imaging galaxy clusters, the Sun, the Galactic Center, etc.

    - *Total bandwidth:* **$\geq$2-4 GHz (prefer 10 GHz at high frequencies) (full pol'n).** See Table 1 for a list of the bands at the VLA and the desired maximum bandwidths within those bands.
    - *Frequency resolution:* We require narrow enough channels to ensure minimal bandwidth smearing at the half-power point of the primary beam. A 5% loss corresponds to

    $$\frac{d\nu}{\nu}\frac{\theta_0}{\theta_{\rm syn}} = 0.50$$

    where $d\nu$ is the channel width, ν is the observing frequency, θ_0 is the source offset from the delay center, and $\theta_{\rm syn}$ is the synthesized beam (*e.g.*, Bridle and Schwab

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[2] These parameters are "demanding" in that they are more stringent than other experiments might require; they are not always technically difficult to achieve, although some certainly are.

1994). The half-power point of the primary beam corresponds to $\theta_0 = \frac{\lambda}{2D}$, where λ is the observing wavelength, D is the antenna diameter (25m for the VLA), and the factor 2 results from being interested in the half-power radius rather than the half-power diameter. The FWHM of the synthesized beam is to the same approximation $\theta_{\rm syn} = \frac{\lambda}{B_{\rm max}}$, where $B_{\rm max}$ is the maximum baseline of the upgraded array (~ 36.4 km for the current A configuration, and ~ 250 km for the proposed A+ configuration). The requisite channel width is then

$$\begin{aligned} d\nu &= \frac{D}{B_{\rm max}}\,\nu \\ &= 6.9\times10^{-4}\,\nu \quad \text{for A config.} \\ &= 10^{-4}\,\nu \quad \text{for A + config.} \end{aligned}$$

For a frequency around 200 MHz, about the lowest for which bandwidth smearing could conceivably be a limiting problem, this gives channel widths of 140 kHz for A and **20 kHz** for A+ configuration.
Radio frequency interference (RFI) may push for even narrower channels than this expression would imply; see the discussion towards the end of this memo.

- *Number of channels:* Given a total bandwidth $\Delta\nu$, the number of channels (assuming a constant frequency width for each channel) is $N_{\rm chan} = \frac{\Delta\nu}{d\nu}$, or

$$\begin{aligned} N_{\rm chan} &= \frac{B_{\rm max}}{D}\frac{\Delta\nu}{\nu} \\ &= 0.15\times10^4\,\frac{\Delta\nu}{\nu} \quad \text{for A,} \\ &= 10^4\,\frac{\Delta\nu}{\nu} \quad \text{for A + config.} \end{aligned}$$

which depends only on the fractional bandwidth. ν in this expression is actually $\nu_{\rm lower}$, the frequency at the lower end of the observed band, since that sets the required channel width $d\nu$. With the bandwidth ratio $BWR \equiv \nu_{\rm upper}/\nu_{\rm lower}$ the above expression is equivalent to

$$\begin{aligned} N_{\rm chan} &= 0.15\times10^4\,(BWR-1) \quad \text{for A,} \\ &= 10^4\,(BWR-1) \quad \text{for A + config.} \end{aligned}$$

The bandwidth ratio is set by the front ends, and is shown in Table 1 below. The maximum bandwidth ratio currently planned is 2, when observing over the full band at the lowest frequencies, C band and below – if the correlator can handle the number of channels required by low frequencies, it will be more than sufficient for all the higher frequencies as well. The requisite number of channels is then

$$\begin{aligned} N_{\rm chan} &= \mathbf{1500} \quad \textbf{for A,} \\ &= \mathbf{10000} \quad \textbf{for A + config.} \end{aligned}$$

This is comparable to the number of channels needed for the most demanding spectral line projects. One would presumably like **full polarization** information for all these channels, *i.e.*, each channel should carry with it all four Stokes parameters.

- *Time averaging:* As with bandwidth smearing we would like to limit the effects of time averaging smearing to 5% at the half-power point of the primary beam. From Bridle and Schwab (1994), the time-averaging loss is roughly

$$\epsilon \approx \frac{\ln 2}{3}\,\omega_e^2\,\tau_a^2\left(\frac{\theta_0}{\theta_{\rm syn}}\right)^2$$

where $\epsilon = 0.05$ is the acceptable time-averaging loss, $\omega_e \approx 7.27 \times 10^{-5}$ radians/sec is the angular rotation speed of the Earth, and τ_a is the averaging time. Plugging in for θ_0 and $\theta_{\rm syn}$, and solving for τ_a, gives

$$\begin{aligned}\tau_a &\approx \sqrt{\frac{3\epsilon}{\ln 2}}\,\frac{1}{\omega_e}\left(\frac{2D}{B_{\rm max}}\right)\\ &= 12800\left(\frac{D}{B_{\rm max}}\right)\\ &= 8.8\,\text{seconds}, \quad \text{for A},\\ &= 1.3\,\text{seconds}, \quad \text{for A+ config.}\end{aligned}$$

Note that the averaging time for 5% losses in A configuration given here is a factor two larger than that given in Table 7 of the *Observational Status Summary (1996).* This difference is apparently due to considering a source at the half-power *radius*, vs. one at the half-power *diameter*, of the primary beam (R. Perley, priv. comm.).

- *Data rate:* The total number of visibilities produced per second is

$$\begin{aligned}\frac{dN_{\rm vis}}{dt} &= (N_{\rm base} + N_{\rm auto})\,N_{\rm Stokes}\,N_{\rm chan}/\tau_a\\ &= \frac{N(N+1)}{2}\,N_{\rm Stokes}\,\frac{B_{\rm max}}{D}\,\frac{\Delta\nu}{\nu}\Big/12800\left(\frac{D}{B_{\rm max}}\right)\\ &= N(N+1)\,N_{\rm Stokes}\left(\frac{B_{\rm max}}{D}\right)^2 (BWR-1)\Big/25600\end{aligned}$$

where $N_{\rm base}$ is the number of baselines, $N_{\rm auto}$ is the number of autocorrelation spectra, $N_{\rm Stokes}$ is the number of Stokes parameters (correlations), and N is the number of antennas. With 36 antennas, full polarization information (four Stokes parameters), $B_{\rm max} = 36.4$ km for A or 250 km for A+ configuration, and $BWR = 2.0$, this yields

$$\begin{aligned}\boldsymbol{\frac{dN_{\rm vis}}{dt}} &= \mathbf{4.4 \times 10^5 vis/sec,\ for\ A,}\\ &= \mathbf{2.0 \times 10^7 vis/sec,\ for\ A+\ config.}\end{aligned}$$

Note that this is to be a *sustainable* rate. Assuming a minimum of 3 bytes per visibility, this is 1.3 MB/sec for A, and **60 MB/sec** for A+ configuration. For comparison, a VLBA tape has a maximum rate of about 30 MB/sec: the required correlator output rate is of order the maximum raw data rate we can record on the VLBA today.

- *Misc.:* RFI excision over entire bandwidth.
- *NOTE:* Given the extreme requirements for full polarization imaging of the entire primary beam in the most extended configurations, it seems worth noting that no-one has yet suggested any experiment which would mandate such an observation (if you have one in mind, please let me know!).

Table 1. Imaging the Primary Beam in A+ Configuration

Band	ν_l	ν_u	$\Delta\nu$	BWR	$d\nu$	$N_{\rm chan}$	Data rate
UHF-1	240 MHz	380 MHz	140 MHz	1.6	24 kHz	5850	1.2×10^7 vis/sec
UHF-2	380 MHz	620 MHz	240 MHz	1.6	40 kHz	6000	1.3×10^7
UHF-3	620 MHz	1000 MHz	380 MHz	1.6	60 kHz	6350	1.3×10^7
L	1 GHz	2 GHz	1 GHz	2.0	0.1 MHz	10000	2.0×10^7
S	2	4	2	2.0	0.2	10000	2.0×10^7
C	4	8	4	2.0	0.4	10000	2.0×10^7
X	8	12	4	1.5	0.8	5000	1.0×10^7
Ku	12	18	6	1.5	1.2	5000	1.0×10^7
K	18	26.5	8.5	1.5	1.8	5000	1.0×10^7
Ka	26.5	40	10	1.5	2.7	5000	1.0×10^7
Q	40	50	10	1.25	4.0	2500	0.5×10^7

Bands and upper and lower frequencies from R. Perley, priv. comm.
UHF bands are illustrative possibilities only.
$d\nu$ and $N_{\rm chan}$ should be divided by ~ 7, and data rates by ~ 47, for A config.

3. Multifrequency synthesis, rotation measure studies, and other observations involving many widely separated "chunks" of frequency:

    - *Number of independently tunable IFs:* **4 − 8, each with full polarization** information. Set mainly by studies at high frequencies, where even multi-GHz bandwidths (with several 1000s of channels) don't cover the entire observing band.

3.2 Solar System

1. Solar flares: radio spectra taken on short timescales (§2.1.1)

    - *Number of independently tunable IFs:* ≥ 2 (dual polarization)
    - *Misc.:*
        - **ability to re-tune and lock in $\ll 1$ sec**

  - **robust total power data**

2. Solar radio bursts: very rapid imaging spectroscopy (§2.1.1)
   - *Total bandwidth:* as wide as possible ($\frac{\Delta\nu}{\nu} \sim 1$) in UHF bands
   - *Number of channels:* 512, dual pol'n
   - *Data rate:* One wants to **dump 128-256 channels in 10-20msec**. With the full array this is $1.7 - 3.4 \times 10^5$ visibilities, assuming dual polarization. At a minimal 3 bytes per visibility, this comes to 0.1-0.2 MB. A burst mode (writing 10msec worth of data every second) would be acceptable, but note that a 100% duty cycle gives data rates (25-100 MB/s) quite similar to those required for imaging the full primary beam without significant bandwidth or time averaging smearing (see above).
   - *Misc.:*
   - **robust total power data**

3. Bistatic radar: planets and asteroids (§2.3.1)
   - *Total bandwidth:* **few to few 10s of kHz**
   - *Frequency resolution:* $\leq$ **5 Hz** over narrow bands (to see cometary/asteroid rotation, and to resolve radar features in frequency for maximal signal-to-noise)
   - *Number of channels:* 500-1000, full pol'n (cross-polarized signal has been seen, e.g. on Mercury)
   - *Misc.:*
     - simultaneous good continuum measurement
     - **total power data**

4. OH masers in comets: outgassing (18cm) (§2.4.3)
   - *Frequency resolution:* 1.5 kHz
   - *Number of independently tunable IFs:* 4 (to observe all 4 18cm lines at once)
   - *Number of channels:* 64/IF, dual pol'n
   - *Misc.:*
     - RFI excision at 1612, 1720 MHz

3.3 Milky Way Galaxy

1. Radio recombination lines (RRL) in hypercompact H II regions: RRL associated with high-mass star formation (§3.3)
   - *Frequency resolution:* 600 kHz (4 km/s @ 45 GHz)

2. Circumstellar OH masers: (18cm) (§3.8)

- *Frequency resolution:* **0.5 kHz** (0.1 km/s @ 18cm), full pol'n

3. RRL in ultra-compact H II regions: (§3.9)
    - *Total bandwidth:* 70 MHz (500 km/s @ 45 GHz, for H+He+C)
    - *Frequency resolution:* $\leq$ 1 km/s
    - *Number of channels:* 500, dual pol'n

4a. NH_3: single line (23-25 GHz) (§3.10)

- *Total bandwidth:* 8 MHz (100 km/s @ 25 GHz) usually adequate; 250 MHz for broadest reasonable line
- *Frequency resolution:* 3.8 kHz (0.05 km/s/chan)
- *Number of channels:* 2000, dual pol'n
- *Misc.:* see other ammonia projects, below

4b. NH_3, all 6 transitions across 23-25 GHz, with continuum (§3.10)

- *Total bandwidth:* **6 × 8 MHz, + continuum**
- *Frequency resolution:* 8 kHz
- *Number of independently tunable IFs:* **7**
- *Number of channels:* **1000/IF for 6 IFs**
- *NOTE:* this is in some respects an artificial project, asking what the most demanding possible spectral line experiment would be. Experiments like this currently comprise only a few per cent of current observing time (B. Clark, priv. comm.).

5. Simultaneous observations of multiple molecular lines: see above for NH_3, which is the most obviously demanding (§3.10)
    - *Number of independently tunable IFs:* **8 (could survive with 4)**
6. OH masers (18cm) (§3.10)
    - *Total bandwidth:* 430 kHz (80 km/s @ 18cm)
    - *Frequency resolution:* **< 0.5 kHz** (0.1 km/s/chan @ 18cm); better for Zeeman
    - *Number of channels:* 1000, full pol'n
7. CH_3OH, SiO masers (7mm) (§3.10)
    - *Total bandwidth:* 12 MHz (80 km/s @ 7mm)
    - *Frequency resolution:* < 15 kHz (0.1 km/s/chan @ 7mm); better for Zeeman
    - *Number of channels:* 1000, full pol'n

8. Galactic Center RRL – see Extragalactic RRL, below (§3.14.1)

9. Galactic H I survey (21cm) (§3.14.4)
    - *Total bandwidth:* 2.4 MHz (500 km/s @ 21cm)
    - *Frequency resolution:* 2.4 kHz (0.5 km/s/chan @ 21cm)
    - *Number of channels:* 1000, dual pol'n

10. Pulsars
    - *Misc.:*
        - Wide bandwidths: to use broad bandwidths for pulsar observations requires tracking the dispersed signal across frequency, as the ON part of the cycle will occur at different times at different frequencies. For the very wide bandwidths of the upgraded VLA, the dispersed signal can spread across more than the pulsar period, so that a new pulse may begin at one frequency before the old pulse has even appeared at the other end of the band. In an XF correlator the best one can do is bin the signal up in time, as is currently done (with a single bin) at the VLA. This works so long as the dispersion does not spread the signal over more than the observed band within a single pulse. This sets an lower limit to the observable pulsar's period of

$$P > 2.8\mu\mathrm{sec}\, N_{\mathrm{bin}} \left(\frac{\nu}{1.4\,\mathrm{GHz}}\right)^{-3} \Delta\nu_{\mathrm{MHz}}\, DM$$

          for a pulsar with period P and dispersion measure DM, when observing at frequency ν over a bandwidth $\Delta\nu$ with N_{bin} temporal bins. For the current VLA, $N_{\mathrm{bin}} = 1$ and $\Delta\nu \leq 50\,\mathrm{MHz}$, so $P > 14$ msec for $DM = 100$. To take advantage of the broader bands available with the VLA upgrade will clearly require many more bins, if the new correlator is also of the XF variety. FX correlators can handle a more sophisticated system of time- and frequency-dependent "flagging", as can be done now with the VLBA correlator. If the new VLA correlator is also FX it should definitely include this sort of capability, at the same level as the design specs for the VLBA correlator.
        - Phase bins: Currently at the VLA one must know not only the period but also the phase of the incoming pulse, because only one (temporal) segment of the incoming signal is recorded[3]. By contrast the ATCA bins the outgoing data stream into 16 phase bins, so that one can select the ON bin after the fact. This is particularly useful for narrow (and highly dispersed) H I absorption observations of pulsars, where the phase is at best difficult to calculate ahead of time. Since the duty cycle of pulsars is typically $\sim 3\%$, finer phase binning would allow one to optimize the sensitivity of the experiment even further, by

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[3] Actually both ON and OFF may be recorded simultaneously, by piping them to separate IF pairs.

picking out a sample where the pulse is ON for the entire bin. This would require ~ 100 phase bins. Studies of the character of the pulse itself – tracking polarization changes and the like – would benefit greatly from having even more (~ 1000) phase bins.

3.4 Extragalactic Research and Cosmology

1. H I in single galaxies: (21cm) (§4.3.1)
   - *Total bandwidth:* 7 MHz (1500 km/s @ 21cm: big spiral, reasonable elliptical)
   - *Frequency resolution:* 6-12 kHz (1.25–2.5 km/s/chan @ 21cm)
   - *Number of channels:* 1200-2400, dual pol'n
   - *Misc.:*
     - resolution adjustable in factors of two
     - trade bandwidth for resolution
2. H I all-sky E array survey: (21cm) (§4.3.2)
   - *Total bandwidth:* 125 MHz (26500 km/s @ 21cm)
   - *Frequency resolution:* 61 kHz (12.6 km/s/chan @ 21cm)
   - *Number of channels:* **2048, dual pol'n**
3. H I cluster plus pencil-beam C array survey: (21cm) (§4.3.2)
   - *Total bandwidth:* 62.5 MHz + 250 MHz ($13000 + 51200$ km/s @ 21cm)
   - *Frequency resolution:* 30 kHz + 250 kHz ($6.3 + 50$ km/s/chan @ 21cm)
   - *Number of channels:* **2048 + 1024, dual pol'n**
4. H I $0.2 < z < 0.8$ B array survey: (12-18cm) (§4.3.2) (in the current scheme, this would require using two different feeds; but the requirements would be similar *e.g.* for a survey from $0.4 < z < 1.3$, using a single UHF feed)
   - *Total bandwidth:* 500 MHz
   - *Frequency resolution:* 250 kHz
   - *Number of channels:* 2048, dual pol'n
   - *Misc.:*
     - RFI excision

5a. Extragalactic RRL: a few RRL (§4.3.4)

   - *Total bandwidth:* $4 \times 150\,(\nu/45GHz)$ MHz/IF (4×1000 km/s)
   - *Frequency resolution:* $0.75\,(\nu/45GHz)$ MHz (5 km/s/chan)

- *Number of independently tunable IFs:* **4**
- *Number of channels:* 200/IF
- *Misc.:*
  - spectral dynamic range $10^5 : 1$. The best currently achieved is of order $10^4 : 1$; the improved sensitivity of the upgraded VLA should make more impressive maps routine.

5b. Extragalactic RRL: stacking lines for sensitivity (§4.3.4)

- *Total bandwidth:* **1 GHz** (gives 20 lines at 2.76 GHz, 50 lines at 1.42 GHz)
- *Frequency resolution:* **200 kHz** (21 km/s/chan @ 2.76 GHz; 42 km/s/chan @ 1.42 GHz)
- *Number of channels:* **5000** (dual polarization) (need high resolution to separate lines before stacking) (dual polarization for sensitivity)
- *Misc.:*
  - spectral dynamic range $10^5 : 1$. See above for rationale.

6. OH masers in nearby galaxies: (18cm) (§4.3.5)

- *Total bandwidth:* 5 MHz (900 km/s @ 18cm)
- *Frequency resolution:* $<$ 5 kHz (1 km/s/chan @ 18cm) use 4 to get 4 transitions at once)
- *Number of channels:* $>$ 1000, dual pol'n (full pol'n would be better)

7a. H_2O megamasers: (1.3cm) searches (§4.3.6)

- *Total bandwidth:* 156 MHz (2000 km/s @ 1.3cm)
- *Frequency resolution:* 40 kHz (0.5 km/s/chan @ 1.3cm)
- *Number of channels:* **4000** (dual polarization)

7b. H_2O megamasers: (1.3cm) separate IFs for central and outlying lines (e.g. N4258) (§4.3.6)

- *Total bandwidth:* $40 + 2 \times 15$ MHz ($520 + 2 \times 200$ km/s @ 1.3cm)
- *Frequency resolution:* 8 kHz (0.1 km/s/chan @ 1.3cm)
- *Number of independently tunable IFs:* **3**
- *Number of channels:* **5000 + 2 × 2000** (could be single polarization)
- *NOTE:* Although people have been looking hard, NGC 4258 is currently the only galaxy known with this sort of line structure. Unless more are found it would be unwise to let this drive the correlator design.

8. Misc. extragalactic molecules: (7mm–1.3cm) (§4.3.7)

- *Total bandwidth:* 50 MHz (300 km/s @ 7mm)
- *Number of independently tunable IFs:* 2–3

9. AGN absorption lines (BLR etc.): (§4.4.7)
   - *Total bandwidth:* 7(ν/GHz) MHz (2000(ν/GHz) km/s)
   - *Frequency resolution:* 1.7(ν/GHz) kHz (0.5(ν/GHz) km/s/chan for narrow lines)
   - *Number of channels:* **4000** (could make do with fewer)
10. High-z source counts: NVSS at 30 GHz (§4.6.1)
    - *Total bandwidth:* 1–2 GHz (as wide as possible)
    - *Misc.:*
      - **0.1 sec sustainable dump times** (for continuous scans in D array) (R. Perley, priv. comm.)
11. High-z molecular lines: (§4.6.2)
    - *Total bandwidth:* 1-2 GHz (6000-12000 km/s @ 50 GHz (CO))
    - *Frequency resolution:* 1.7 MHz (10 km/s/chan @ 50 GHz (CO))
    - *Number of channels:* 600-1200

3.5 Summary

Table 2 summarizes the basic requirements of the experiments listed above. The columns are: (1) name of the project, and its requirements for (2) total bandwidth, (3) frequency resolution (highest – might not be needed across the entire bandwidth indicated), (4) number of independently tunable IFs, (5) number of channels (total or per IF, as indicated), plus whether dual polarization (RR, LL) or full polarization (RR, LL, LR, RL) data are needed, (6) data rate, calculated assuming 10s averaging below 30 GHz, and 3s averaging above, except for primary beam imaging (see §3.1). Again the most demanding requirements are shown in **boldface**. There are many additional requirements imposed by various individual experiments; Table 2 simply lists those which are common to most or all. All the requirements are considered together in the following section.

Table 2. Basic Astronomical Constraints on the Correlator

Project	Bandwidth	Freq. Res.	N_{IF}	N_{chan}	Data Rate
Radio continuum:					
High-sens. cont.	**≥ 2-4 GHz**			**fp**	
	(10 GHz)			**dp**	
Primary beam imaging					
A config.	**2-4 GHz**	**140 kHz**		1500 fp	4×10^5 vis/sec
A+ config.	**2-4 GHz**	**20 kHz**		**10000 fp**	**2×10^7 vis/sec**
MFS, RM studies			**4-8**		
Solar system:					
Solar flares			≥ 2		
Solar radio bursts	$\sim \nu$ (UHF) + cont.			512 dp	
Bistatic radar	few to 10s of kHz + cont.	**≤ 5 Hz**		500-1000 fp	3×10^5 vis/sec
OH masers in comets		1.5 kHz	4	64/IF dp	3×10^4 vis/sec
Milky Way:					
RRL in HCHIIs		600 kHz			
Circum. OH masers		**0.5 kHz**		**fp**	
RRL in UCHIIs	70 MHz	1 km/s		500 dp	7×10^4 vis/sec
NH_3, single line	8-250 MHz	3.8 kHz		2000 dp	3×10^5 vis/sec
NH_3, 6 lines	**6×8 MHz, + cont.**	8 kHz	**7**	**6×1000**	4×10^5 vis/sec
Mult. mol. lines			**≥ 4**		
OH masers (18cm)	430 kHz	**< 0.5 kHz**		1000 fp	3×10^5 vis/sec
7mm masers	1.2 MHz	< 15 kHz		1000 fp	9×10^5 vis/sec
Galactic HI survey	2.4 MHz	2.4 kHz		1000 dp	1×10^5 vis/sec
Extragalactic:					
H I in single gal.	7 MHz	6-12 kHz		1200-2400 dp	3×10^5 vis/sec
H I all-sky survey	125 MHz	61 kHz		2048 dp	3×10^4 vis/sec
H I cluster survey	62.5+250 MHz	30+250 kHz		**2048+1024 dp**	4×10^5 vis/sec
H I mid-z survey	500 MHz	250 kHz		2048 dp	3×10^5 vis/sec
Extragal. RRL	4×150 MHz	5 km/s	4	200/IF dp	1×10^5 vis/sec
Extragal. RRL stack	**1 GHz**	**200 kHz**		**5000 dp**	7×10^5 vis/sec
Extragal. OH masers	5 MHz	< 5 kHz		> 1000 fp	3×10^5 vis/sec
H_2O Mmaser search	156 MHz	40 kHz		**4000 dp**	**2×10^6 vis/sec**
H_2O Mmaser N4258	$40 + 2 \times 15$ MHz	8 kHz	**3**	**5000+2×2000**	**3×10^6 vis/sec**
Misc. extragal. mol.	50 MHz		2–3		
AGN abs. lines	7 MHz	0.5 km/s		≤ 4000	**2×10^6 vis/sec**
NVSS at 30 GHz	**1-2 GHz**			**dp**	
High-z molecules	**1-2 GHz**	1.7 MHz		600-1200	7×10^5 vis/sec

dp ⇒ dual polarization (RR LL)

fp ⇒ full polarization (RR LL RL LR)

Data rates assume 10s integrations below ∼ 30 GHz, 3s above, except for primary beam imaging

4 The Dream Correlator

Based on the above requirements, the ideal correlator should have the following capabilities (the *minimal* capabilities are also indicated):

- *Number of antennas:* 36. This is set by the rest of the VLA upgrade plan, which now envisions 6 additional antennas and connections to three inner VLBA dishes.
  This is also the *minimal* requirement, to allow for expansion of the VLA even if some antennas are not built immediately.

- *Total bandwidth:* routinely process *at least* 2 GHz (preferably 4 GHz) bandwidth in each polarization, producing all four polarization products. This requirement is set primarily by deep imaging experiments, and is essential to much of the most interesting science which would be done with the upgraded VLA. Even larger bandwidths (up to 10 GHz in each polarization) would be wonderful, and should be considered if the other elements of the VLA upgrade would allow them; some tradeoffs when observing with these wide bandwidths (restrictions to number of channels, integration times, or the like) would be a small price to pay for the capability.
  1 GHz (in each polarization) is the *minimal* requirement.

- *Frequency resolution:* The frequency resolution must be tunable between a few Hz (set by bistatic radar observations of solar system objects) and some 10s of MHz (for convenience, to allow relatively slow data rates for those experiments which can use them). Apart from bistatic radar, the highest frequency resolutions required are ~ 250 Hz, for observations of OH masers, particularly in Zeeman experiments; and around a kHz, for a wide variety of experiments (masers, molecules, H I).

- *Number of independently-tunable IF pairs:* at least 4; preferably 8. 4 IF pairs are essential for line studies, especially molecular observations of species such as OH, H_2O, and NH_3, and observations of radio recombination lines. The ability to observe 4 frequencies within a single observing band is also vital for multi-frequency synthesis, spectral index, rotation measure experiments, all of which demand observations at frequencies as widely separated as possible. This capability is particularly important for the wide bands which will be available to the upgraded VLA: if one front end can handle frequencies between (for instance) 26.5 and 40 GHz, one would like to be able to observe, say, 26.5-29.5, 30-32, 35-37, and 38-40 GHz, all at once. 8 IF pairs would be even better, and would also allow the observation of all 6 NH_3 transitions between 23 and 25 GHz, while leaving one IF for a continuum band. While 16 IF pairs would undoubtedly be used if we had them, I see no strong argument that more than 8 are necessary.

  - One should ideally be able to select the bandwidth and channelization of each IF pair independently, as well as the requested polarization products.
  - One must be able to observe simultaneously with both narrow (as narrow as a few kHz) and wide (preferably ≥ 1 GHz, but even 100 MHz would be helpful) band-

widths. Among the many experiments for which this is relevant are: bistatic planetary radar (need good continuum measurement as well); observations of multiple transitions of NH_3 (again good continuum measurement is helpful); use of bright masers or continuum to calibrate simultaneous observations of faint continuum/line sources; "piggy-back" surveys like the pencil-beam H I experiment to be done simultaneously with H I observations of a cluster (§4.3.2 of *The VLA Development Plan*).

- *Number of channels:* The maximum number of channels, for any bandwidth, should be at least 2000 dual polarization (1000 full polarization) per IF, and at least 8000 (full polarization) total (summed over all IFs). A factor of two higher for each of these limits would be useful but is not essential. The requirement for $\sim$ 8000 channels with full polarization over 4 GHz comes from the desire to image the full primary beam in A+ configuration, in all four Stokes parameters, without bandwidth smearing. Dropping that particular experiment relaxes the requirement to 8000 channels with dual polarization (4000 channels with full polarization). This and the 2000 channels per IF requirement are set mostly by line studies, particularly those of NH_3, H_2O megamasers, and extragalactic RRLs, and various H I surveys.
  - The channels should be (able to be) split flexibly among the IFs: one "special" IF covering 250 MHz with 6000 channels is not acceptable, if the other 7 could only have at most 32 channels each.
  - Either the correlator itself or the on-line system must allow the user to select a subset of the correlated channels for writing to tape. At least initially, computers and tape drives may not be able to handle the recording rate necessary to write every channel. Note that it would be very helpful to be able to select arbitrary channels from the data stream – for instance, channels 1-100, 200-300, 800-900 out of (say) 1024 channels.
- *Flexibility:*
  - Frequency resolution: must be able to change the frequency resolution by something like factors of two, between a few Hz and several MHz. Factors of two are not magical, but some such geometric choice of resolution is essential.
  - Trade-offs: one should be able to make trade-offs between number of baselines, total bandwidth, number of channels, polarization products, and time resolution, with at least as much flexibility as the current correlator affords. One of the main reason to make these trade-offs will be the huge rate at which data flows from the correlator when it's going full blast; see *Data rate*, below.
  - Subarrays: must support at least 3, and preferably 4, subarrays. Currently the VLA can handle up to 5, but this has almost never been used. Subarrays could be pointing at different sources, operating at different bands, using different bandwidths

  and numbers of channels, and possibly all using all IF pairs. Subarrays are useful for simultaneous observations at different frequencies, flexible use of some fraction of the antennas (not just one) for VLBI, and splitting the array between several projects when required e.g. for monitoring projects which need good time coverage but not spectacular sensitivity.

  - VLBI: should be able to phase up four separate subarrays, writing the output independently to separate VLBI tapes.

- *Integration times:* To keep time-averaging losses to below 5% when imaging the entire primary beam requires averaging times of about 8 seconds for A, and 1 second for A+, configuration. Fast-switching schemes like that currently employed at 7mm also demand short integration times; to avoid losing data most observers using this mode opt for integrations of order 1 second. With the improved sensitivity of the VLA upgrade calibrators will be closer and can be observed for shorter times, arguing for possible integration times as short as a fraction of a second, say 0.2 seconds (though the antenna 'settling' time will probably be 0.5 seconds at best). The most stringent requirement for sustainable dump times is 0.1 seconds, for large surveys continuously scanning the telescopes across the sky (§4.6.1). These surveys would presumably use relatively few channels (a few 10s to 100), as they are unlikely to be done in the most extended A and A+ configurations. Even shorter integration times are required for observations of solar radio bursts, which would involve processing 128-256 channels (dual polarization) of data taken over 10-20 msec. This could involve a number of trade-offs, for instance processing only 10-20 msec of data out of each second on-source, or using a subarray of 9-10 telescopes, with the rest doing continuum observations. Pulsar gating is discussed separately below.
  On the other end of the scale, the maximum integration time should probably be similar to what we have now, 60 seconds or so. This is not particularly critical.
  In sum, integration times between 0.2 and 60 seconds should be available routinely, with the minimum integration time for continuous processing being $\sim$ 50 msec. Integration times even below that (down to 10 msec) should be achievable with some trade-offs, the most obvious possibilities being to limit the number of antennas involved, and to process only a small fraction of the data taken every second.

- *Total data rates:* The most demanding observation in this respect is again that of imaging the full primary beam, with only 5% losses due to bandwidth smearing and time-averaging. In the A+ array this gives required, sustainable data rates of a few times 10^7 visibilities per second. After this the next most difficult experiments are high-resolution spectral line observations at high frequencies (since that may require sub-second integration periods), which give data rates of about 10^6 visibilities per second. Even at the lower frequencies ($\nu < 30$ GHz, say), spectral line projects will give several times 10^5 visibilities per second (see Table 2). The requirement for such large, sustainable data rates is one of the most difficult ones to meet, as it asks that of order $60 \frac{dN_{vis}/dt}{10^7\,\mathrm{vis/sec}}$ Mbytes/sec be written, if not routinely, at least with fair regularity. Even if tape drives, or even hard disks, cannot sustain this rate by the time the Upgrade is well underway, the correlator should still be *capable* of producing this sort of output. Computers and related hardware have advanced at an astonishing rate since the VLA was built; it would be a pity to allow correlator limitations to prevent us from taking advantage of similar advances in the future.

- *Autocorrelations:* Many experiments require good total power measurements, including solar observations of all types, planetary radar experiments, H I mosaics, and almost anything that would be done in the ultra-compact E array. Some of these – notably H I mosaics – would find total power spectra useful as well, and it would be convenient to have this done by the VLA at the same time as the interferometric data were taken. Further, autocorrelation spectra are useful in themselves, for calibrating experiments with strong lines (masers), for looking at bandpass shapes, and (perhaps most importantly) for RFI detection and excision. The new correlator should therefore routinely provide autocorrelation spectra, in all Stokes parameters.

- *RFI:* With the GHz bandwidths, continuous frequency coverage, and UHF capability of the upgraded VLA, radio frequency interference (RFI) will be a continual and worsening problem. Unfortunately although the seriousness of the problem is obvious the solutions are not, which makes designing a correlator to cope with RFI rather difficult. However a few capabilities will obviously be needed:
  - As many channels as possible, to isolate the effects of narrow-band interference.
  - Clever spectral and temporal smoothing. E.g., Hanning smoothing is quite effective at minimizing ringing due to sharp spikes; there may be even more effective algorithms, which we must be prepared to implement, possibly even in the firmware.
  - Automatic flagging, preferably on timescales much below the integration time. One might envision for instance keeping running statistics on the incoming data, and flagging that which deviates from the norm by "too much" *before* adding it to the correlator's accumulators; or possibly checking relatively short (0.01-0.1s?) accumulations before adding them to the final (output) sum. With the huge data rates possible with the upgraded instrument, good automatic flagging could be extremely important in allowing longer integration times than most users currently contemplate; in many cases the integration time used is set by the desire to allow careful flagging, rather than any purely astronomical constraint.
  - High dynamic range within the correlator (high spectral dynamic range). Some channels may have 10^6 (or more) times as much signal as their neighbors; this must either be caught and excised before accumulation, or some allowance must be made for the possibly-huge dynamic range requirements. In particular this is a strong argument for more bits per sample, and more sampling levels – the Green Bank Telescope will employ a 9-level correlator, in part to allow for the extremely strong RFI routinely encountered there.

- *Dynamic range:* The best images made so far with the VLA have dynamic ranges of about $2 \times 10^5 : 1$ (peak to rms noise). With the improved sensitivity of the proposed upgrade, noise levels of about a micro-Jansky will be fairly routine; given a typical 1 Jy radio source, this means dynamic ranges of $10^6 : 1$, possibly $10^7 : 1$ for the brightest sources. Planetary radar experiments also need higher dynamic ranges than currently achieved, at least $10^5 : 1$ and more likely $10^6 : 1$, to allow for features ranging in brightness from 100 to 0.001 Jy/beam. Spectral dynamic ranges are set astronomically by observations like those of very faint extragalactic RRLs, which currently achieve only about $10^4 : 1$; at least $10^5 : 1$, and preferably $10^6 : 1$, (line rms-to-continuum peak) should be achievable with the new instrument. RFI considerations, as discussed above, also push the spectral dynamic range to roughly this level. These requirements affect the correlator design in many ways. Obviously one must avoid closure errors to a very high level, with the side implication that all data should be line data before averaging; polarization purity is also essential. The data representation in the correlator, and on output, are also affected, and Van Vleck corrections become more important (in any case, note that with the improved sensitivity Van Vleck corrections will be mandatory for almost all sources when observed in continuum mode).

- *Gating:* Gating in time – using only some of the input data stream, or storing different segments in different registers – is useful in a variety of settings. On-line RFI flagging clearly requires something like the ability to recognize and toss bad data on timescales of seconds, if not shorter. A particularly obnoxious example is afforded by the IRIDIUM satellites, which will cause the whole sky to pulse with a 45 msec period in the radio astronomy allocation band at 1612 MHz. We must be able to gate the data to eliminate this kind of periodic interference. Pulsar observations would also benefit from the ability to select out chunks of the input data stream on timescales of a millisecond or better; this should certainly not be neglected if an FX design is selected. In any case it would probably also be helpful to record two separate streams of data, as currently allowed at the VLA, corresponding to pulse or cal ON and OFF.

- *Extraordinary experiments:* these are requirements imposed by a few interesting observations, which the correlator should be able to handle occasionally, possibly with some trade-offs, as discussed below.
  - *Ultra-wide bandwidths for sensitivity:* process as large a bandwidth as possible (10 or more GHz) at the higher frequencies, for the utmost in sensitivity. Possible trade-offs: many fewer channels and longer integration times (hence a restricted field-of-view); producing only dual (RR, LL) rather than full polarization products. This may require a special (analog?) correlator.
  - *Phase binning:* one would certainly like at least two phase bins, corresponding to pulse or cal ON and OFF. Pulsar experiments would benefit from having at least ~ 100, and preferably ~ 1000, phase bins; the former to obtain maximum sensitivity by selecting only the ON part of the pulse, the latter to sample the pulse itself in

detail. One could conceive of finding the pulsar phase in real time, by using the same machinery normally used to detect RFI to instead find the peak among the various phase bins; these could then be 'fine-tuned' to focus on that peak, or some other arbitrary part of the pulse.

- *Miscellaneous:*
    - Phase cals (pure tones), as the VLBA: These are useful for phase alignment across frequency, and for giving the right/left phase difference for polarization calibration. This last is probably essential if linear feeds are used. Whether this demands anything of the correlator is not clear, but at the least the autocorrelation spectra (with phase tones) would have to be recorded.
    - There is some argument for 8 tunable IFs, simply to match the 8 BBCs available to the VLBA antennas.

4.1 Summary

Table 3 summarizes the various requirements for the new VLA correlator. Table 4 compares the proposed with other current and proposed NRAO correlators.

Table 3. Astronomical Requirements for the New VLA Correlator

	Minimal	Preferred
Number of antennas	36	36
Max. total bandwidth	2-4 GHz	10 GHz
Freq. resolution (with full pol'n)		
finest possible	few Hz	few Hz
finest over 2 GHz	1 MHz	300 kHz
coarsest possible	50 MHz	100 MHz
– must be tunable in factors of 2 (or whatever) from highest to lowest		
Number of tunable IF pairs	4	8
– must be able to select (bandwidth, channelization, pol'n) for each IF pair independently		
– must be able to observe narrow and wide bands simultaneously		
Number of channels (with full pol'n products)		
max. per IF pair	1000	1000
max. over 4 GHz	4000	8000
max. at any res.	8000	8000
channel selection on output	random chunk	random channels
– channels should be split flexibly amongst the IFs		
Integration times		
min. for RFI excision	$\ll 1$ sec	$\ll 1$ sec
minimum	20msec	10msec
minimum sustainable	200msec	100msec
minimum w/ all channels etc.	1 sec	1 sec
maximum	60 sec	60 sec
Image dynamic range	$10^6 : 1$	$10^7 : 1$
Spectral dynamic range	$10^5 : 1$	$10^6 : 1$
Miscellaneous		
must be able to trade off (baselines, bandwidth, channels, pol'n, time resolution)*		
Autocorrelations (all Stokes)	yes	yes
Gating in time	yes	yes
Phase bins	2	100-1000
Number of subarrays	3	5
Max. sustainable data rate	10^6 vis/sec	2×10^7 vis/sec

* or some subset of these, depending on the correlator type (XF vs. FX).

Table 4. Existing and Proposed NRAO Correlators

Correlator	N_{ant}	BWmax	Freq. Res.	N_{IF}	N_{chan}	Time Res.	Max. data rate	Size [mult./s]
VLA/now	27	0.1 GHz fp	12.5 MHz	2	4/IF	1.7s	3.3e3 vis/s	1×10^{12}
VLA/min.	36	4 GHz fp	2 MHz	4	500/IF	1.0s	1.0e6 vis/s	4×10^{16}
VLA/ideal	36	10 GHz fp	1.5 MHz	8	1000/IF	1.0s	2.0e7 vis/s	4×10^{17}
VLBA/now	24	64 MHz fp	0.031 MHz	8	256/IF	0.131s	3.3e6 vis/s	2×10^{15}
GBT/soon	1	1 GHz fp	0.061 MHz	4	4096/IF	0.016s	4.1e6 vis/s	4×10^{15}
MMA/prop.	40	16 GHz fp	2 MHz	8	1024/IF	1.0s?	2.7e7 vis/s	8×10^{17}

N_{ant}= number of antennas cross-correlated at max. bandwidth
(VLA/min can handle 33 with lower bandwidth)
BWmax= max. bandwidth
Freq. Res.= freq. resolution for the max. bandwidth
N_{IF}= no. of independently-tunable IF pairs
N_{chan}= no. of channels per IF for max. bandwidth
Time Res.= shortest integ. time for max. bandwidth
Max. data rate= max. sustainable data rate (visibilities/sec)
Size= number of multiplications per second ($N_{ant}^2 \, BW \, N_{\rm stokes} N_{IF} N_{chan}$)
The VLBA correlator is currently limited by disk write time to writing only 6.4e4 vis/s

5 End Notes

The astronomical requirements for the VLA Upgrade correlator are fairly clear, with one major exception: RFI excision. We simply do not know much about the interference which will be encountered over the proposed bands and bandwidths, which leaves both excision algorithms and correlator desiderata (spectral dynamic range, temporal and spectral resolution) distressingly vague. It is not at all obvious how we are going to figure out where the interference is, fast enough for the correlator to excise it on sub-integration timescales. Some basics are obvious – one needs access to a lot of data on very short timescales, a fairly general but very fast pattern recognition facility, and a programmer-friendly interface so we can tell it the characteristics of new RFI sources as they come online. Figuring out the characteristics of the RFI likely to be encountered, and developing methods to deal with it, must be a very high priority. This argues for a quite flexible correlator, since it's unlikely we'll either fully understand the RFI environment or have come up with perfect excision algorithms by the time the VLA Upgrade is completed.

Apart from the RFI issues, the proposed Upgrade correlator is remarkably similar to that planned for the MMA (see Table 4), suggesting the possibility of substantial savings through concurrent design and construction. Both are much larger than any of our current correlators; perhaps more importantly for the scientist, they are also intended to be much more flexible, giving interferometric arrays much of the agility and freedom heretofore reserved for single antennas. How nearly we meet the correlator goals set forth in this document will to large extent determine the scientific output of the upgraded VLA.

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