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Chapter 1

INTRODUCTION

The Very Large Array has transformed many areas of radio astronomy with a powerful combination of angular resolution and brightness sensitivity. Even so, twenty years of research have also exposed many ways in which the VLA's limitations direct our observations. Depending on the field of study, we may be biased to objects that are unusually luminous examples of their class, or unusually nearby, or not too extended, or in a particular redshift range, because of constraints on the VLA design that were accepted in the 1970's. Many of these constraints can be greatly relaxed today.

The scientific capabilities of the VLA can again be transformed by returning it to the state of the art in sensitivity, frequency coverage, angular and spectral resolution. **An enhanced VLA could be over one hundred times faster at high frequencies, several times more frequency-agile, and one hundred times better at resolving details at all frequencies, for substantially less than the replacement cost of the instrument.**

Many important observing programs are limited (or prohibited!) by sensitivity. The VLA's intermediate-frequency transmission system and correlator were designed with a maximum total bandwidth of 200 MHz. This limits the sensitivity, particularly at frequencies above 2 GHz, where wider bandwidths are permitted by the antennas, the feeds, and the level of interference. The higher frequencies are very attractive for many fields of research, including studies of the Sun and solar system objects, of thermal (stellar and circumstellar) sources in the Milky Way, of young supernovae in other galaxies, of polarimetry of the jets from active galactic nuclei, of the dense magnetized media in gas-rich clusters of galaxies, and of "radio-quiet" source populations at high redshifts. Fiber optic signal transmission, combined with a new correlator, can increase the maximum total bandwidth to 16 GHz, enabling a huge improvement in the VLA's capability in many astrophysical arenas.

Similarly, the VLA correlator is based on a custom ECL circuit that was the state of the art in the 1970's. The correlator limits the number of frequency channels and frequency resolution in ways that are particularly onerous for spectral studies at high frequencies, and for wide-field surveys at low frequencies. Modern designs allow much greater spectral resolution, wider bandwidths, and increased flexibility. A new state-of-the-art correlator would, for example, allow complete surveys of the neutral hydrogen gas in the Universe out to $z \sim 0.2$, avoiding bias in present surveys of the local structure that are based on cataloging galaxies. We could also independently and simultaneously observe multiple spectral transitions in one or two frequency bands. An expanded correlator would let us exploit the sensitivity of broad-band systems to image wide fields of view in the continuum, *e.g.*, by using bandwidth synthesis to image nearby galaxies and to inventory their stellar and interstellar emissions with less bias toward the brightest or most compact features.

The VLA antennas can be used up to roughly 50 GHz, and we have experience with holography and reference pointing to optimize their high-frequency performance. These techniques justify outfitting the VLA more fully for frequencies above 20 GHz, where we can explore thermal processes around galactic stars, image the structures of protoplanetary disks, detect young supernovae in nearby galaxies, and study CO and other molecules in galaxies at high redshifts.

The VLA's maximum baseline of 35 km sets an *angular resolution limit* at any frequency. The VLBA's inner baseline scale (about 250 km) similarly sets a *largest angular scale* that it can image efficiently at any frequency. The disparity, or "gap", between these two scales leaves a wide range of interesting astrophysical phenomena, including stellar winds, star-forming regions, and the inner regions of bright extragalactic jets, inaccessible to imaging by either instrument. These phenomena are, in effect, unresolved to the VLA but over-resolved by the VLBA, even when existing VLA antennas are used in VLBA observations. In many cases, the VLA has the sensitivity, but not the resolution, to make useful observations — a situation which will be much more general if we upgrade only its sensitivity. The "coverage gap" also seriously restricts the range of observing frequencies at which angular resolutions between one arcsecond and tens of milli-arcseconds are available. This frequency "inagility" at fixed angular resolution limits our ability to explore the frequency dependence (and hence the physics) of phenomena with angular scales of tens of milli-arcseconds.

Bridging the "VLA-VLBA" imaging gap with new antennas in New Mexico and Arizona will greatly enhance the scientific productivity of both major centimeter-wave instruments. Operating the "intermediate-baseline" antennas as part of either instrument would let us match spatial filters to the needs of a wide range of astrophysical studies that cannot be pursued satisfactorily with either instrument alone.

Finally, some planned VLA subsystems were never built for lack of development (infrastructure) funding, although there are strong scientific reasons for adding them. For example, the 2.4 GHz system, initially of interest for planetary radar and for Faraday depth studies of galactic and extragalactic sources, is now of interest to all continuum projects because RFI from mobile communications systems is proliferating at lower frequencies.

It has long been clear that the VLA could be transformed into a much more powerful tool for astrophysics at only a modest cost relative to the original investment (in today's dollars). Ideally, its construction would have been followed by timely upgrades of the technology in its infrastructure, allowing a steady increase in its scientific capabilities. In fact, the NRAO's operating budget has not kept pace with inflation since the construction of the VLA, so only a few high-priority, but still *incremental*, improvements have been possible, and several of these have been done with non-NSF funds. The imbalance between our *technical* ability to increase the VLA's scientific productivity and the ability to fund even modest improvements to the instrument has grown steadily. The accumulated imbalance can now be addressed only by pervasive upgrades to the VLA technology.

In January 1995, the NRAO hosted a workshop at which VLA users and NRAO staff reviewed technical aspects and scientific benefits of an upgraded VLA. The conclusions of six topical working groups (on Solar System research, on galactic astronomy (2 groups), on extragalactic astronomy (2 groups) and on technical issues) during and after this meeting were published as the "VLA Development Plan" in July 1995. At the same time, the NRAO formally organized a VLA Upgrade Project to prepare a more detailed design document summarizing the technical and engineering goals of a VLA Upgrade, the technical means and costs to achieve them, and an ongoing review of the scientific benefits to be obtained.

The general goal of the VLA Upgrade is to improve, by at least an order of magnitude, every key instrumental characteristic of the VLA The resulting scientific benefits are enormous, as the existing infrastructure and sound basic design of the VLA now let us exploit upgraded technologies at modest cost.

It is important to note that much of this greatly enhanced scientific potential can be achieved by using well established, *i.e.*, well understood, technologies, and at only slight increases in operations cost, because many of the changes are improvements to existing structures and units. The one exception to this — proposed new antennas in New Mexico and possibly Arizona — offers a unique opportunity to enhance the scientific capabilities of two major instruments (the VLA and VLBA) simultaneously.

This document describes the goals, scientific capabilities, costs, and implementation schedule of the VLA Upgrade.

Chapter 2

TECHNICAL OVERVIEW

The VLA Development Plan identified scientific motivations for improving the VLA in four major areas:

- **Sensitivity**.
- **Frequency coverage**.
- **Spectral line resolution, bandwidth, and flexibility**.
- **Angular resolution**.

The general goal of the VLA Upgrade is to improve, by at least a factor of 10, the performance of the VLA in all four areas.

2.1 Primary Goals for the VLA Upgrade

Ongoing development of the upgrade concept has demonstrated that improvements of a factor of ten or more over current capabilities are achievable in all four key areas. We define the following as primary performance goals of the VLA Upgrade:

- **Sensitivity** The current sensitivity limit (the expected rms in an image made with 12 hours' data, natural weighting, all available antennas, and the maximum available bandwidth) for the VLA is approximately 6 microJy at the most sensitive bands – 1.4 GHz, 4.9 GHz, and 8.4 GHz. Improvements in bandwidth, receiver design, and antenna efficiency can greatly improve the sensitivity at all bands, especially at the higher frequencies. At the lower frequencies, the sensitivity limit is reached in practice only over a limited area of the primary beam at high angular resolution, because of the effects of bandwidth smearing; an upgraded correlator can relieve this restriction. We therefore define as a goal:

  1 microJy Sensitivity between 2.0 and 40 GHz over as much of the primary beam as possible

  The means by which this sensitivity will be obtained will also give significant improvement at other frequencies – typically by a factor of five at frequencies below 2 GHz, and a factor of ten to thirty for the 40 to 50 GHz band. Improved sensitivity also brings improved calibration (and self-calibration) quality because the averaging time needed to reach given phase and amplitude noise is reduced, and because more (weaker) sources can be used for phase-referencing.

- **Frequency Coverage** The current VLA has very limited frequency coverage – targeting only the major centimeter-wavelength spectral lines (*e.g.*, H I , OH, H_2O , NH_3) and selected narrow continuum bands. Many considerations, based both on continuum and spectral line observing, now argue for a much expanded frequency tunability. We therefore define as a goal:

  Complete Frequency Coverage from 1 to 50 GHz

  This frequency range is that which can be accessed from the Cassegrain secondary focus ring. We would like to obtain similar frequency availability at lower frequencies as well, although not at the cost of diminishing the array's capabilities at higher frequencies. We thus define a secondary goal:

  Complete Frequency Coverage from 200 MHz to 1 GHz

  which must be accomplished from the prime focus.

- **Spectral Line Resolution, Bandwidth, and Flexibility** The current correlator severely restricts the science from the VLA. A modern correlator is critically needed to keep pace with the array's current, and future observing capabilities. A primary goal is:

  A modern correlator handling at least 40 stations, 8 GHz bandwidth per polarization, and 8000 spectral channels per polarization product

  but note that these are not all required simultaneously.

- **Angular Resolution** The VLA Development Plan detailed the broad-based scientific benefits from increasing the VLA's resolution. Because the objects we wish to observe are complex, it is not sufficient to add a *sparse* sampling of intermediate-length baselines. To maximize the scientific return, we define as a goal:

  Expansion of the VLA's maximum baseline to about 400 km, while maintaining the imaging performance characteristic of the current VLA

These improvements would make a "new VLA" that would continue to set the world standard for radio astronomical imaging from meter wavelengths to long millimeter wavelengths for another generation.

2.2 Components of the Upgrade

The elements of the VLA Upgrade can be categorized in two broad groups: an **Ultra-Sensitive Array**, with many separable improvements to the on-site capabilities, and an **A+ Configuration**, an expansion of the array by a factor of about ten with antennas that will also be cross-linked to the VLBA. The combination of these enhancements will yield an instrument with many fundamentally new capabilities, as well as significantly improving the imaging and scaled-array performance of the VLBA.

2.2.1 The Ultra-Sensitive Array

These enhancements can be made entirely within the existing infrastructure at the VLA Site:

- **New Cassegrain receivers**: lower noise temperatures and much wider bandwidth performance (up to 8 GHz in each polarization channel) in existing bands; add 2.4 GHz and 33 GHz bands; complete the outfitting at the 40-50 GHz band; extend the 1.4 GHz band downwards to 1.1 GHz or lower.
- **New prime focus receivers**: rebuild the focus-rotation mount so that the subreflector can be removed, and add at least three low-frequency feeds at the prime focus.
- A **fiber-optic data transmission system** to transmit the broad-band signals and monitor data, replacing the original waveguide.
- A **new correlator**, able to support at least 40 antennas, with up to 8 GHz in each polarization and up to 8,000 spectral channels per baseline per polarization product, and the ability to independently process up to 8 different frequencies from one or two frequency bands.
- **Improved antenna performance** by adjusting panels for higher efficiency and developing techniques to permit better pointing.
- **New antenna stations** for a "super-compact" E configuration to enable fast mosaicing of large fields.

The continuum sensitivity will improve by more than an order of magnitude in some bands. Figure 2.1 shows the current and expected sensitivity for both line and continuum observations, and demonstrates how these various improvements will impact all observing frequencies. Typical spectra for an optically thin object, and an optically thick thermal object are shown to demonstrate how the proposed S and Ka bands will be the best for work on these objects. New and powerful spectral line observations will be possible and significantly more frequency choices will be available.

Note also that although the sensitivity improvements per spectral line shown in Figure 2.1 are modest below 10 GHz, the proposed new correlator will allow several different transitions to be observed simultaneously. Some multi-transition spectral-line experiments will be more sensitive because longer integration times are available *per line*.

2.2.2 The A+ Configuration

These enhancements involve the development of new infrastructure at locations away from the VLA Site:

- **New antennas** to provide now-unavailable baselines between those in the VLA and in the VLBA. To maintain VLA-like imaging fidelity, of order eight new stations will be be required.
- **Fiber-optic links** between the VLA and the inner VLBA antennas, and between the VLA and the proposed new antennas, to provide for real-time data correlation with the upgraded correlator.

The new antennas will be VLBA stations while the VLA is in its compact configurations, and must also be equipped with a complete VLBA data recording system. Adding eight or more new antennas to the VLBA will enormously improve its imaging flexibility and performance.

Linkages to the innermost VLBA antennas and the new antennas will increase the maximum angular resolution by a factor of about ten. The sensitivity increases will allow this increased angular resolution to be exploited fully when observing a wide (and in many cases for the first time, representative) variety of thermal and nonthermal objects, both galactic and extragalactic.

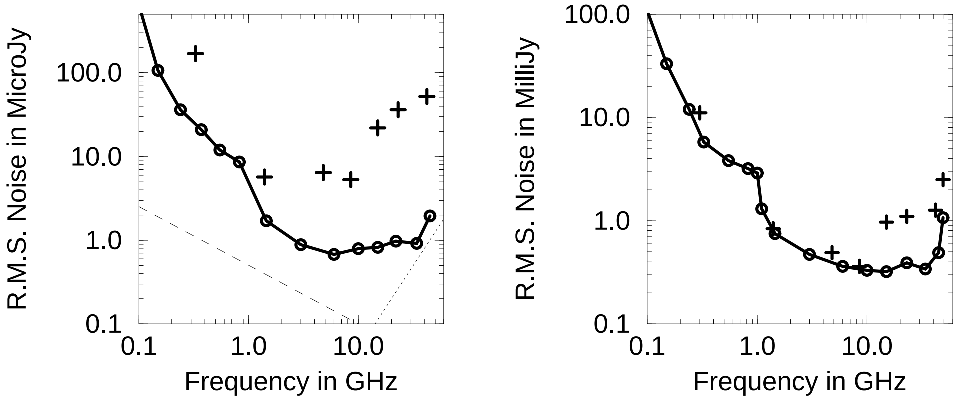


Figure 2.1: The current (+) and predicted (o) continuum (left) and spectral line (right) sensitivity of the VLA after the upgrade. For both panels, a 12-hour observation with 27 antennas and with the efficiencies and system temperatures listed in Table 2.3 are assumed. The continuum sensitivity assumes bandwidths given in Table 2.3, while the line sensitivity is based on a bandwidth equivalent to 1 km/s. (Note the different vertical scales.) For the **A+** configuration and 36 antennas, the sensitivity would be improved by a further factor of 1.33. To illustrate the *relative* sensitivities of the proposed new bands for nonthermal and thermal objects, the left panel also shows the *slopes* of a typical synchrotron spectrum (dashed) and of an optically thick thermal spectrum (dotted). The vertical placement of these spectra is arbitrary.

2.3 Antenna and Receiver Improvements

The primary goals of providing continuous frequency coverage and sub-microJy sensitivity require many changes to the antennas and receiver ensemble. At the antennas, the project involves: i) improving receivers at existing observing bands; ii) adding new observing bands; iii) modifying the quadrupod legs and focus-rotation mount system to permit access to the prime focus; and, iv) modifying the antenna surface for improved operation.

2.3.1 Improved Low Noise Receivers

The VLA receivers have been upgraded gradually since the early 1980s. Initially, better low-noise amplifiers were used in existing receivers. More recent systems have used the VLBA design, in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This design reduces the noise contribution from the polarizer and eliminates long, ambient temperature waveguide runs that added to the system temperature.

The “VLBA-style” receivers are now used at 1.4, 8.4, and 40–50 GHz. These receivers will likely remain, with the only changes being new, modern amplifiers. For the former two bands, new wide-band polarizers and feeds will be required. The greatest improvement in system temperature can be made in the 5, 15, and 23 GHz bands using the VLBA-style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands, and should reduce the system temperatures by up to a factor of three. The new receivers will also provide much wider bandwidth capability (needed for continuum sensitivity) and will tune over a wider frequency range (to include spectral lines, *e.g.*, methanol, whose astrophysical significance was unknown when the VLA was built, and permit observing of redshifted molecular lines from distant galaxies). Current plans call for bandwidth ratios of order 1.5 to 2.0 in all bands.

At present, only thirteen VLA antennas are outfitted for 40–50 GHz operation; this band will be made available on all antennas.

2.3.2 New Observing Bands at the Cassegrain Focus

Table 2.1: Proposed VLA Cassegrain Observing Bands

Band	Range (GHz)	Bandwidth Ratio	Polarization	Status
L	1.10-2.00	1.82	Circular/Linear?	New Feed
S	2.00-4.00	2.0	Circular/Linear?	New
C	4.00-8.00	2.0	Circular/Linear?	Upgrade
X	8.00-12.0	1.5	Circular	New Feed
Ku	12.00-18.00	1.50	Circular	Upgrade
K	18.00-26.50	1.47	Circular	Upgrade
Ka	26.50-40.00	1.51	Circular	New
Q	40.00-50.00	1.25	Circular	Complete

Table 2.1 summarizes the proposed Cassegrain receiver suite. Figure 2.2 shows the arrangement of the feeds around the secondary focus.

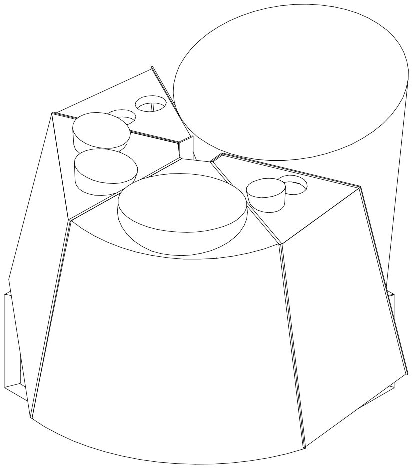


Figure 2.2: A possible arrangement of eight Cassegrain feeds around the secondary focus circle.

Two new receiver systems will be added at the Cassegrain focus: 2.4 GHz and 33 GHz. A stand-alone 2.4 GHz feed will fit on the feed ring and will give higher performance than, *e.g.*, an 1.4 GHz/2.4 GHz dual-band feed such as that on the Australia Telescope Compact Array. The 2.4 GHz band offers the highest sensitivity for studies of optically thin synchrotron-emitting objects, as shown in Figure 2.1 by the proximity of the sensitivity curve to the dashed synchrotron-spectrum line. It will also let the VLA participate in VLBA observations, and in bistatic planetary radar observations with Arecibo Observatory and Goldstone, at this wavelength.

The 33-GHz band is potentially the most sensitive band for detecting and imaging thermal objects with the VLA (as shown in Figure 2.1 by the proximity of the sensitivity curve to the dotted thermal-spectrum line). It is a band rich in molecular transitions, and is of interest to studies of optically thick (very compact) synchrotron sources.

It is advantageous to use circular polarization in the signal transmission, as amplitude and phase variations between the two oppositely polarized channels then have less effect on the measurement of linear polarization. The five high frequency bands, each covering a bandwidth ratio of 1.5:1, will use polarizers of a design now being tested with the new K-Band VLA receivers. These devices are large, and therefore unsuitable for the three lowest bands, where we will use polarizers employing a 3 dB hybrid design that are expected to provide sufficiently pure conversion from linear to circular polarization.

2.3.3 New Prime Focus Systems

Plans for new prime focus receiver systems are less well defined. The VLA's current low frequency capability consists of a fixed 300-340 MHz band and a dismountable, trial 73.4 - 74.2 MHz band. Both use crossed, on-axis dipole feeds with the (curved) subreflector as a backplane – a very low efficiency arrangement. The scientific potential of these lower frequency systems is high, so it is desirable to replace both systems with an arrangement which would permit continuous frequency coverage below 1 GHz from the prime focus with higher efficiency if this can be done without degrading antenna performance at high frequencies.

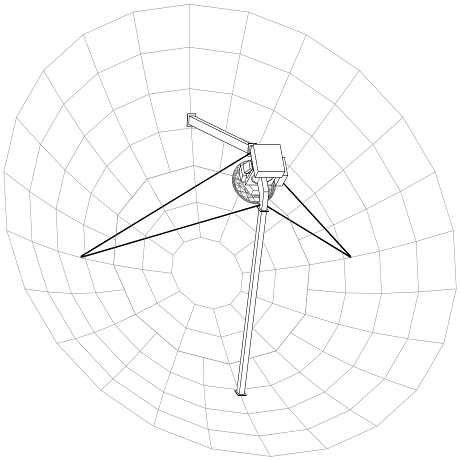


Figure 2.3: A sketch of the modified quadrupod and rotating feed assembly at the prime focus. The horizontal quadrupod legs would be replaced with narrow tubes, allowing the subreflector to be rotated away from the prime focus about a vertical axis and exchanged for any of four potential UHF feeds (shown in outline).

The current plan is to replace each of the horizontal quadrupod legs with a pair of thinner tubes which would permit rotation of the subreflector between them. Three or more low frequency feeds could then be mounted as part of the entire rotating package to permit excellent low frequency coverage. One of these could, for example, be a broad-band UHF (~150 to 1000 MHz) system. A suggested receiver suite is given in Table 2.2. A sketch of the proposed new feed-rotation system is shown in Figure 2.3

Table 2.2: Potential Prime Focus Observing Bands

Band	Range (MHz)	Bandwidth Ratio
U1	700 – 1100	1.57
U2	450-700	1.56
U3	300-450	1.50
U4	200-300	1.50

2.3.4 Sensitivity Goals

Figure 2.1 compares the continuum and line sensitivity of the current instrument to that we expect to achieve with the VLA Upgrade. We assume a maximum usable bandwidth with RFI excision at the lower frequencies, and add an atmospheric and galactic contribution to the system temperature, assuming a typically dry atmosphere, and (for the low frequency cases), observations away from the galactic plane. The system temperature assumes new, modern receivers, employing cooled polarizers (the "VLBA design") and new, wide-band feed horns. The values for the receiver and system temperatures, efficiency, and bandwidth used for the calculation of the upgraded sensitivity are shown in Table 2.3. The listed bandwidth is the sum of the orthogonal polarizations, and the quoted sensitivity is 1σ for a 12-hr observation.

Table 2.3: VLA Upgrade Sensitivity Goals for 12-hr Synthesis

Band Name	Frequency (GHz)	T_{sys} (K)	η	$\Delta\nu$ (GHz)	σ_S microJy
	.240	135	0.40	.10	36
	.370	80	0.40	.10	21
	.825	58	0.40	.50	8.6
L	1.42	28	0.55	1.0	1.7
S	3.0	29	0.62	3.0	0.88
C	6.0	31	0.60	6.0	0.68
X	10.0	34	0.56	6.0	0.79
U	15	39	0.54	8.0	0.82
K	23	54	0.51	12.0	0.98
K_a	34	45	0.39	16.0	0.92
Q	43	66	0.34	10.0	2.0

2.4 A New LO/IF Transmission System

To transmit up to 16 GHz of total bandwidth from each antenna, we will use optical fiber links to all of the VLA stations, to the nearby VLBA antennas and to the new antennas in the A+ configuration (§2.7). Separate fibers will carry the LO reference signal and the wide-band IF signal. Between four and six single mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round trip phase correction system probably will still be needed. The detailed design will be based on the MMA development of a similar system and on experience gained with the VLA-to-Pie-Town link project. An important ingredient for using the more remote antennas with the VLA will be to explore the use of commercial digital networks to transmit the IF signals.

2.5 A New Correlator

Table 2.4 shows the capacity of the current VLA correlator, whose properties were specified in the mid-1970's. One measure of correlator size is the number of multiplications required per second, which scales as: (Number of antennas)^2 × (Maximum value of: (Bandwidth × Number of channels at that bandwidth)). Table 2.5 compares this figure of merit for existing or proposed synthesis-array correlators.

Table 2.4: Maximum Channels in Current VLA Spectral Line Modes

Bandwidth (MHz)	Channels	Separation (kHz)
50	16	3125
25	32	781.25
12.5	64	195.313
6.25	128	48.828
3.125	256	12.207
1.5625	512	3.052
0.78125	512	1.526
0.195313	512	0.381

Table 2.5: Sizes of Synthesis Correlators

Correlator	Antennas N	Bandwidth B (MHz)	Channels C	"Size" (N^2BC)
VLA now	27	50	16	5.8 E 5
ATCA	6	128	128	5.9 E 5
VLBA	20	128	128	6.6 E 6
WSRT	20	160	512	2.1 E 7
SMA	6	1968	3072	2.2 E 8
MMA	40	2000	1024	3.3 E 9

The scientific drivers for a new VLA correlator have been reviewed by Rupen (1997; *VLA Upgrade Memo #8*). A new, and much larger, correlator is clearly required because (a) the maximum of 16 channels at 50 MHz bandwidth is inadequate for most spectroscopy, (b) much wider bandwidths (8 GHz per polarization, versus the current 100 MHz) are now proposed for the higher observing frequencies, and (c) the number of antennas whose outputs must be correlated will increase to forty or more from the current twenty-seven as we pursue increased angular resolution.

The new correlator must also provide flexibility in choice of bandwidths and frequency resolution (numbers of channels) that will allow observers to take full advantage of the improved sensitivity and broad-band capability of the instrument. This broad requirement of flexibility encompasses several other *desiderata*, notably high linearity, so that strong interfering signals can be removed in post-processing without corrupting nearby channels; the ability to recognize and remove time-variable interference on sub-integration timescales; the availability of temporal gating for pulsar observations and to blank out pulsed RFI. It also requires support for up to five independent subarrays, and most importantly the ability to use different frequency resolutions for each of several independently-tunable IF's (sub-bands).

From the point of view of spectroscopy, a reasonable maximum requirement for the VLA Upgrade is 8192 channels (summing 4096 in each of RR and LL) over 125 MHz. As this replicates the MMA correlator's capacity in this key quantity, one option that may be attractive logistically is to duplicate the proposed MMA correlator (Escoffier 1997; Rupen and Escoffier 1998). This correlator is described in more detail elsewhere, and we discuss here only how it would appear to the VLA Upgrade observer. The 16 GHz bandwidth (8 GHz in each of two polarizations) available for each antenna is presented to the correlator in four pairs of baseband signals, each with a maximum bandwidth of 2 GHz. The possible modes for a single baseband pair (*i.e.*, pair of oppositely polarized signals) are given in Table 2.6.

Table 2.6: Bandwidths and number of spectral line channels for one baseband pair

Bandwidth	Single polarization product$^{(1)}$ No.	Single polarization product$^{(1)}$ Freq.	Two polarization products$^{(2)}$ No.	Two polarization products$^{(2)}$ Freq.	Four polarization products$^{(3)}$ No.	Four polarization products$^{(3)}$ Freq.
MHz	Channels$^{(4)}$	Separation kHz	Channels$^{(4)}$	Separation kHz	Channels$^{(4)}$	Separation kHz
2000	256	7812.5	128	15625	64	31250
1000	512	1953.1	256	3906	128	7812.5
500	1024	488.28	512	976.56	256	1953.1
250	2048	122.07	1024	244.14	512	488.28
125	4096	30.52	2048	61.04	1024	122.07
62.5	8192	7.629	4096	15.259	2048	30.518
31.25	8192	3.815	4096	7.629	2048	15.259
15.625	8192	1.907	4096	3.815	2048	7.629
12.0	8192	1.465	4096	2.930	2048	5.859

Notes: The channel separation refers to that *before* Hanning smoothing. (1) Single polarization product, *e.g.*, RR. (2) Two polarization products, RR and LL. (3) Full (four) polarization products: RR, LL, RL, and LR.

Each of the four baseband pairs can operate independently, giving a great deal of flexibility. Most obviously, one can use the baseband pairs together to cover a wider bandwidth at the same frequency resolution: the widest-band mode uses all four baseband pairs to cover $4 \times 2 = 8$ GHz with $4 \times 256 = 1024$ channels, if only a single polarization product were desired; or one could cover $4 \times 0.25 = 1$ GHz with $4 \times 512 = 2048$ channels and full polarization information (four polarization products), yielding a channel separation of 490 kHz. One could also use more than one baseband pair to produce higher frequency resolution for the same input bandwidth, *e.g.*, to provide 32768 (single polarization product) channels over 15.625 MHz, with a channel separation of 0.48 kHz. For comparison, the current VLA correlator gives a channel separation of 195 kHz over 12.5 MHz with 64 channels (see Table 2.4).

More complicated modes are also possible, since each baseband pair is independent. One might, for instance, use one baseband pair to produce a 512-point, full polarization spectrum covering a total of 250 MHz; employ another two to cover a total bandwidth of 62.5 MHz at 3.8 kHz resolution, RR only; and use the last baseband pair to "zoom in" on 1 MHz of the spectrum with 4096 dual-polarization channels, giving a resolution of 0.24 kHz. The highest available frequency resolution is set by the IF/LO system rather than the correlator; if that system could provide a 32.8 kHz bandwidth to the samplers, the resulting channel separation could be as little as 1 Hz. Finally, this correlator design can handle up to four independently-tunable IF pairs if these are provided by the LO system. Even with only two independent LO systems, one could observe simultaneously two lines, or a narrow line and a broad-band continuum.

The MMA correlator requirements do differ from those of the VLA Upgrade in several respects, however. For the VLA Upgrade there is little scientific case for a *contiguous* bandwidth greater than 500 MHz, and only one scientific driver requires more than 16384 channels (full-field, full-band, full-polarization imaging at L, S, or C Bands in the A+ configuration). Deep continuum imaging experiments would use a total bandwidth of 16 GHz, as in the MMA, apportioned as two polarizations of 8 GHz each. As 500 MHz is the widest required individual bandwidth, sixteen separate input pairs of this width or eight pairs of 1 GHz would be appropriate for the VLA Upgrade correlator. For the VLA Upgrade the desire to do bistatic radar experiments sets a very small narrowest channel width of a few Hz, but this need only be available for about 2048 channels total; the lowest channel width driven by (extra-solar-system) spectroscopy is about 200 Hz.

The design of the VLA Upgrade correlator must also address two concerns driven by the current and expected future “hostile environment”. It is important to have considerable tuning flexibility to avoid harmful RFI. This is primarily of concern to designing the LO/IF system: very strong RFI must be blocked before reaching the correlator. Having more, but narrower, pairs of inputs to the correlator will, however, help strategies to avoid “mid-strength” RFI. As there will always be some RFI within the bands input to the correlator, a high spectral dynamic range is also important. This requires more quantization levels than the MMA’s planned 2-bit, 4-level system, especially at the narrower input bandwidths which would be used at lower frequencies.

The new correlator must also be designed to be “VLBA-Enabled”. To include more distant antennas in the A+ configuration, it must be able to handle high fringe rates and delays, and include buffering to account for delays in signal transmission over commercial fiber optic lines. Ultimately, the correlator could become a 50-station unit, processing all the current VLA and VLBA antennas in real time, plus as many as eight new antennas, plus a number of “foreign” stations, for special experiments that require the ultimate in spatial frequency coverage.

The VLA Upgrade clearly requires a very large correlator to achieve the desired scientific productivity, but one that is technically feasible and in many respects similar to that required for the MMA. Plans for the development of the MMA and VLA Upgrade correlators will therefore be closely coordinated, whether or not the two are ultimately identical.

2.6 Improved Surface-Brightness Sensitivity

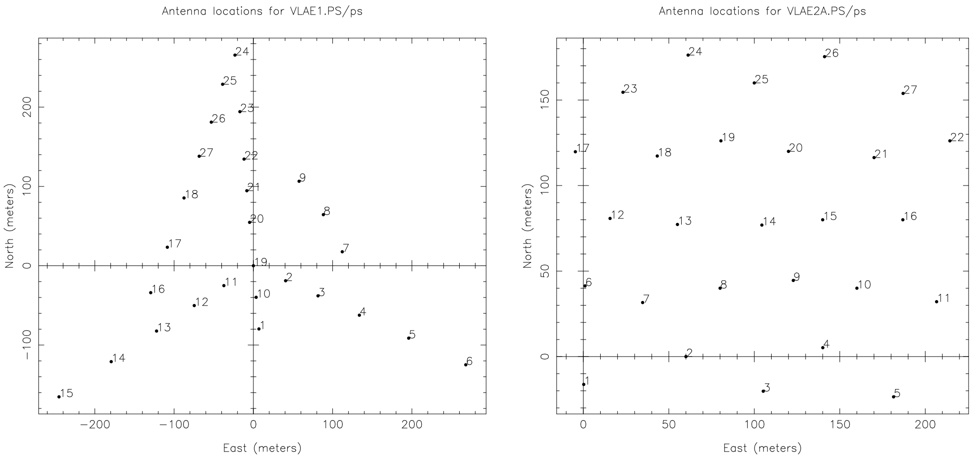


Figure 2.4: Examples of possible E configurations: the E1 (left) requires only 9 new antenna stations and two new rail spurs; the E2 (right) requires 27 new stations and five or six new spurs.

When the VLA was designed, little emphasis was given to achieving good sensitivity to low surface brightness features, to imaging of fields of view wider than its primary beam, or imaging with lower angular resolution than that provided by the D configuration. Mosaicing had not been developed and it was believed that, in any case, such issues were better addressed by large single dishes. It is now recognized that compact arrays with total power capabilities fill a gap between the imaging capabilities of conventional interferometer arrays and those of single dishes.

An ultra-compact E configuration with maximum baseline lengths of a few hundred meters would allow efficient high-fidelity imaging of extended, low-surface brightness emission on angular scales larger than the primary beam. Support of this configuration will require new antenna stations and rail access to them.

The E1 option is to move the outer three antennas from each arm of the D configuration to the inner part of the configuration. This would require nine new stations and two new rail spurs (Figure 2.4) and provide a maximum baseline of 500 m. Simulations show that it would reach a given surface brightness sensitivity twice as fast as the optimally tapered D configuration.

The E2 option would use 27 new stations and five or six new rail spurs to provide essentially Nyquist-sampled u-v coverage and a small grating response. Simulations of the configuration in Figure 2.4 show that it will reach a given surface brightness sensitivity five to ten times faster than the D configuration.

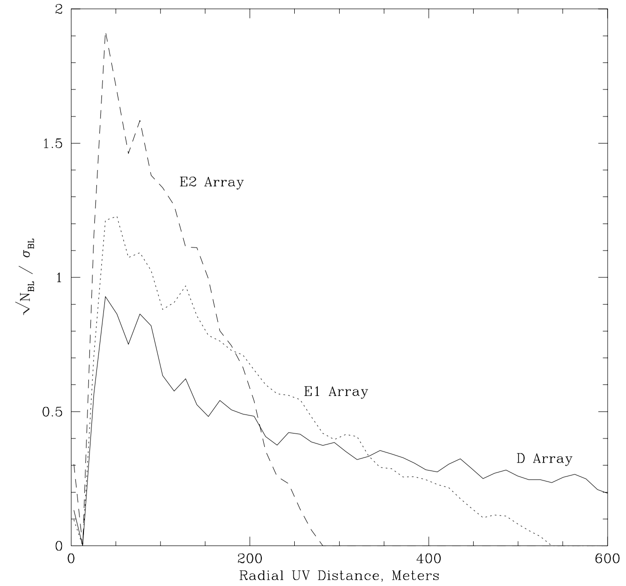


Figure 2.5: Relative sensitivities of the D, E1 and E2 configurations.

Fig. 2.5 compares the relative sensitivities of the D, E1, and E2 configurations (parameterized as the filling factor of antennas in the area covered by the array). The E2 configuration is preferable, but is estimated to cost about four times the E1. Shadowing is of little concern for either possibility for hour angles $-3^{\mathrm{h}} < \mathrm{HA} < +3^{\mathrm{h}}$ and source declinations $\delta \geq -10$ deg. Long tracks are not needed for good u-v coverage; snapshots at several hour angles will suffice for many programs. For low declination sources, a hybrid or “E-south” array configuration may be needed.

In principle, much of the same capability for imaging low-surface-brightness emission could be obtained by using array feeds on a large single dish, *e.g.*, the GBT. In practice, the E configuration would guarantee this capability for all VLA observing frequencies and simplify mingling of the data with those from other configurations.

An alternative to constructing new rail spurs and VLA antenna stations might be to develop the E configuration as a test-bed for prototype antennas for (some versions of) the proposed Square Kilometer Array.

2.7 High Angular Resolution—The A+ Configuration

There is a serious gap in u-v coverage between the 35-km longest baseline of the VLA and the 200-km shortest baseline of the VLBA. This gap is well illustrated in the frequency-resolution plot shown in Figure 2.6.

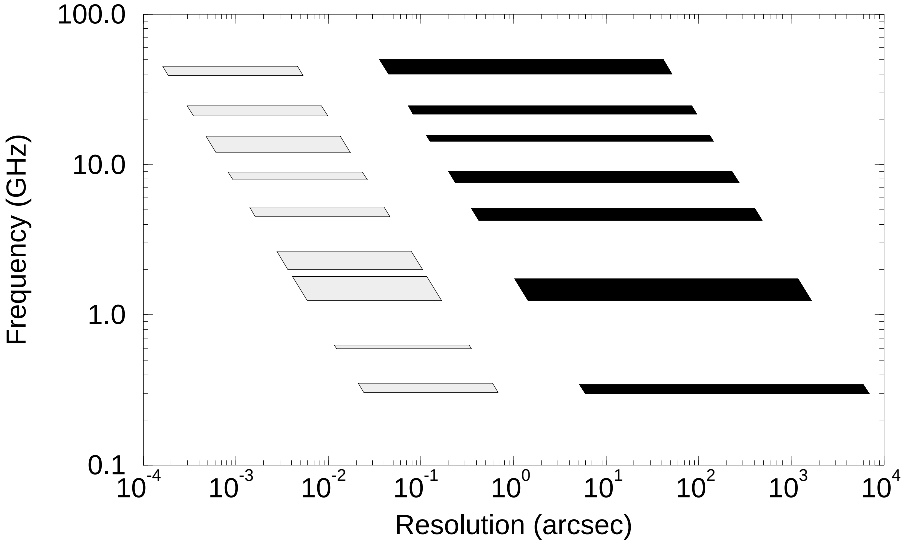


Figure 2.6: The frequency-resolution coverage of the VLA (dark) and VLBA (shaded). The sloping "VLA-VLBA Gap" is caused by the absence of antennas with separations between 35 and 250 km. Much astrophysical analysis depends on imaging at fixed angular resolution over a wide frequency range, *i.e.*, on *vertical* lines in this diagram. The "gap" seriously restricts interpretative work at resolutions from a few hundred milli-arcseconds to one arcsecond.

The absence of imaging capability on scales between the VLA and VLBA severely limits scientific investigation of a wide range of phenomena. The gap extends over angular scales of tens to hundreds of milli-arcseconds – a range critical for studies of stellar emission, star-formation, radio jets, and gravitational lenses, to name just a few.

Sub-arc-second resolution observations with the present VLA are possible only at the higher frequencies where the brightness sensitivity needed to detect nonthermal phenomena is usually inadequate because of the source spectra. These frequencies may also be inappropriate for projects in which Faraday depth effects, wide-band spectral shapes, or low-frequency spectral lines are needed to probe source physics at these resolutions. There are also many instances where studies of

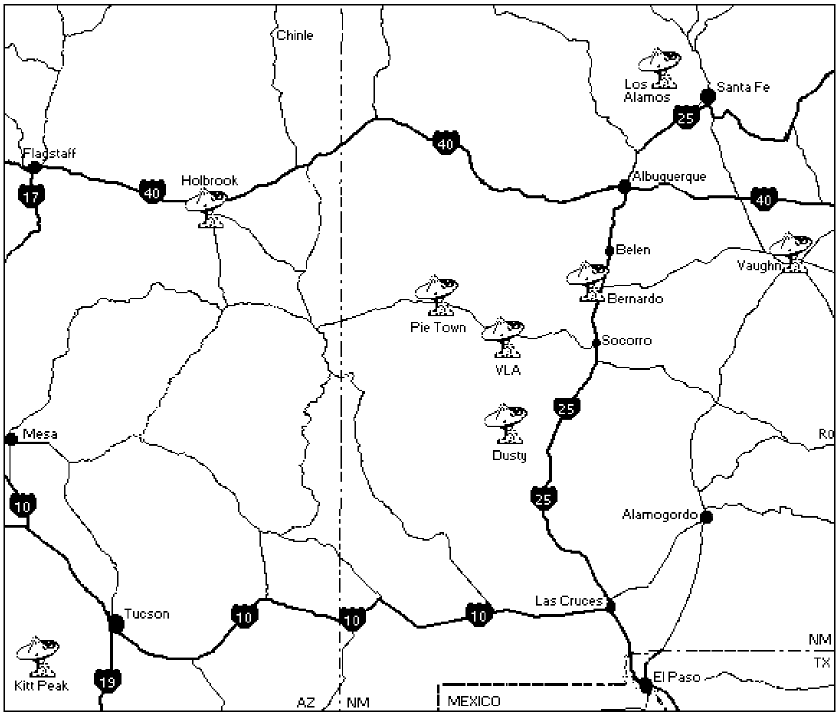


Figure 2.7: Possible antenna locations for a six-antenna A+ configuration, as suggested in the VLA Development Plan (1995). Four new antennas are added, at Dusty, Bernardo and Vaughn in New Mexico and at Holbrook, in Arizona.

normal stellar radio emission will benefit greatly from increasing both the resolution and sensitivity of the VLA together at higher frequencies.

The reconfigurability of the VLA (its capacity for "scaled array" observations with the same angular resolution at several frequencies) has been vital to its astrophysical success. This distinctive capability of the VLA is now present across the *whole* frequency range from 330 MHz to 22 GHz *only* at resolutions between $5''$ and $40''$. No problem that requires higher angular resolution than $5''$ and full frequency coverage can now be tackled in scaled-array mode. This situation improves dramatically – by a factor of order ten – if we can add data from longer baselines in an A+ configuration that includes the two innermost VLBA antennas.

Finally, we note that the availability of optical imagery at $0.05''$ resolution from the Hubble Space Telescope is emphasizing the need for better coverage of this resolution regime over a full range of radio frequencies. This resolution falls squarely in the "uncovered gap" between the VLA and VLBA at just the frequencies where imaging would be least corrupted by atmospheric and ionospheric phenomena. The NGST may also provide complementary near infrared imaging at similar resolutions.

We therefore plan to bridge this gap by adding new antennas distributed between 50 and about 400 km from the VLA, and by enabling some VLA, some VLBA, and all of the new antennas to be used interchangeably as members of either array.

These enhancements will (a) increase the resolution of the VLA at all frequencies and enlarge the *range* of resolutions over which it has "scaled-array capability", (b) improve the dynamic range, field of view and low-surface-brightness sensitivity of the VLBA, and (c) provide the VLBA with a “scaled-array” capability similar to the VLA’s, which it presently lacks.

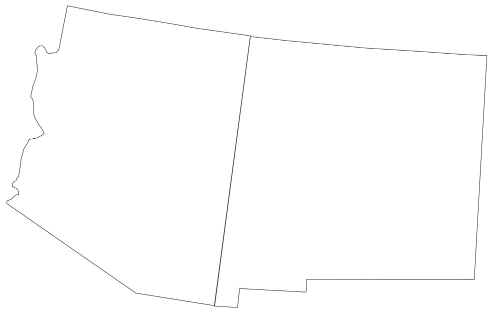


Figure 2.8: Possible antenna locations for a ten-antenna A+ configuration. Eight new antennas are added in this configuration, at Dusty and Bernardo for the inner ring, and at Vaughn, Carrizozo, Truth Or Consequences, Red Hill, Gallup and Bloomfield for the outer ring.

New antennas would therefore be built in New Mexico and Arizona to improve the density of u-v coverage in the 35–400 km baseline range.

All proposed distributions include completing the “Pie Town ring” around the VLA by adding two new antennas at distances of 50 to 80 km to the south and north-east of the VLA at Dusty, NM and Bernardo, NM. Adding only the existing Pie Town VLBA antenna to the VLA (as in the demonstration project that the NRAO is undertaking with NSF Major Research Instrumentation funding) doubles the resolution of the A configuration, but only for northern sources. Adding the two new antennas at approximately the same distance from the VLA as Pie Town extends this capability to the whole sky.

A further step is to add new antennas in the “Los Alamos ring”. Several configuration options are being investigated to determine the cost-effectiveness of using different numbers of antennas in this outer ring. Figure 2.7 shows the minimal arrangement that was proposed in the VLA Development Plan. This places one new antenna in the outer ring near Vaughn, New Mexico and a second antenna in this ring near Holbrook, Arizona. This configuration fills the major holes in the u-v plane at most declinations, but denser coverage of this baseline range, *e.g.*, the configuration with eight new antennas shown in Figure 2.8 would be needed to retain VLA-like image quality with the A+ configuration resolution in the presence of realistic noise, as demonstrated with example imaging below. The configuration shown in Figure 2.8 approximates a $\sim$ 300-km ring of seven equally-spaced antennas (to give uniform coverage), including the Los Alamos VLBA antenna, and centered on a line between Los Alamos and the VLA. The antenna locations have been adjusted from the uniform spacing on the ring to allow access from nearby major roads.

2.7.1 Example imaging with the A+ configuration

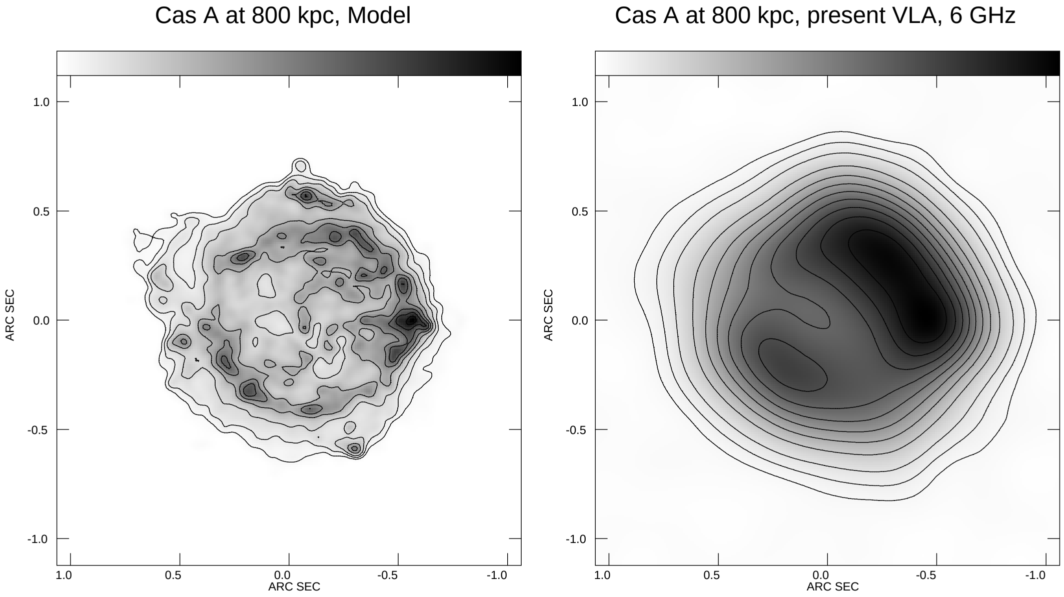


Figure 2.9: (left) The supernova remnant Cassiopeia A, rescaled to a distance of 800 kpc, (right) as imaged with the present VLA in the A configuration at λ5cm, (FWHM $\sim 0.3''$) giving only a rudimentary indication of shell structure.

We illustrate the improved imaging capability of the expanded u-v coverage in the A+ configuration by considering an observation of a "twin" of the Cassiopeia A supernova remnant at the distance of about 800 kpc, as if the remnant were in M 31. The angular extent of the remnant would be about $1.5''$, and the total flux density at λ5cm (the center of the proposed new 4-8 GHz observing band) would be 12 mJy.

The left panel of Figure 2.9 shows how this object should appear at 35 milli-arcsecond FWHM resolution in the absence of noise — a suitably scaled model of Cassiopeia A has simply been convolved to the appropriate resolution.

The right panel of Figure 2.9 shows the image that would be obtained using the present VLA A configuration, with the noise appropriate for the present VLA C Band system. The shell structure of the remnant is barely hinted at, and no details of the knot structure are seen.

The left panel of Figure 2.10 shows the image obtained using the A+ configuration with four new antennas as proposed in the VLA Development Plan in 1995 (Figure 2.7).

The right panel shows the image obtained using the A+ configuration with eight new antennas as shown in Figure 2.8.

In both cases the FWHM of the synthesized beam is $\sim$ 35 milli-arcseconds, revealing many details of the shell and filament structure. Noise appropriate for the upgraded VLA was added to the model during these imaging simulations.

At first sight, the image obtained with the six-element A+ configuration (four new antennas) contains much of the fine scale information present in the model. It is, however still only a first-order representation of the model brightness distribution. Although the off-source noise is well-behaved in this image, the *on*-source information is contaminated by "lumpy" artifacts arising from the paucity of baseline coverage and limited sensitivity in the outer u-v plane.

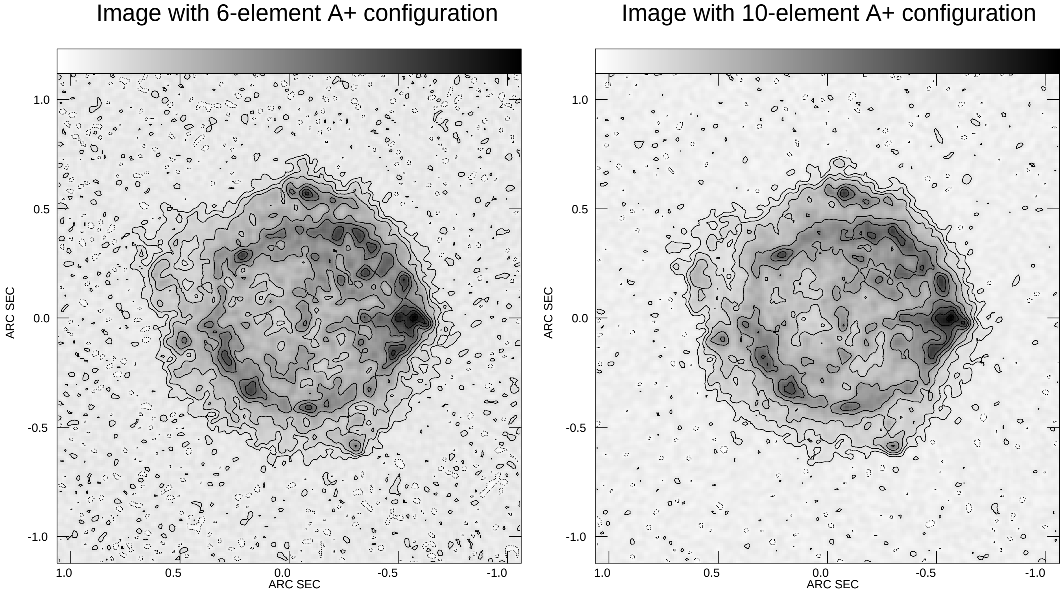
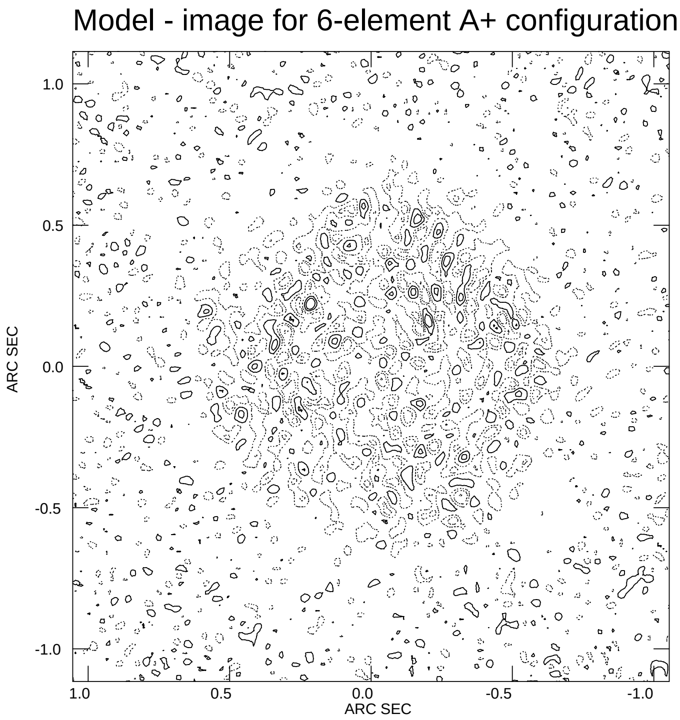


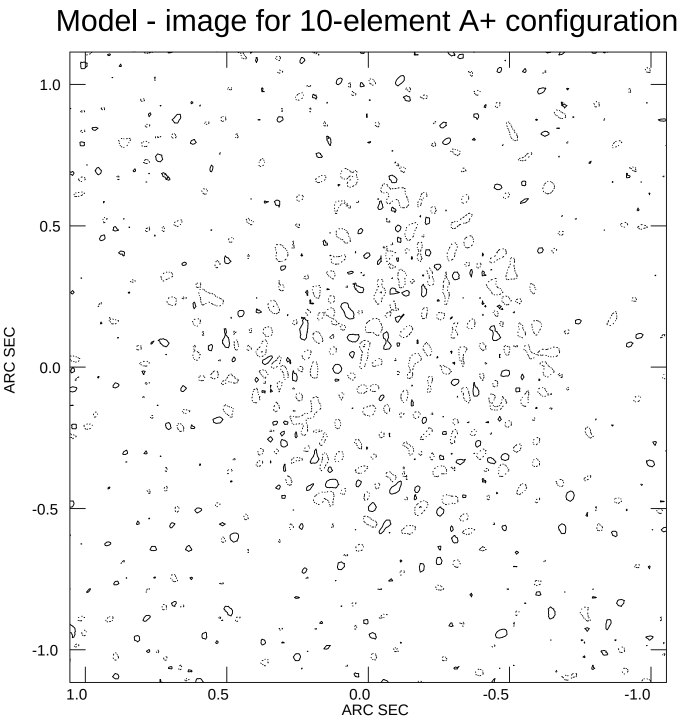
Figure 2.10: Cassiopeia A rescaled to 800 kpc distance, as imaged at λ5cm with (left) the proposed 6-element A+ configuration (four new antennas), (right) the proposed ten-element A+ configuration (eight new antennas). Contours are shown at -1.4, 1.4, 3.5, 7, 14, 21, 28, 35 and 42 microJy per beam.

These artifacts can clearly be seen in Figure 2.11, which shows the difference between the reconstructed images and the original model at the same resolution and with the same intensity scale. There are localized on-source errors up to ten times the off-source "noise" in the image obtained with the six-element A+ configuration. These could severely compromise work on the fine structure and time evolution of the supernova remnant. Local errors in the intensities in this image are as large as 30%, even where the ratio of the signal to the rms *off*-source noise is as high as 20:1. The peak residuals inside the source are seven times the rms noise off-source.

This demonstrates that the number of antennas that should be placed in the "second ring" around the VLA depends strongly on the target image quality. In this example, an eight-antenna extension reduces the differences between the image and model almost to the level of the off-source noise, while the image obtained from the four-antenna extension would be much less useful for quantitative work on the fine structure in the remnant. It is, of course, difficult to predict how specific image imperfections will affect the astrophysical goals of particular projects. These simulations do, however, suggest that the number of new antennas added for the A+ configuration must not be less than four, and that an array with as many as eight new antennas is needed for good image fidelity.



Contours are shown at -7, -3.5, -1.4, +1.4, +3.5 and +7 microJy per beam



Contours are shown at -7, -3.5, -1.4, +1.4, +3.5 and +7 microJy per beam

Figure 2.11: The differences between the model image and the reconstructed images of the scaled Cassiopeia A remnant shown in Figure 2.9. The rms residuals within the source for the six-element A+ configuration (four new antennas) are about three times larger than for the ten-element A+ configuration (eight new antennas), and the largest localized errors are ten times the off-source "noise".

2.8 On-Line Computing

A new software control system for the VLA will be required to interact with hardware upgrades such as a new LO/IF transmission system and correlator, to support new observing modes and strategies such as mosaicing, dynamic scheduling and real-time imaging, and to enable more operator and user interaction with the data being produced by the array.

The VLA's on-line system is now based on two MODCOMP computers of mid-1980's vintage, and the last major rewrite of the control system occurred in 1989.

As part of the VLA Upgrade we propose to replace the software and hardware controlling the VLA and the existing correlator with modern technology. A design study is currently underway, including an end-to-end analysis of information flow through the entire proposal/observing/reduction process. We expect to coordinate these efforts with parallel on-going VLBA and MMA projects.

2.9 Other Capabilities

Several other instrumental improvements that lead to new scientific capabilities are also being considered. They include: a robust total power system to support mosaicing, simultaneous multi-band performance (2.4 and 8.4 GHz or 4.9 and 15 GHz), and outfitting the VLA antennas with 80-GHz receivers.

Chapter 3

NEW SCIENCE WITH THE ENHANCED VLA

Chapters 2–4 of the VLA Development Plan described an ambitious scientific program that takes full advantage of the project elements outlined above and imposes demanding performance specifications on the enhanced VLA. In this section, we select a few scientific highlights and mention their impact on the goals of the VLA Upgrade. In making this selection, we emphasize projects for which the VLA Upgrade changes the character of the work that can be done, or introduces entirely new capabilities. Virtually all research programs already active on the VLA will also benefit greatly from the proposed improvements.

3.1 Imaging-Spectroscopy of Solar Radio Bursts

Solar radio bursts have long been observed using dynamic spectra (records of intensity *vs.* time and frequency), and it is only recently that joint spectroscopic and (fixed frequency) imaging experiments have been conducted. An extremely exciting possibility is imaging-spectroscopy of solar radio bursts over an octave, or more, of bandwidth using a broad-band UHF system at the prime focus. Using such techniques, it will be possible to constrain the point of origin and the subsequent propagation of both electron beams (type III bursts) and MHD shocks (type II bursts) in the solar corona. As such, it offers a powerful tool for probing coronal dynamics, beam propagation, and shock acceleration.

Unlike other proposals for feeds at the prime focus, a broad-band UHF system does not need to be a high performance system. As such, it may require the fewest modifications to the quadrupod and FRM. On the other hand, it imposes demanding specifications on other aspects of the project, requiring:

- A wide-band data transmission system and correlator.
- Dual circular polarization measurements.
- A spectral resolution of ~ 1 MHz and a time resolution as small as 10 ms, which may require the use of a "burst mode".
- Fast, accurate measurements of $T_{\rm sys}$.

3.2 Bistatic Radar Observations of Planets and Minor Bodies

Bistatic radar experiments with the VLA/Goldstone 8.4 GHz system are an unanticipated use of the VLA which have produced a number of exciting results, including: (i) the discovery of ice deposits at the poles of Mercury, (ii) the discovery of the "Stealth" feature on Mars, which produces no detectable echo, and (iii) the discovery that Titan has no deep global ethane/ methane ocean, contrary to expectations.

New 2.4 GHz receivers would enable bistatic radar experiments to be done with both Goldstone and the newly upgraded Arecibo transmitter. Furthermore, the VLA will be better able to support future planetary missions if it is equipped for both the 2.4 and 8.4 GHz telemetry bands.

To maximize support of bistatic radar experiments, the VLA Upgrade must include:

- Adding the 2.4 GHz receivers.
- A correlator with a spectral resolution as high as 5 Hz.
- A correlator which supports simultaneous line and continuum observing as well as simultaneous high- and low-resolution line observing.
- Robust total power measurements.

3.3 High-resolution Imaging of Thermal Emission

At present, milli-arcsecond imaging is restricted to objects with high surface brightness, *i.e.*, non-thermal radio emitters. Large improvements in sensitivity coupled with the A+ configuration will allow imaging of thermal radio sources with milli-arcsecond resolution, opening an entirely new area of astrophysical inquiry. Examples of the kinds of objects which could be imaged out to distances ranging from several hundred pc to several kpc include i) interacting binaries containing giant stars (*e.g.*, symbiotic stars and recurrent novae); ii) stellar winds on giant stars—expansion rates could be measured directly; iii) the early stages of nova outbursts; iv) the photospheres of giant stars, and v) circumstellar disks.

We stress that most elements of the VLA expansion project are required *simultaneously* for these research programs, including:

- A wide-band data transmission system and correlator.
- The A+ configuration.
- Adding the 33 GHz band, completing the outfitting for 40 to 50 GHz band.
- Correlator flexibility, including support of simultaneous line and continuum observing.

3.4 Imaging Protoplanetary Disks

Young stars are expected to be surrounded by protoplanetary disks. To date, such stars have only been observed at optical wavelengths in silhouette against bright nebulae using, *e.g.*, the Hubble Space Telescope. Their inner regions are optically inaccessible since they are opaque to visible photons.

The VLA 40–50 GHz system, when completed on all antennas and supported by a wide-band data transmission system will have three times the angular resolution of the Hubble Space Telescope and 36 times the sensitivity of the present 40–50 GHz system (a factor of over a thousand improvement in observing time!). The VLA will be the only instrument able to penetrate the inner regions of protoplanetary disks. The disks are optically thick to optical wavelengths, and they cannot be resolved at longer wavelengths. Present estimates suggest that roughly 100 protoplanetary disks with angular extent exceeding $0.5''$ exist within 200 pc of the Sun with total flux densities of 1 mJy at λ7mm wavelength. Such a source could be imaged with a signal-to-noise ratio of 10:1 in 12 hrs with the A-configuration.

Technical requirements essentially match those of §3.3.

3.5 Transient Phenomena

The high sensitivity of the VLA at the high observing frequencies (15 GHz and above) will open a new domain of rapid response to transient phenomena that are initially optically thick at lower frequencies. For example, to observe young extragalactic supernovae in their earliest phases we need to be able to self-calibrate (or phase-reference) sources fainter than 1 mJy in the presence of rapid phase fluctuations in the wider VLA configurations. This is impractical with the current VLA high-frequency systems because of their relatively poor sensitivity and the need for long integration times. The improved high-frequency coverage and wide bandwidths planned for the enhanced VLA will allow good multi-frequency light curves to be obtained for extragalactic supernovae even in their first few days of activity. Rapid response and good data quality for this phase of the outburst are crucial for testing particle acceleration models, and for looking for inhomogeneities and/or instabilities in the emission/absorption region. Similar considerations apply for detection and early imaging of other transient phenomena, such as X-ray transients and flare stars.

Technical requirements include:

- Multiple receivers covering 15 to 45 GHz.
- Wide-band IF transmission system for maximum sensitivity.

3.6 Extragalactic H I Surveys

The VLA Upgrade will have a major impact on unbiased surveys in H I . Our view of the large scale structure of the universe, with its large filaments, sheets, walls and voids, is based almost entirely on observations of high-luminosity galaxies, observed at optical wavelengths. Since nearly all investigations of the properties and spatial distribution of galaxies begin with optically (or IRAS) selected galaxy catalogs, any population of gas clouds with very low optical luminosity or surface brightness would largely have escaped detection. Direct searches in the H I line circumvent these optical selection biases. Such searches would make it possible to construct an unbiased H I mass function for the local universe and to probe the evolution of galaxies and the formation of large scale structure in the range $0 < z < 0.8$. Three examples of such surveys are:

- An All Sky H I survey in $0 < z < 0.2$: the good surface brightness sensitivity of the VLA D configuration, combined with the large instantaneous velocity coverage of the new correlator will finally make such a survey feasible.
- The structure of a cluster of galaxies, combined with a pencil beam survey: at higher redshifts an entire cluster can be imaged within one VLA primary beam, *e.g.*, at $z = 0.1$, an Abell

diameter is about 20′. In parallel, a sensitive pencil beam survey can be carried out to sample the entire cone within this primary beam at $0 < z < 0.2$ (RFI permitting).

- The evolution of gas at $0.2 < z < 0.8$: a direct test of how the gas content of galaxies evolves with redshift, using the B configuration to survey a cone to as high a redshift as possible (again, RFI permitting). The large instantaneous velocity coverage of the new correlator will make it possible for a single pointing and LO setting to cover the range $0.2 < z < 0.8$, and to sample a volume of $3.2 \times 10^5 h_{100}^{-3}$Mpc^3. In a 100-hr integration more than thousand galaxies will be detected with the upgraded VLA.

While Arecibo is more sensitive for directed studies, and the GBT about as sensitive, the VLA's large field of view relative to both single dishes makes it many times faster than either for unbiased H I surveys. At higher redshifts ($z \geq 0.06$) the higher angular resolution and better interference rejection of the VLA are also major advantages.

The technical requirements include:

- Robust total power measurements.
- Wide-band spectral line capability.
- RFI excision and extending the 1.4 GHz band down to 800(?) MHz, for the high-redshift survey.

3.7 Clusters of Galaxies

The nature of the intragalactic medium (IGM) in clusters and groups of galaxies is an important subject for understanding the large scale properties of the universe. X-ray observations show this plasma, which exists on a scale of hundreds of kiloparsecs up to at least many Megaparsecs, has hot thermal gas as a major component. However, radio observations show that, in many cases, large-scale magnetic fields make up another important component of the medium. The physics of this medium is important in its own right since it represents an extreme environment to investigate complex plasma processes. How ubiquitous and how well organized are the magnetic fields in the IGM? How were they formed? Are dynamo processes responsible? What rôle do they play in so called "cooling flows"? Is the energy in the magnetic fields, or that imparted to the medium by AGN's, important relative to thermal content of the gas? Are relativistic particles accelerated and/or re-accelerated on large scales? Are they energetically important? What is the range of temperatures in the thermal IGM and how is it regulated? The enhanced VLA will allow significant progress on these issues, primarily through ultra-sensitive observations of i) cluster radio halos; ii) Faraday rotation studies; iii) the Sunyaev-Zeldovich effect; iv) radio galaxies in clusters; and v) gravitational lensing and mass measurements of clusters.

Technical requirements:

- Broad-band data transmission system and correlator.
- Adding 2.4 and 33 GHz receivers.
- The E configuration.

3.8 Objects at High Redshift

The VLA Upgrade will open new ways to study the evolution of the radio properties of galaxies with redshift directly. The strong (*i.e.*, AGN) radio source population clearly evolves with cosmological epoch — the apparent density of sources increases rapidly with redshift. This also seems to be true for optically selected, often radio weak or silent, QSOs. Not far below the 3CR flux density limit, most sources are at high redshifts ($z \geq 1$ and many as high as $z = 3$ to 5). Recently, the IRAS catalog has added a sample in which dust and molecular emission can be detected beyond $z = 2$. Closer by, the Hubble Space Telescope has imaged clusters of galaxies beyond $z = 0.4$, confirming that the Butcher-Oemler effect (the blueing of cluster galaxy populations with redshift) is related to increased star formation in clusters at higher redshifts and that galaxies themselves have different shapes as we look further back. The direct study of the evolution and possibly the formation of galaxies appears to be a real possibility. The enhanced VLA would play a crucial rôle in this arena through detailed exploration of i) the evolution of radio source populations; ii) molecules, dust and free-free emission in distant galaxies; iii) starbursts at high redshifts; and iv) Faraday rotation in magnetized gas-rich environments.

Technical requirements:

- Broad-band data transmission system and correlator.
- Multiple receivers covering 15–50 GHz.
- 2.4 GHz system.

Chapter 4

IMPACT ON SCIENCE WITH THE VLBA

The NRAO now operates 37 “synthesis array elements”, broken into a 27-element sub-array (the VLA) and a 10-element sub-array (the VLBA), with only one provision for cross-linking them (using one antenna or the whole VLA in its phased-array mode for VLBI). Much could be gained by allowing individual elements of the VLA, the new antennas proposed for the A+ configuration, and the inner elements of the VLBA, to join in observations with either array.

4.1 Improved Image Quality

The information gathered by an N-element synthesis array varies as N^2 for large N, so linking four new antennas to the VLBA would *double* the information content of VLBA observations by doubling the number of correlations, and adding as many as eight new antennas would more than triple the information collected. This increased information content would translate into improved image quality via

- a wider field of view,
- greatly improved sensitivity to extended structures,
- increased dynamic range and and image fidelity, especially for larger emission regions, and
- improved instantaneous, *i.e.*, “snapshot” image quality.

World-array experiments have shown that the apparent simplicity of many VLBI images reflects a lack of information gathered about the sources more than any intrinsic simplicity of Nature on these scales. We expect many extragalactic sources to have complex structures on scales from 1 to 100 milli-arcseconds. Physical interpretation of these structures will require “movies” with high dynamic range and wide fields of view over a large range in frequency. For studies of rapidly-evolving galactic relativistic-jet sources, we need the ability to construct such “movies” from snapshots of ≤ 1 hour duration.

4.2 Closing the Coverage Gap

The VLA and VLBA, taken separately, leave the 40-to-400 km range of baselines relatively unsampled. This “coverage gap” obstructs work on many astrophysical problems. For example, the VLA now images well down to about $0.1''$ FWHM at λ2cm and proportionally lower resolution at longer wavelengths. The VLBA images up to a few milli-arcsecond at λ2cm. They fail to meet by about a factor of ten in resolution at any frequency. The missing regime is now of great interest to AGN jet dynamics, observations of galactic X-ray transients, of circumstellar masers, protoplanetary disks, and of supernova remnants in external galaxies.

It is already common to include one VLA antenna in VLBA observing programs. This is a small step in the right direction, but we need many more baselines in the "gap" to image the full range of interesting phenomena satisfactorily.

Figure 4.1 illustrates how the new A+ configuration antennas could improve image quality by providing short-baseline u-v coverage in VLBA observations.

4.3 Extended Scaled-Array Capability

The VLBA currently has limited "scaled-array" capability compared to that of the VLA. Because of its small number of antennas, the image quality deteriorates if any antennas are removed at one frequency to "match" the coverage at another. It is also not reconfigurable. Multi-frequency coverage at a fixed angular resolution can be obtained only by adding data from baselines shorter than 400 km at the higher frequencies (*e.g.*, Figure 4.2). Cross-linking an expanded VLA with the VLBA will extend the scaled-array capability of *both* instruments to cover a much greater domain of angular resolution, providing well-filled u-v coverage that can be scaled with wavelength over a wide frequency range. For example, when studying relativistic jets in AGN's or galactic X-ray transients, we must be able to image total and polarized emissions at the same resolution over a wide range of frequencies to determine spectral energy distributions, Faraday rotations and magnetic field directions, as well as the collimation and proper motion information that are available from single frequencies.

4.4 Snapshot Mode

The VLBA "snapshot" u-v coverage will be augmented to produce better images of transient galactic sources that can vary significantly in structure and amplitude on times scales of a few hours. The VLBA configuration is fairly sparse and now relies on rotational synthesis over several hours to obtain good image quality. The use of the proposed A+ configuration antennas as VLBA elements would significantly improve the "instantaneous" image quality. This can be critical to studies of the time development and evolution of active galactic objects with relativistic jets, for which high angular resolution imaging is appropriate but "superluminal" features may move by many beamwidths per day.

4.5 Synergy

Although a separate "100-km" array (*e.g.*, MERLIN) can provide some of the "missing coverage" at $\lambda>$6cm for northern sources, the high-frequency coverage that is critical to much of the astronomical program, and the N^2 "baseline synergy" with the VLA or VLBA can be obtained *only* with antennas in the Southwestern United States. Furthermore, MERLIN has poorer image fidelity and sensitivity (having only 4 to 7 antennas) and less frequency flexibility, than the proposed VLA Upgrade.

Ultimately, to study how the properties of astronomical sources change with frequency without changing resolution, we should be able to select the antenna combinations needed to create the most appropriate set of matched spatial filters for any given multi-frequency experiment. We could do this at high angular resolution if we were able to choose “sub-arrays” that include VLA and VLBA baselines almost interchangeably. The NRAO prepared for this by siting the VLBA antennas around the VLA as their centroid, and by co-locating the main VLA and VLBA operations centers. The VLA Upgrade is needed to exploit the unique opportunity that this creates. It gives us a way to transform the scientific capabilities of *two* major instruments significantly at once.

To take full advantage of this, we must outfit the new antennas and a few existing VLA antennas with VLBA back-ends. The new antennas would be operated as part of the VLBA when the VLA is in its more compact configurations, and would need VLBA data acquisition systems. It is also desirable to have enough hardware at the VLA site itself to record signals from four VLA antennas at once. An upgrade of recording and formatter systems to reach 1 or 2 Gbps is also desirable. Astrometric VLBI observations would benefit from a 2.4 GHz/8.4 GHz (S/X) dual frequency system. The VLBA correlator was designed to handle 20-station experiments, so no new correlator capacity is required specifically for the new antennas proposed as part of the VLA Upgrade.

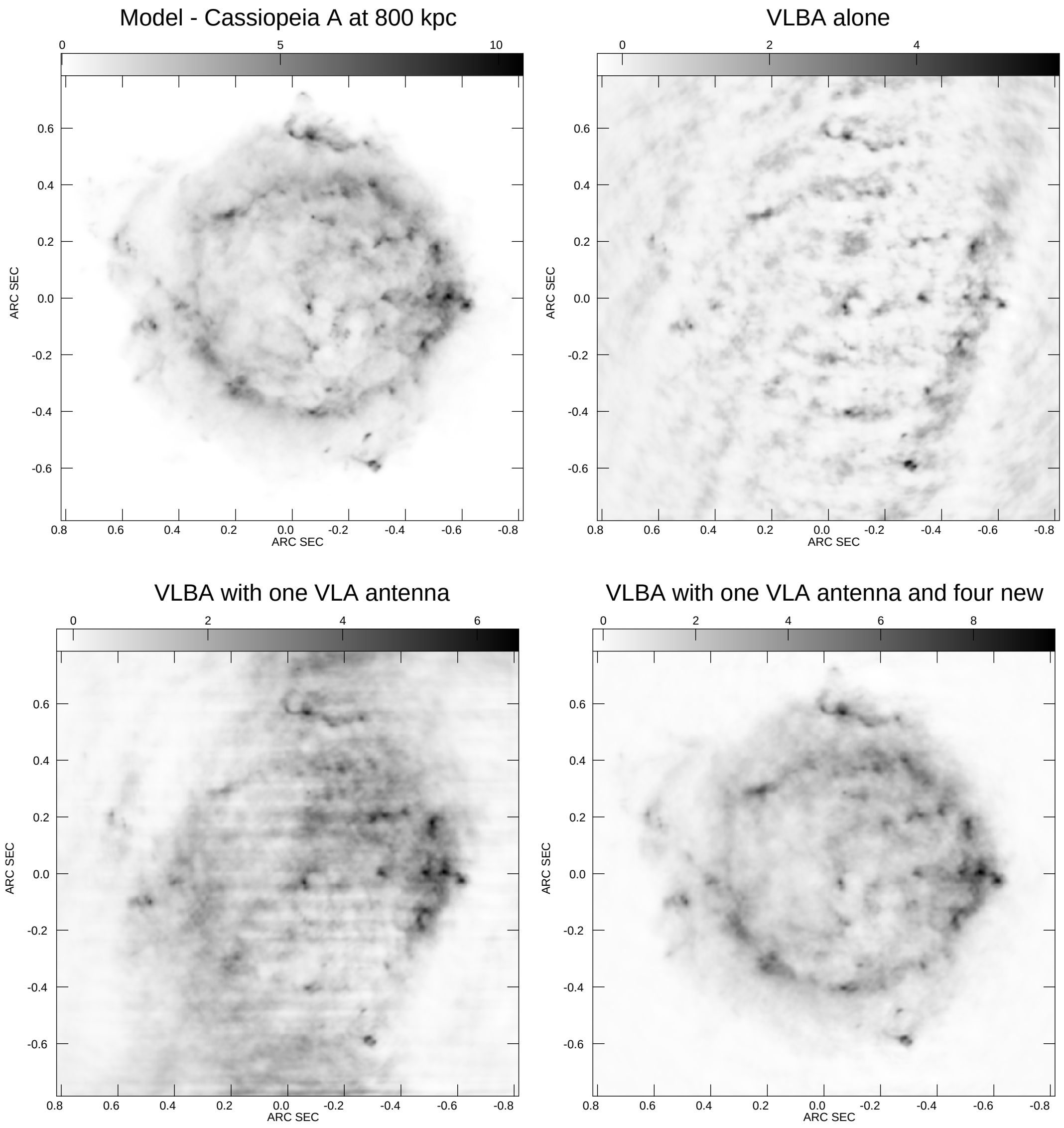


Figure 4.1: (upper left) The supernova remnant Cassiopeia A, rescaled to a distance of 800 kpc (M31), at 8 milli-arcseconds resolution. (upper right) An image obtained by sampling this structure with the u-v coverage of the present VLBA alone at λ21cm and 30 degdeclination. Only the most compact emission is represented at all; the diffuse ring and "plateau" emission are resolved out and scattered into large-scale fringes. (lower left) An image obtained by sampling this structure with the u-v coverage of the present VLBA and one VLA antenna at λ21cm and 30 degdeclination. The more diffuse emission is detected, but its brightness distribution is poorly represented. (lower right) An image obtained with the u-v coverage of the array shown in Figure 2.7, with four new antennas and one VLA antenna added to the VLBA at λ21cm and 30 degdeclination. All of the major emission is now correctly located. For this specific example, the image obtained with eight new antennas as shown in Figure 2.8 is only marginally better.

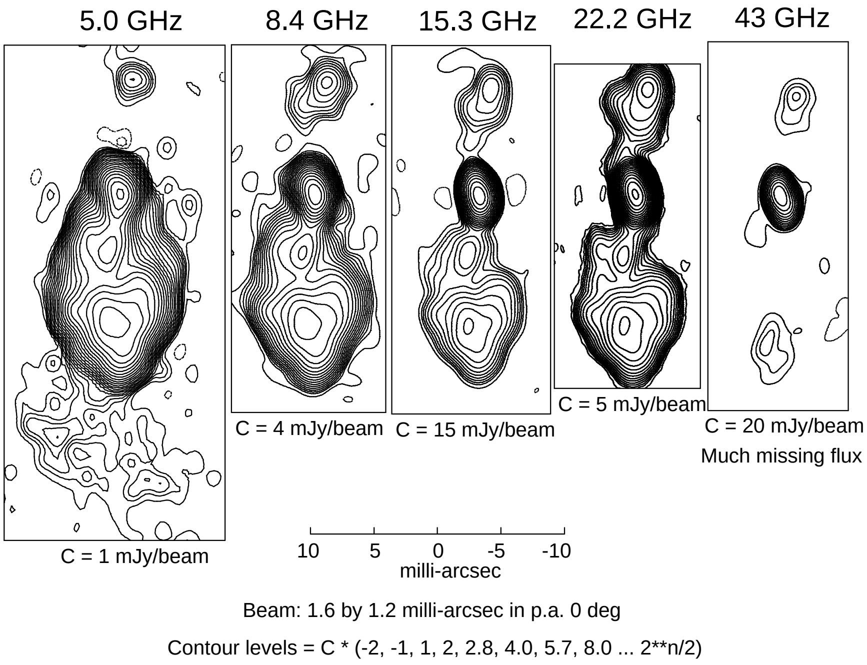


Figure 4.2: VLBA images of the nucleus of the active galaxy 3C 84 at five frequencies. Note the differing sensitivities. The extent to which the detailed differences between these images are real frequency-dependent properties of the source (rather than differences in the u-v coverage of the VLBA at these frequencies) would be unclear even with matched sensitivities. The high-resolution 43-GHz image clearly under-samples the broader (>5 milli-arcsecond) structure in the lower-frequency images, however and accounts for only about 3/4 of the known total flux density. These uncertainties could be much reduced by cross-linking the expanded VLA and the VLBA to provide a scaled-array capability, especially at the highest frequencies.

Chapter 5

BUDGET AND SCHEDULE

(under construction)

Chapter 6

SUMMATION

The VLA Upgrade addresses the demands of a wide variety of scientific programs for greatly increased sensitivity, much broader frequency coverage, enhanced spectral line capabilities, and better angular resolution. It does so largely by returning the VLA to the state-of-the-art in receiver technology, in the transmission and processing of broad-band signals, and in correlator design. The scientific requirements also pose new technological challenges. How can optimum performance (polarization and sensitivity) be maintained across the large bandwidths now proposed? Can broad-band, high-performance, low-frequency feeds be designed? What is the optimum way to transmit broad-band signals from antennas hundreds of kilometers from the VLA for real-time ultra-high-resolution interferometry?

The impact on astrophysics of returning the VLA to the current state of the art will be profound. Many hard limitations now constraining VLA observations will be removed or greatly relaxed. The continuum sensitivity will increase by ten-fold in several bands. New frequency bands and increased bandwidth ratios will increase frequency coverage almost three-fold. The bandwidth which can be processed by the spectrometer, and its spectral resolution, will simultaneously increase by about ten-fold. The minimum beam area will improve a hundred-fold. Finally, cross-linking the upgraded VLA with the VLBA will produce a VLBI instrument with greatly increased dynamic range, field of view and frequency scalability relative to the present VLBA.

The VLA Upgrade thus offers far more than an incremental improvement to existing scientific capabilities. Almost all areas of research now done with the VLA will benefit greatly from it. It also provides fundamentally new science in many arenas. Much of the new scientific capability depends on the cumulative effects of many improvements in the VLA Upgrade, rather than critically on any one of them. For example, high-resolution imaging of stellar thermal emission requires the sensitivity improvements *and* the A+ configuration; imaging protoplanetary disks requires the 40–50 GHz upgrade *and* enhanced sensitivity; deep H I surveys require extending the 1.4 GHz band to lower frequencies and the new correlator.

If past experience is any guide, this initial account of the possible scientific program, while exciting, will prove to be far from complete. Some scientific arenas that will benefit from the enhancement will almost surely have been overlooked, and innovative uses of the improved instrument will not have been anticipated.

We urge everyone in the VLA user community to add their thoughts on the astrophysical goals and technical challenges of the enhanced VLA to these discussions. This document is intended to evolve into one that makes the scientific case to the NSF for supporting these enhancemen