The VLA Development Plan

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PREFACE

The Very Large Array has allowed enormous advances in almost all areas of radio astrophysics. Since its dedication almost fifteen years ago, it has been used by more astronomers, and has produced more scientific papers, than any other radio telescope.

Although observing time remains in great demand (the VLA is used by over 600 researchers from over 150 institutions every year) and the VLA's scientific output is still prodigious, key parts of the array still contain the technology of the 1970's. Major improvements in receivers, in the correlator and in broadband signal transmission are needed and are now possible at only moderate cost.

It has been clear for some time that the VLA's impact on astrophysics can be dramatically increased by upgrading or replacing the receivers, data transmission system, and correlator; by improving its frequency coverage; by improving its ability to image large regions of low surface brightness and wide fields of view with a super-compact configuration; and by increasing its angular resolution by adding antennas between the VLA and the VLBA. Some scientific rewards of enhancing the VLA were described to the Bahcall Committee in 1991; their report recommended extending the VLA as a "moderate"-scale new program. More recently, the NRAO has included a comprehensive VLA upgrade in its Long Range Plan for the National Science Foundation.

In January 1995, the NRAO hosted a workshop to discuss the scientific program of an enhanced VLA. This document is based on the discussions of six working groups during and after this meeting, which was attended by about 60 scientists and engineers from the NRAO and VLA user institutes. It illustrates—but likely does not exhaust—the rich astronomical opportunities offered by an enhanced VLA. It outlines capabilities that could transform research in areas ranging from the nearby Solar System to the furthest reaches of the Universe. It also aims to identify technical issues that now need detailed design studies.

We thank all the workshop participants for their input, and especially the chairs of the working groups for their ongoing help with assembling this report.

We ask all potential users of the enhanced array for feedback both on the scientific programs and on the relative priorities of different enhancements described in this VLA Development Plan. Such feedback will be an essential part of making the VLA again a state-of-the-art instrument, with new and more ambitious scientific goals. E-mail on these topics will be welcomed at `newvla@nrao.edu`.

Progress on the VLA Development Plan will be reported in the NRAO Newsletter, in a memo series, and on the World-Wide-Web at `http://www.nrao.edu/vla/upgrade/newvla.html`.

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Chapter 1

OVERVIEW

1.1 INTRODUCTION

The VLA has transformed many areas of radio astronomy with a powerful combination of angular resolution and brightness sensitivity. Even so, fifteen years of research with the VLA have also exposed the many ways in which its limitations direct, or bias, our observations. Depending on the field of study, we may be restricted 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 limits to the VLA design that were accepted in the 1970's. Many of these limits can be greatly relaxed today. A second transformation of the scientific capabilities of the VLA is possible if it could be returned to the state of the art in sensitivity, frequency coverage, angular and spectral resolution. **An enhanced VLA could be a hundred times faster, several times more frequency-agile, and fifty times better at resolving details, for only a few tens of per cent of the replacement cost of the instrument.**

For example, many observing programs are limited (or prohibited!) by sensitivity. The VLA's intermediate-frequency transmission system was designed with a maximum bandwidth of 100 MHz. This limits the sensitivity, particularly above 2 GHz, where wider bandwidths are permitted by the antennas, the feeds, and the interference conditions. These higher frequencies are very attractive for studies 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 for examining radio "quiet" source populations at high redshifts. Fiber optic signal transmission could increase the maximum bandwidth to 2 GHz, enabling a huge leap in the VLA's capability in all such astrophysical arenas.

Similarly, the VLA correlator is based on a custom EGL circuit that was the state of the art in the 1970's. Modern designs allow much greater spectral resolution, larger bandwidths, and increased flexibility. By reaching the state of the correlator art *again* in the 1990's, we could, for example, allow complete surveys of the neutral hydrogen gas in the Universe out to $z \sim 0.1$, avoiding any bias in present surveys of the local structure that are based on cataloging galaxies. We could also use an expanded correlator to exploit the sensitivity of broad-band systems to image wide fields of view in the continuum at lower frequencies, *e.g.*, 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 are useful to $\sim$ 45 GHz, and we now have experience with holography to optimize their performance. This increases interest in outfitting the VLA more completely at 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 in galaxies at high redshifts.

The *u-v* coverage of the VLA was optimized for the astrophysical purposes (and the computing context) of the 1970's. Computing limitations, both in software and in hardware, discouraged imaging and deconvolving large fields of view, especially at high angular resolution. These limitations have been reduced to the point where many wide-field and/or high-resolution experiments could now be supported if the VLA had the requisite inner and outer *u-v* coverage. Whether mosaicing large-scale galactic features or entire external galaxies, or making high-resolution images of the interior structures of star-forming regions, circumstellar winds, young supernovae, or jets from galactic X-ray sources and AGNs, we may now be limited by the available *u-v* coverage, not by our ability to compute the images.

Finally, some VLA subsystems were planned but never built for lack of development (infrastructure) funding. The 2.4 GHz system, which has always been of interest for planetary radar experiments and for Faraday depth studies of galactic and extragalactic sources, is now of increasing interest to all continuum projects as RFI from mobile communications systems proliferates at lower frequencies.

It has therefore been clear for some time that the VLA could be made a much more powerful tool for astrophysics at a moderate cost relative to the original investment (in today's dollars). Ideally, its construction would have been followed by funding a timely inflow of new technology into its infrastructure. This would have allowed for a *steady* expansion of its scientific capabilities. But in fact the operating budget has not kept pace with inflation, so only a few high-priority but *incremental* improvements have been possible, some with non-NSF funds. The imbalance between our technical ability to increase the VLA's scientific productivity and our capacity to fund technical improvements has grown steadily. This imbalance may only worsen in future, absent an explicit proposal to the NSF for a major re-capitalization of the VLA hardware.

This document reviews the technical possibilities for enhancing the VLA, and their scientific potential, as a first step toward such a proposal.

1.2 TECHNICAL OVERVIEW

Earlier informal reviews of the scientific motivations for enhancing the VLA identified needs for *major* gains in four areas:

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

The following technical capabilities are therefore key ingredients in a VLA Development Plan:

Phase 1: An Ultra-Sensitive Array

- **New receivers**: lower noise temperatures and much wider bandwidth performance (≈ 1 GHz in each polarization channel) in existing bands; add 2.4 GHz and 33 GHz bands at the Cassegrain focus; complete the outfitting at the 40-50 GHz band; extend the 1.4 GHz band to lower frequencies.
- A **fiber-optic data transmission system** to transmit the broadband signals and monitor data, replacing the original waveguide.

- A **new correlator**, able to support ≥ 32 antennas, to process both broadband continuum signals and to provide improved resolution and flexibility for spectral line work.
- **New antenna stations** for a "super-compact" E configuration to enable fast mosaicing of large fields.

Phase 2: The VLA Expansion

- **New antennas** to provide now-unavailable baselines between those in the VLA and in the VLBA.
- **Fiber-optic links** between the VLA and the inner VLBA antennas, and between the VLA and the proposed new antennas.

The combination of these enhancements will yield an instrument with many fundamentally new capabilities. The continuum sensitivity will improve by more than an order of magnitude in some bands (Table 1.2). New and powerful spectral line observations will be possible and significantly more frequency choices will be available. The super-compact E configuration will allow fast imaging of large fields and large objects, greatly enhancing the capabilities of surveys. Linkages to the innermost VLBA antennas and the new antennas will increase the maximum angular resolution by a factor of seven. The sensitivity increases will allow the increase in 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. Each of these project elements is now discussed in more detail.

1.2.1 Antenna and Receiver Improvements

At the antennas, the project involves: i) improving receivers at existing observing bands; ii) adding new observing bands; and, iii) modifying the antenna structure for improved operation.

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 remain with perhaps only minor modification. The greatest improvement in system temperature can be made in the 5, 15, and 22 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 3. The new receivers will also provide ≈ 1 GHz bandwidth per polarization channel (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). Current plans call for bandwidth ratios of order 1.4–1.5:1 in many bands.

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

New Observing Bands at the Cassegrain Focus

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 at the Cassegrain focus and will give higher performance

Table 1.1: Proposed VLA Cassegrain Observing Bands

Band	Range (GHz)	Bandwidth (GHz)	BW Ratio	
L	1.20-1.75	0.55	1.46	Upgrade
S	2.13-2.70	0.57	1.27	New
C	4.80-6.70	1.90	1.40	Upgrade
X	8.00-9.10	1.10	1.14	Unchanged
Ku	12.00-18.00	6.00	1.50	Upgrade
K	18.00-26.50	8.50	1.47	Upgrade
Ka	26.50-40.00	13.50	1.51	New
Q	40.00-50.00	10.0	1.25	Complete

than, *e.g.*, an 1.4 GHz/2.4 GHz dual-band feed such as that used on the Australia Telescope. The 2.4 GHz band is potentially the highest sensitivity VLA band. It will also let the VLA participate in bistatic planetary radar observations with Arecibo Observatory. The 33 GHz band can also support bistatic radar experiments with the Goldstone 70 m antenna and would allow imaging of many interesting molecular lines, including red-shifted CO. Table 1.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

New Prime Focus Systems

Plans for new prime focus receiver systems are less well defined. A 330 MHz system is currently located at the prime focus, as is a low-performance, dismountable 74 MHz system on 8 antennas. The presence of the 74 MHz dipole feed degrades performance of the 1.4 GHz band by about 10%. Hence, if 74 MHz feeds are deployed on all antennas, it must be possible to dismount them (or otherwise move them from the prime focus position by mechanical means).

Other specific proposals for prime focus systems include:

- A new system covering 580–640 MHz, matching that of the VLBA.
- A broadband UHF ($\lesssim$150–600 MHz) system, including a low-performance system for solar work.
- A sensitive 800–1200 MHz system.

Sensitivity Goals

Table 1.2 compares the continuum sensitivity of the current instrument to that we hope to achieve. We assume a maximum useable bandwidth with RFI excision at the lower frequencies, and add an atmospheric contribution where relevant. The number under ΔS refers to the continuum sensitivity in μJy/beam achieved in 12 hrs integration, summing over two orthogonal polarizations. The total bandwidth assumed for 0.33, 0.60, 1.0, 1.4, and 2.4 GHz is 50, 100, 200, 500, and 1000 MHz, respectively. All other estimates assume 2 GHz net bandwidth.

1.2.2 A New LO/IF Transmission System

To transmit $\sim$2 GHz of bandwidth from each antenna, we will use optical fiber links to all of the VLA stations, to the nearby VLBA antennas and to new antennas between the VLA and present

Table 1.2: VLA Sensitivity

	Enhanced	VLA	Current	VLA
Band (cm)	T_{sys} (K)	ΔS (μJy)	T_{sys} (K)	$\Delta S_{current}$ (μJy)
90	80-135	40-70	150	120
50	45-90	13-25	-	-
30	25-32	5.3	-	-
20	30	2.7	33	6.0
11	31	1.9	-	-
6	29	1.3	45	6.7
3.6	31	1.3	31	4.4
2	37	1.7	110	20
1.3	50-70	2.6	160	37
0.9	38	2.0	-	-
0.7	55	3.5	80	165
0.6	170	15	-	-

VLBA stations (§1.2.5). 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.

1.2.3 A New Correlator

The specifications for a new correlator are still under discussion (see Chapter 5), as is the architecture best suited to meet them. It is not yet clear whether the more appropriate architecture is a lag correlator, as presently used at the VLA, or an FX correlator, as used by the VLBA. A detailed design study is needed to choose between the two options. Note that the product of the number of antennas, N, and the maximum bandwidth, B, analyzed by the correlator is $N \times B \sim 64$ GHz. This "figure of merit" for the correlator is comparable to that of the Millimeter Array ($N \times B = 80$ GHz); both correlators will be at least an order of magnitude larger than the existing VLA correlator ($N \times B = 5.4$ GHz) or the VLBA correlator ($N \times B = 2.6$ GHz).

The new correlator should be able to process data from at least 32 antennas and have enough delay to accommodate baselines up to 500 km. It could then process some combination of the twenty-seven VLA antennas, two or three of the innermost VLBA antennas (those at Pie Town, Los Alamos, and Fort Davis), and up to four new antennas on baselines between those in the VLA and in the VLBA (§1.2.5).

1.2.4 Improved Surface-Brightness Sensitivity

When the VLA was designed, most astronomers were not overly concerned with good sensitivity to low surface brightness features, with imaging of fields of view wider than its primary beam, or with imaging at angular resolutions below 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 dish instruments. 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 large single dishes. An ultra-compact E configuration with maximum baseline lengths of a few $\times 100$ m would provide this capability.

Given that the Arecibo telescope (for example) samples a similar aperture how, specifically, do the capabilities of an E configuration compare with those of such a large single dish? The single dish has superior point-source sensitivity—the 225-m aperture that is illuminated at Arecibo would be ≈ 3 to 4 times more sensitive than the proposed E configuration. The basic advantage of an ultra-compact array is its *imaging* capability, *e.g.*, the proposed E configuration could be roughly 10 times faster than Arecibo for survey work. Hence, the main rôle of the E configuration is to provide a fast, low-resolution wide-field imaging capability via mosaicing. The VLA also has access to 85% of the sky (unlike Arecibo, from which ≈ 30% of the sky is visible), and will provide frequency coverage up to 50 GHz. As an interferometer, the VLA also has lower systematic errors than a large single dish; it is less susceptible to pointing errors, and ground pickup is uncorrelated between antennas, as is RFI in many cases.

1.2.5 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. We plan to bridge this gap by allowing some VLA, some VLBA and some new antennas to be used interchangeably as members of either array. These 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 extended-source sensitivity of the VLBA, and (c) provide the VLBA with a "scaled-array" capability similar to the VLA's, which it presently lacks.

New antennas would be built in New Mexico and Arizona to make the density of u-v coverage in the 40–400 km baseline range the same as that in the VLBA now beyond 400 km. The first step would be to complete the "Pie Town ring" around the VLA by adding antennas near Dusty, NM and Bernardo, NM. (Linking just the Pie Town antenna to the VLA would double the resolution of the A configuration for northern sources only. Linking the Dusty and Bernardo antennas extends this capability to the whole sky.) The second step would be to add further antennas in the "Los Alamos ring": two possible sites are near Holbrook, AZ and Vaughn, NM. The VLA's delay and fringe rotation systems would be expanded to correlate these signals in real time with the present A configuration (processing would be done at the new 32-station VLA correlator).

Figure 1.1 illustrates how the expanded u-v coverage in the A+ configuration would improve the imaging of a "twin" of the Cas A supernova remnant at the distance of about 1 Mpc, for example in M 31. The angular extent of the remnant would be about $0''75$. Panel (a) shows the image that could be obtained at λ6cm with the present VLA A configuration. Panel (b) shows the dramatic improvement obtainable with the proposed A+ configuration.

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 may be inadequate because of the source spectra. These frequencies may also be inappropriate for any 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 (Chapter 3) where studies of 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 near $5''$. No problem that requires higher angular resolution than $5''$ and full frequency coverage can now be tackled in scaled-array mode. This situation changes dramatically if we can add data from longer baselines in the A+ configuration or the VLBA.

Finally, we note that the availability of optical imagery at $0.1''$ resolution from the Hubble Space Telescope is emphasizing the need for better coverage of this resolution regime over a full

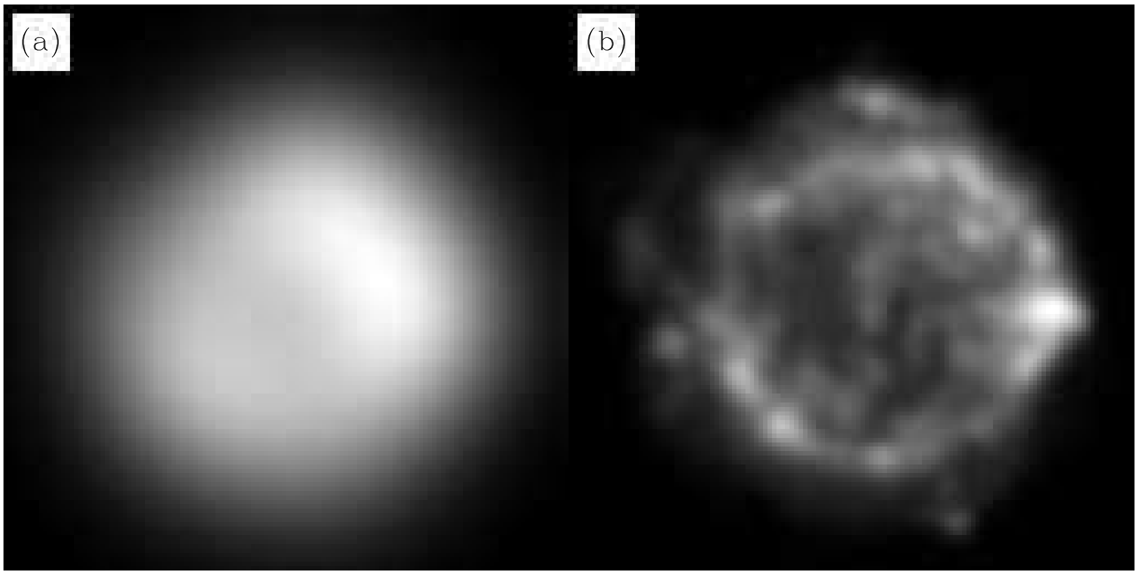

Figure 1.1: (a) An image obtained by using the full u-v coverage of the VLA in the A configuration at λ6cm to sample a model derived from the radio structure of the supernova remnant Cassiopeia A, rescaled to a distance of 1 Mpc. Only a rudimentary indication of shell structure is visible at this resolution (FWHM $\approx 0.3''$). (b) An image obtained by sampling the same model with the full u-v coverage proposed for the A+ configuration. The FWHM of the synthesized beam is about 8 times smaller, revealing many details of the shell and filament structure. Neither simulation is noise-limited.

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.

1.2.6 Other Capabilities

Several other instrumental improvements that lead to new scientific capabilities are also being considered. They include: ultra-wide (~35%) bandwidth at the highest frequencies, 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 cross-linking the VLA and VLBA. These are discussed in Chapter 5.

1.3 NEW SCIENCE WITH THE ENHANCED VLA

Chapters 2–4 describe 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 Development Plan. In making this selection, we emphasize projects for which the VLA Development Plan changes the character of the work that can be done, or introduces entirely new capabilities. Many research programs already active on the VLA will also benefit greatly from the proposed improvements, as also described in Chapters 2–4.

1.3.1 Imaging-Spectroscopy of Solar Radio Bursts

Solar radio bursts have long been observed using dynamic spectra (records of intensity *vs.* time and frequency), 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 of bandwidth, or so, using a broadband 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, the broadband 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_{sys}.

1.3.2 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. JPL is committed to installing a new transmitter on the Goldstone 70 m antenna, operating at ~ 33 GHz, in support of the Cassini mission to Saturn. Hence bistatic radar experiments will be possible in three frequency bands spanning more than a decade in frequency. 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 Development Plan must include:

- Adding the 2.4 and 33 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.

1.3.3 High-resolution Imaging of Thermal Emission

At present, milli-arcsecond imaging is restricted to objects with high brightness, *i.e.*, nonthermal radio emitters. Large improvements in sensitivity coupled with the A+ configuration would 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 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 40–50 GHz band.
- Correlator flexibility, including support of simultaneous line and continuum observing.

1.3.4 Imaging Proto-planetary Disks

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

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 1300 improvement in observing time!). The VLA will be the only instrument able to penetrate the inner regions of proto-planetary disks. The disks are optically thick to shorter wavelengths, and they cannot be resolved at longer wavelengths. Present estimates suggest that roughly 100 proto-planetary disks exist within 200 pc of the Sun with flux densities of 1 mJy/beam ($0.05''$). Such a source could be imaged with a signal-to-noise ratio of 20:1 in 12 hrs.

Technical requirements essentially match those of §1.3.3.

1.3.5 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 15–45 GHz.
- Wide-band IF transmission system for maximum sensitivity.

1.3.6 Galactic HI Survey

VLA D-configuration mosaics of relatively small fields of Galactic HI emission reveal complicated filaments and structures on all angular scales. With an ultra-compact antenna configuration it will be possible to survey HI in large parts of the Galactic plane with an angular resolution of $3'$ and a velocity resolution of 0.5 km s^{-1} in a very short time. A survey covering one quadrant and 10 degrees of Galactic latitude would take only 120 hour of observing to complete. A high resolution, fully sampled survey of Galactic HI would provide an important data base for: i) modeling gas dynamics in the Galaxy; ii) comparing HI with molecular gas, allowing detailed modeling of the conversion between atomic and molecular gas in molecular clouds or photodissociation regions; iii) comparison with continuum emission, possibly allowing a distance determination to continuum features if an HI /continuum correlation is found; iv) the study of the interaction between violent events in the disk - SNR, disk blowout events, HII regions – and HI .

Technical requirements include:

- The E configuration.
- Robust total power measurements.
- A wide-band spectral line capability.

1.3.7 Extragalactic HI Surveys

The VLA Development Plan will have a major impact on unbiased surveys in HI . 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 HI line circumvent these optical selection biases. Such searches would make it possible to construct an unbiased HI 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 HI survey in $0 < z < 0.1$: the good surface brightness sensitivity of the VLA E 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 $3.2 \times 10^5 h^{-3}$Mpc^3. In a 100-hr integration more than thousand galaxies would be detected.

While Arecibo is more sensitive for directed studies, the VLA's large field of view makes it 25 times faster than Arecibo for unbiased HI surveys. At higher redshifts ($z \geq 0.06$) the much higher angular resolution of the VLA is another major advantage.

The technical requirements are as in §1.3.6, with the addition that the 1.4 GHz band should be extended to cover frequencies down to 800 MHz for the high-redshift survey.

1.3.8 Clusters of Galaxies

The nature of the intragalactic medium (IGM) in clusters and groups of galaxies is an important subject for understanding of the large scale properties of the universe. X-ray observations show us 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 us 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 AGNs, 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.

1.3.9 Objects at High Redshift

The VLA Development Plan 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 $z = 3$–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.

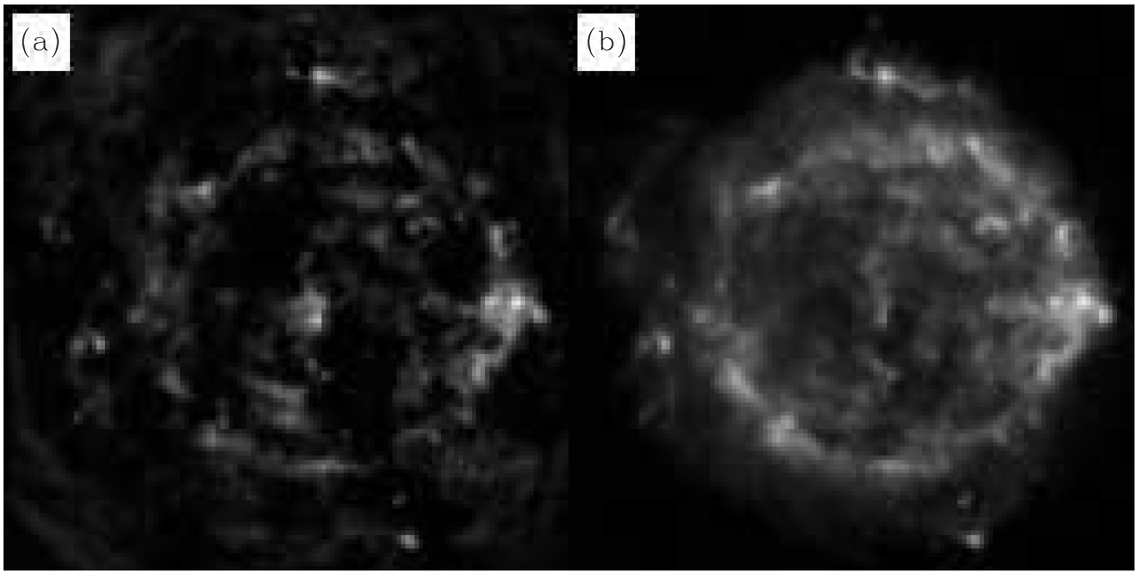

Figure 1.2: (a) An image obtained by using the full *u*-*v* coverage of the present VLBA at λ21cm to sample a model derived from the radio structure of the supernova remnant Cassiopeia A, rescaled to a distance of 1 Mpc. Only the most compact emission is represented at this resolution (FWHM ≈ 8 milli-arcsec). (b) An image obtained by sampling the same model with the full *u*-*v* coverage obtained by adding the Dusty, Bernardo, Holbrook and Vaughn antennas to the VLBA. The FWHM of the synthesized beam increases by only about 4% but the larger-scale structure of the remnant is now correctly represented at this resolution. Neither simulation is noise-limited.

1.4 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 and VLBA to join in observations with the other array, especially if we build the new antennas described earlier.

First, the information gathered by an N-element synthesis array varies as the number of baselines, *i.e.*, as N^2 for large N. Linking even four VLA antennas to the VLBA would *double* the information content of VLBA observations by doubling the number of correlations. This doubled information content would translate into improved image quality via (i) a wider field of view, (ii) improved sensitivity to extended structures, and (iii) increased dynamic range (image fidelity) for the VLBA. The more ambitious world-array VLBI experiments have also shown that the apparent simplicity of typical VLBI images reflects a lack of information gathered about the sources more than any intrinsic simplicity of Nature on these scales. We can expect many extragalactic sources to have complex structures on scales from 1 to 100 milli-arcseconds. Physical interpretation of these structures will require images with high dynamic range and wide fields of view over a large range in frequency.

Second, the VLA and VLBA, taken separately, leave the 40–400 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-arcsec at λ2cm. They fail to meet

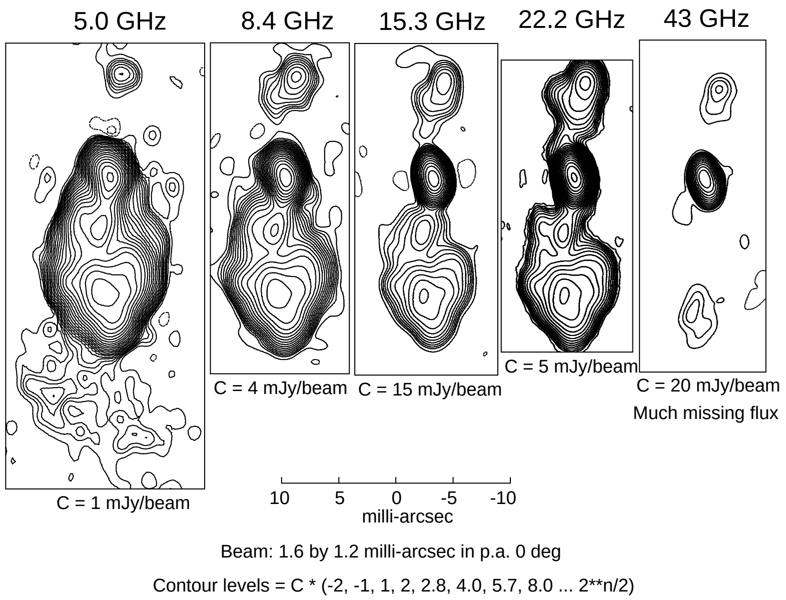

Figure 1.3: Preliminary VLBA images of the nucleus of the active galaxy 3C 84 at five frequencies. Note the differing sensitivities. The extent to which the detailed differences between these images are real frequency-dependent properties of the source (rather than differences in the *u*-*v* coverage of the VLBA at these frequencies) would be unclear even with matched sensitivities. The 43-GHz image clearly under-samples the broader (>5 milli-arcsec) structure in the lower-frequency images, however: it accounts for only about 3/4 of the known total flux density. These uncertainties could be eliminated by cross-linking the expanded VLA and the VLBA to provide a scaled-array capability, especially at the highest frequencies.

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, proto-planetary disks, and of supernova remnants in external galaxies.

Figure 1.2 illustrates how the new antennas proposed for the A+ configuration could also improve image quality when used to provide short-baseline *u*-*v* coverage in observations with the VLBA. As in Section 1.2.5, we consider observing a "twin" of the Cas A supernova remnant at a distance of about 1 Mpc, so the angular extent of the remnant is about $0.75''$. Panel (a) shows the image that could be obtained at λ21cm with the present VLBA. Panel (b) shows the dramatic improvement obtainable by adding the data from the proposed new antennas.

Third, it is important to realize that the VLBA has very limited "scaled-array" capability because of its small number of antennas (image quality deteriorates rapidly if any antennas are removed at one frequency to "match" the coverage at another), and because it is not reconfigurable. We can have multi-frequency coverage at a fixed angular resolution only by adding data from baselines shorter than 400 km at the higher frequencies (*e.g.*, Figure 1.3). Cross-linking an expanded VLA with the VLBA will extend the scaled-array capability of *both* instruments to cover a huge domain of angular resolution, providing well-filled *u*-*v* coverage, scaled with wavelength over a wide frequency range. For example, when studying relativistic jets in AGNs 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.

Although a foreign "100-km" array (*e.g.*, MERLIN) can provide some of the "missing coverage" at λ>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 U.S.

Ultimately, to study how the properties of astronomical sources change with frequency without changing resolution, we should be able to select antenna combinations to create the 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 Expansion 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 should also plan to 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 for much of the time that 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 4 VLA antennas at once. An upgrade of recording and formatter systems to reach 1 or 2 Gbps in a mode compatible with Mark IV is also desirable. Astrometric VLBI observations would benefit from a 2.4 GHz/8.4 GHz (S/X) dual frequency system.

This Science Workshop was directed only toward examining the astronomical motives for operating the new antennas as the VLA's A+ configuration. A further working group is now being set up to explore the impact of the VLA Extension on science with the VLBA.

1.5 SUMMATION

The VLA Development Plan 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 broadband 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 broadband, high-performance, low-frequency feeds be designed? What is the optimum way to transmit broadband 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 state of the art near the millenium 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 10-fold. The minimum beam area will improve fifty-fold. Finally, the new instrument, when cross-linked with the VLBA, will result in a VLBI instrument with greatly increased dynamic range, field of view and frequency-scalability relative to the present VLBA.

The VLA Development Planthus offers far more than an incremental improvement to existing scientific capabilities, though almost all current areas of research done with the VLA will benefit greatly from it. It provides fundamentally new science in many arenas, much of which depends on the cumulative effect of many improvements in the VLA Development Plan, 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 proto-planetary 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 E configuration.

Chapters 2 to 4 below turn to a detailed description of the scientific program which motivates enhancing the VLA. 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 may simply have been overlooked, and innovative uses of the improved instrument will not have been anticipated. Nevertheless, we believe that the science described here clearly demonstrates the need for enhancing the VLA's major capabilities and illustrates how all the key features of the enhancement project will be used in practice.

The science discussions also point to areas where technological challenges exist, and to others where tradeoffs – driven by technological and/or budgetary considerations – are inevitable. These areas are specifically addressed in Chapter 5, which also provides illustrative, but as yet by no means definitive, cost estimates. This Chapter is intended to serve as as background for the detailed studies that will lead to a detailed technical design and better cost estimates.

We strongly 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 enhancements. All comments on it will be welcomed. E-mail comments can be sent to `newvla@nrao.edu`.