Project Summary

The VLA Expansion Project

The purpose of the VLA Expansion Project is to create an astronomical research instrument of unprecedented power and flexibility in the meter-to-millimeter wavelength bands. This instrument, the Expanded Very Large Array, or EVLA, will be utilized by scientists from around the world for cutting-edge research throughout astronomy, providing unique information in such diverse areas as magnetic fields, cosmic sources in dusty regions, transient phenomena, and the formation of stars and galaxies.

The VLA Expansion Project will combine modern technologies with the sound design of the Very Large Array to increase, by an order of magnitude or more, all the existing observational capabilities of the VLA. This will be done at a cost much less than the inflation-adjusted investment cost of the VLA. The VLA Expansion Project will transform the VLA into a scientific instrument of much greater power, enhance the key role of radio astronomy as a scientific discipline, and encourage the future technical and intellectual development of the field.

The VLA Expansion Project consists of two phases of roughly equal cost:

- Phase I, the **Ultrasensitive Array**, which builds entirely on the existing infrastructure to improve all aspects of the VLA *except* its angular resolution; and

- Phase II, the **New Mexico Array**, which focuses *primarily* on improving the VLA's resolution by adding new antennas at distances up to ~ 250 km from the center of the current VLA.

The Ultrasensitive Array is the subject of this proposal, although a basic outline of Phase II is given in Chapter 2 of the Project Description.

The VLA Expansion Project is a leveraged project, building upon an extensive existing infrastructure and utilizing modern technologies of the types being developed for ALMA. These new technologies will confer a double benefit, as they will both improve the instrument's capabilities and reduce maintenance costs in many areas. It is anticipated that the operational costs of the EVLA will be comparable to those for the existing VLA.

The scientific discipline of radio astronomy has a rich record of scientific productivity. The VLA Expansion Project will provide the improvement in observational capability required by the scientific questions of today, and will bring new power that is necessary to the continued health of radio astronomy.

Scientific Impact of the Expanded Very Large Array

Modern astronomy is focused on a range of fundamental questions, including the evolution of galaxies, the formation of stars, and the behavior of matter under extreme conditions. Radio observations of diverse astronomical phenomena have the potential to provide unique and important information on all of these questions, with the ability to:

- measure the distribution, orientation, and strength of cosmic magnetic fields,
- make high-resolution images of objects embedded in even the densest dust,
- image the emission from high-energy particles created in the jets and shocks associated with sources ranging from young stars to black holes and supernovae, and
- distinguish thermal from non-thermal emission processes, and thus give insight into the evolution of phenomena such as star formation and black hole accretion throughout the universe.

The EVLA will make these potentials a reality. Factor-of-ten improvements in sensitivity, resolution, frequency coverage, and flexibility will allow astronomers to:

- observe ambipolar diffusion and thermal jet motions in young stellar objects,
- map the jets arising from X-ray-emitting black hole binaries, and measure the sizes and expansion rates of up to 100 gamma-ray bursts each year,
- image star-forming galaxies and map their magnetic fields out to redshifts of five and beyond, and
- image the three-dimensional structure of magnetic fields in the Sun and in nearby galaxies, and measure the field strengths and topologies in individual galaxy clusters.

These individual examples give only a small hint of the possibilities of this new instrument. The strength of the VLA has always been its ability to contribute to *every* area of modern astronomy – observing objects ranging from solar and stellar photospheres to spiral galaxy rotation curves, quasars, and gravitational lenses. The EVLA, with its vastly expanded sensitivity, resolution, and spectral capabilities, will extend and deepen this tradition, and will stimulate observations by the next generation of instruments at other wavelengths.

Synergy in Astronomy

Modern astronomy utilizes information from across the electromagnetic spectrum, and astronomers commonly use a wide range of instruments, both ground-based and space-based, to gain an understanding of the physics of distant systems. Although the VLA is the premier radio telescope in the world, its present capabilities will not satisfactorily complement those of new instruments, currently being designed or under construction, in other parts of the spectrum, because the VLA's sensitivity, tuning capability, and resolution are insufficient.

The EVLA will provide an excellent match to both ALMA[1] and SIRTF[2], as illustrated in Figure 1. This shows the published continuum sensitivities for the EVLA, ALMA, and SIRTF, along with the spectrum of the ultra-luminous starburst galaxy, Arp 220, redshifted to $z = 0.5$, 2,

[1] Atacama Large Millimeter Array

[2] Space Infrared Telescope Facility

8, and 32. The EVLA will easily detect the redshifted thermal emission from such high-luminosity objects, and will be essential for observations of the non-thermal emission at all redshifts. The key point is that a full understanding of the physics of such an object cannot be obtained with any one of these instruments – all three are needed in concert to map out the spectral energy distribution.

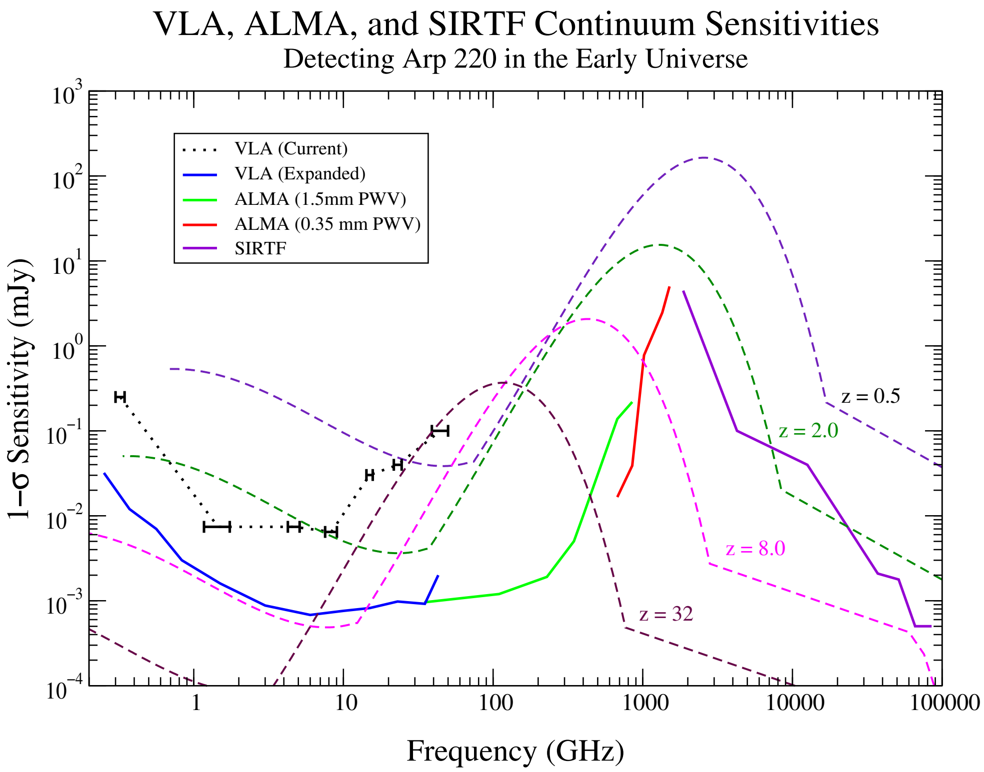

Figure 1: The spectrum of the ultraluminous starburst galaxy Arp 220, (shown with dashed lines), redshifted to various epochs (for an $\Omega_m = 1$ cosmology), with the continuum sensitivity of the EVLA, ALMA, and SIRTF (solid lines) superposed. For reference, the current sensitivity and tuning range for the VLA are shown by the horizontal dashes connected by dotted lines. This plot shows the complementarity of these proposed instruments for determining the entire spectrum of this class of object. The EVLA will be critical for determining the non-thermal emission properties of all objects and will also be able to directly separate the thermal and non-thermal components of their spectra in the very early universe.

An Overview of Phase I – The Ultrasensitive Array

The Ultrasensitive Array will improve, by a factor of ten or better, the following key observational capabilities of the VLA:

- **Sensitivity:** The continuum sensitivity will be improved by factors ranging from a few at lower frequencies (under 10 GHz) to more than twenty at the high-frequency end of the VLA's accessible spectrum (between 10 and 50 GHz).
- **Frequency Accessibility:** The Ultrasensitive Array will be able to operate at any frequency between 1.0 and 50 GHz. Up to four pairs of signals, each pair comprising two opposite polarizations, with selectable frequencies and bandwidths, will be tunable independently.
- **Spectral Capabilities:** A new correlator will provide many more frequency channels (at least 16,384, and possibly as high as 262,144), process wider bandwidths (up to 8 GHz in each polarization), give higher frequency/velocity resolution (to a few Hz), and offer many more powerful operational modes than are now available.

In addition, the Ultrasensitive Array will have a vastly improved user interface, allowing near-real-time access to default images and all data products. Users will then have the capability to monitor the progress of, and modify the course of, their observations.

Attaining the goals of the Ultrasensitive Array will require substantial changes to the electronics, operations, and computing. These include:

- A new fiber-optics signal transmission system, to transport signals with total bandwidths up to 16 GHz.
- New or improved receiver systems, to provide the new frequency capabilities, and to improve the capabilities of existing bands.
- A new design of the full electronics system, to provide high tolerance to radio-frequency interference (RFI), to allow avoidance of the strongest interfering signals, and to permit removal of remaining moderate and low-level RFI through post-correlation processing.
- A new correlator to process the greatly expanded bandwidths provided by the receivers and signal transmission systems. This correlator will provide full polarization capability with the fine frequency resolution necessary for spectral line observations and for robust removal of RFI.
- New on-line computing, monitor and control systems, and software, to provide a much more powerful and flexible operator and user interface with the improved array.
- Standardization of data products and system requirements with those of ALMA and the GBT, to ensure ease of operation and maximum efficiency of use by scientists.

Phase I will also include studies of key aspects of Phase II, as described in the next section.

An Overview of Phase II – The New Mexico Array

The primary goal of Phase II of the VLA Expansion Project is to improve the VLA's resolution by a factor of ten. This will be done by incorporating nearby existing Very Long Baseline Array (VLBA) antennas and approximately eight new antennas, located up to 250 Km from the VLA, with the existing 27 VLA antennas to define a new array – the New Mexico Array. These antennas will be connected to the new VLA correlator by fiber optic lines, resulting in a real-time array with unprecedented sensitivity, resolution, and imaging capability. We are currently studying the optimal number, and placement, of these proposed new antennas.

Phase II may also include the implementation of three other components of the VLA Expansion Project which are currently under study – prime-focus receiver systems to cover frequencies from 300 MHz, or lower, to 1 GHz, a super-compact **E** configurationto provide much improved surface brightness imaging on angular structures on scales comparable to the antenna primary beam, and installation of an 86 GHz capability. A decision on implementation of these components will depend on the results of these studies, and upon the recommendations of our user community.

The Capabilities of the Expanded Very Large Array

The key instrumental parameters of the VLA and the EVLA are summarized in Table 1. This table emphasizes the significant increases in sensitivity, frequency coverage, and spectroscopic capabilities provided by Phase I, and the factor of ten improvement in resolution provided by Phase II. These improvements will increase the maximum bandwidth by a factor of 80, the maximum number of spectral channels by a factor of at least 32, and the (logarithmic) frequency coverage by a factor of 4, in addition to reducing or eliminating most known sources of systematic error, and will result in a transformed instrument providing enormous and unique scientific capabilities.

Table 1: **Key Capabilities of the Current and the Expanded VLA.**

Parameter	VLA	EVLA – Phase I The Ultrasensitive Array	EVLA – Phase II The New Mexico Array
Point Source Sensitivity	10μJy	0.8μJy	0.6μJy
No. of baseband pairs	2	4	4
Maximum bandwidth in each polarization	0.1 GHz	8 GHz	8 GHz
No. of frequency channels at maximum bandwidth	16	16,384	16,384
Maximum number of frequency channels	512	16,384[1]	16,384[1]
Maximum frequency resolution	381 Hz	$\sim$ 1 Hz	$\sim$ 1 Hz
(Log) Frequency coverage, 0.3–50 GHz	25%	75%	100%
No. of baselines	351	351	666
Spatial Resolution (5 GHz)	0.4 arcsec	0.4 arcsec	0.04 arcsec

Figure 2 illustrates two important parameters of instrumental performance: frequency coverage and angular resolution. The area covered in the plane defined by these parameters is, in essence, an instrument's 'discovery space'. In this figure, the existing NRAO interferometers (the VLA and the VLBA) provide the frequency-resolution coverage shown as the thin horizontal blue stripes, while the EVLA will expand these to the areas covered in orange (Phase I) and bright yellow

[1] Likely to increase by a factor of 16, to 262144

(Phase II). It has been assumed that the frequency coverage of the EVLA will be extended down to 300 MHz. Light grey areas could be covered by further improvements to the EVLA and the VLBA.

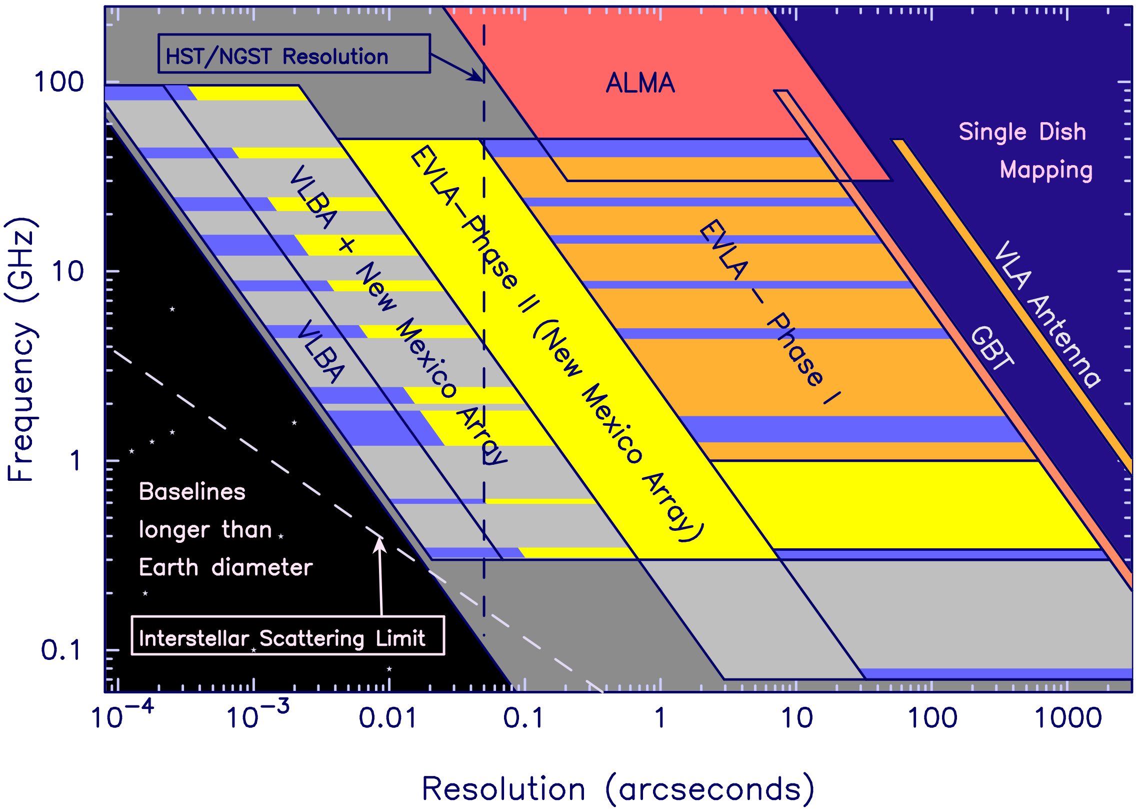

Figure 2: This figure shows the frequency-resolution coverage of current and planned NRAO telescopes. The horizontal blue stripes show the capabilities of the current VLA and VLBA; the orange area delineates the improvement in coverage after completion of Phase I of the VLA Expansion Project. The bright yellow areas show the extension of coverage after Phase II – the New Mexico Array. The light grey areas show additional coverage which could be gained by extending the VLA Expansion Project to lower frequencies, and by upgrading the VLBA. Also shown are the high resolution limits for the GBT and a single VLA antenna. The black area in the lower left of the figure shows regions inaccessible to earth-based observations. Coverage by ALMA (below 250 GHz) is shown in dark red. It is not yet clear what the lowest frequency on ALMA will be, though it will certainly not be less than ~ 30 GHz (as shown in this figure). For comparison, we show the approximate resolution limit for the HST and NGST, and the limit set by interstellar scattering.

Costs and Timescale for Phase I of the VLA Expansion Project

The total cost of Phase I of the VLA Expansion Project has been estimated using a series of estimating, funding, and programmatic assumptions that are more fully detailed in the Budget Justification. This estimated cost, expressed in FY2000 dollars, is \$76.2M. Funding for the Ultrasensitive Array is assumed to come from three sources: a request to the NSF for \$49.9M, contributions of \$12.0M from foreign partners, and \$14.3M from re-directed work of our existing staff, and from previously funded work. Identified foreign partners include Mexico, which has committed to a contribution of \$2M, and Canada, from which a contribution of \$10M is anticipated. The Canadian contribution will most likely take the form of the design and construction of the EVLA correlator. Negotiations between the NRAO and the Herzberg Institute of Astrophysics (HIA) to finalize this arrangement are ongoing.

Implementation of this phase of the project has been planned in two stages. The first stage, costing a total of \$58.9M, of which \$36M will be requested from the NSF, will result in implementation of those components essential to all parts of the project – the correlator, fiber optics, antenna modifications, on-line computing, and associated electronics. This stage will take seven years to complete. The second stage will begin mid-way through Stage 1, and take six years, completing in 2009. This stage, budgeted for a total of \$17.3M, of which \$13.9M in additional NSF funding would be required, will complete the receiver systems, computing, data archiving and communications, and other portions of the project.

This two-stage approach has been designed to minimize the yearly impact of the project request on the NSF by stretching out the project primarily through delaying implementation of the new and improved receivers. An alternate schedule, which would shorten the duration of the project by two years, and decrease the total cost by \$2.3M, is possible and desirable.