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Executive 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 $\sim 250\,\mathrm{km}$ from the center of the current VLA.

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

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.

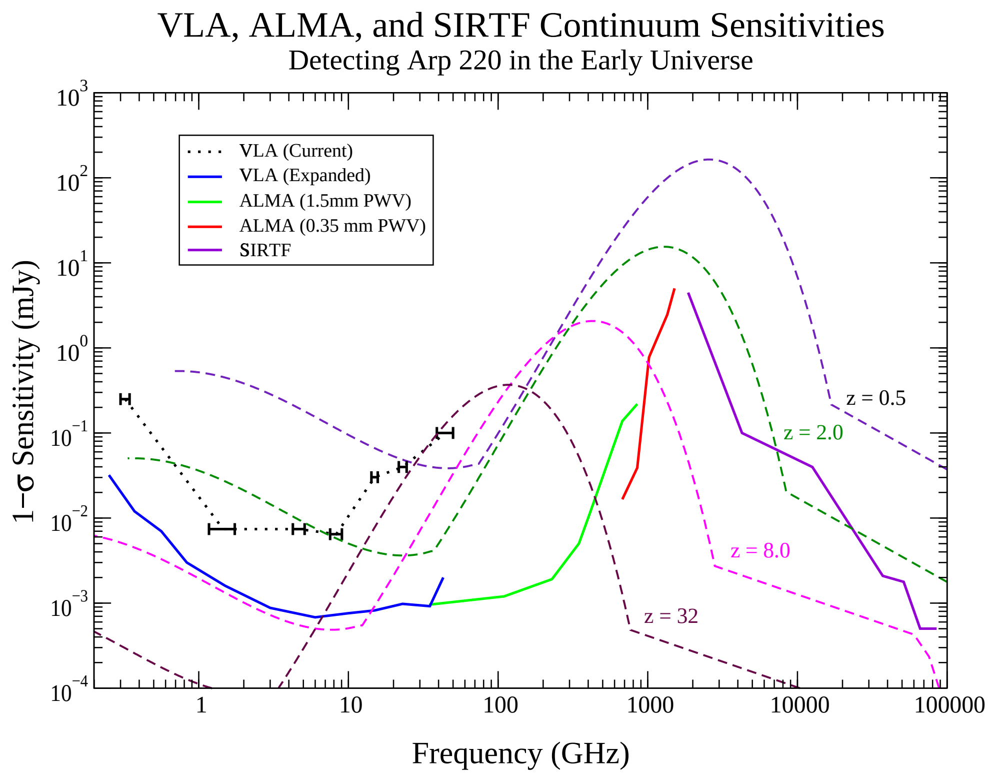


Figure 1: The spectrum of the ultraluminous starburst galaxy Arp 220, (shown with dashed lines), redshifted to various epochs (for an $\Omega_m = 1$ cosmology), with the continuum sensitivity of the EVLA, ALMA, and SIRTF (solid lines) superposed. For reference, the current sensitivity and tuning range 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), 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]
(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 (Phase II). It has been assumed that the frequency coverage of the EVLA will be extended down

[1] Likely to increase by a factor of 2 or more.

to 300 MHz. Light grey areas could be covered by further improvements to the EVLA and the VLBA.

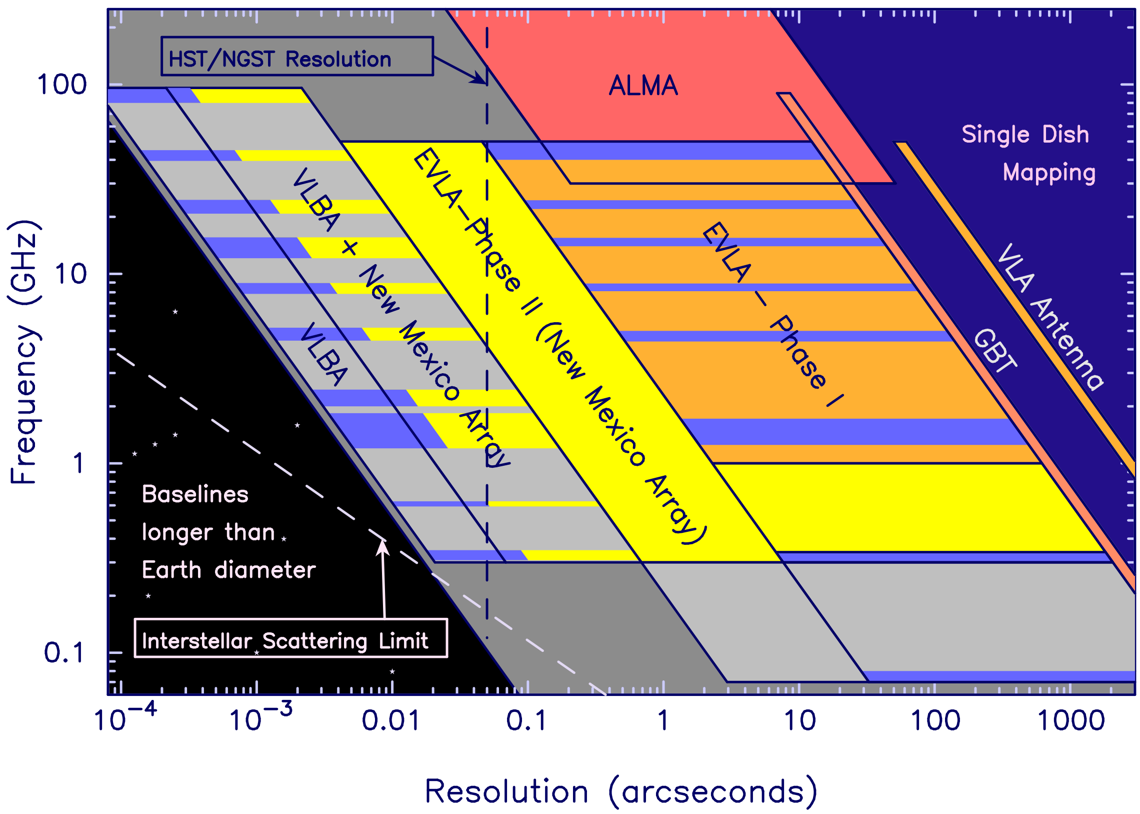


Figure 2: This figure shows the frequency-resolution coverage of current and planned NRAO telescopes. The horizontal blue stripes show the capabilities of the current VLA and VLBA; the orange area delineates the improvement in coverage after completion of Phase I of the VLA Expansion Project. The bright 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 $\sim 30\,\mathrm{GHz}$ (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 Chapter 8. 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.

Chapter 1

Introduction

1.1 Radio Astronomy in the 21st Century

We are living in an exciting era for astrophysics, due largely to the application of recent technological advances to impressive new instrumentation. With concurrent observational improvements across the entire electromagnetic spectrum, astronomers are pursuing such fundamental questions as the size and age of the universe, and the origin and evolution of the planets, stars, and galaxies which inhabit it. Radio astronomy makes important and unique contributions to these studies, by probing the strength and distribution of magnetic fields, seeing through dust obscuration to the hearts of star formation regions, and imaging the emission associated with both star formation and accretion onto compact objects throughout the universe. But even the best current radio telescopes fall far short of this potential, largely because they do not take full advantage of the latest modern technologies. Here we propose outfitting the most flexible and powerful of the world's existing radio telescopes, the Very Large Array (VLA), with the benefits of the past 20 years of technical development. By building on existing infrastructure, and by using proven technologies, the VLA Expansion Project will produce a telescope, the Expanded Very Large Array (EVLA), which will provide order-of-magnitude improvements over the VLA in all important observational parameters, including sensitivity, spatial and spectral resolution, and frequency coverage, at a cost far less than the investment cost (expressed in today's dollars) of the present instrument.

The great strength of the VLA has always been its ability to contribute across the entire range of modern astronomy, with fundamental discoveries in areas ranging from proto-stellar cores to galaxy cluster magnetic fields to gamma-ray burst sources. Most of these discoveries could not have been predicted at the time the VLA was built. The EVLA will keep the VLA, and the radio astronomy discipline as a whole, at the forefront of modern astronomy, and will ensure that this tradition of excitement and discovery continues over at least the next twenty years.

1.1.1 Astronomy and the Very Large Array

The Very Large Array is the most powerful, flexible, and widely used radio telescope in the world. When dedicated in 1980, it provided a factor of ten improvement in observing capability over existing radio telescopes in all key instrumental criteria – sensitivity, spatial and spectral resolution, imaging capability, frequency access, speed, and flexibility. The VLA set a standard for a multi-user, flexible, powerful telescope which has yet to be matched by any other facility.

Astronomers from around the world were quick to utilize the power of the VLA, and demand for the telescope remains strong. The VLA has been used by more than 2200 researchers, from hundreds of universities and institutes in the U.S. and around the world, for more than 10,000 different observational programs. Research conducted with the VLA has had a major impact across the breadth of astronomy – from solar and planetary work, through nearby galaxies, to quasars and forming galaxies at the furthest reaches of our universe.

The best technologies of the 1970s were utilized in the VLA. For the most part, the telescope still uses, and is limited by, these same technologies, particularly in the critical areas of signal transport and correlation. The last 20 years have witnessed a revolution in these technologies; if utilized on the VLA, these will improve all the telescope's capabilities by an order of magnitude or more – nearly the same improvement which the VLA originally provided over existing telescopes, over 20 years ago.

1.1.2 The Future for Radio Astronomy

Two decades ago, the VLA, by expanding the technical capabilities of radio astronomy by one to two orders of magnitude, demonstrated the viability, vitality, and rich potential of this field. Although the VLA remains the world's most useful and widely used radio telescope, we must look beyond the present instrument, and ask whether another leap of one to two orders of magnitude will result in similar advances in science.

The answer is an emphatic 'yes'. Radio emissions from faint, distant, and rare phenomena throughout the universe are undetectable by existing radio telescopes. These phenomena, investigation of which will provide fascinating clues to the evolution of our universe and its constituents, are often too faint or too small to be resolved with present instruments, or radiate at radio frequencies these telescopes cannot detect. Radio observations provide unique information – unavailable at other wavebands – most notably, in investigations of phenomena involving magnetic fields and relativistic particles, and in dusty environments which block optical light. The potential of radio astronomy is unlimited, but more powerful instruments than those currently available are required to realize this potential.

Over the past few decades, decimeter and centimeter radio astronomy has returned many exciting new discoveries, including: the tremendous energy requirements of radio galaxies; the discovery of astrophysical jets, quasars, pulsars, gravitational lensing, and the cosmic microwave background; precise tests of general relativity, including the detection of gravitational radiation; the discovery of interstellar molecules and cosmic masers; and precision measurements of Earth rotation and tectonic plate motions. Inspired by these successes, radio astronomers are now speculating about the scientific impact of the next generation of radio telescopes, including the Square Kilometer Array (SKA), with a million square meters of collecting area, which would offer up to two orders of magnitude improvement in sensitivity over the VLA. However, the technical challenges which must be surmounted before such an instrument can be built are great.

Although the EVLA cannot give the sensitivity that the SKA promises, it will provide up to an order of magnitude improvement over the present VLA in sensitivity and resolution, as well as many orders of magnitude improvement in spectroscopic capability. As discussed in this proposal, the EVLA will do this at reasonable cost, using technology currently being developed for the Atacama Large Millimeter Array (ALMA), with a correspondingly robust budget determination and a well-understood timescale for implementation. Timely initiation of the VLA Expansion Project is required to complement the impressive proposed advances in facilities and instrumentation in other wavelength bands, and to ensure the continued leadership of the United States in radio astronomy.

The VLA is a major instrument, and improving its performance will be a major project. However, implementating these improvements will be much simpler and quicker than what would be required for a completely new facility, since the project

- builds upon the existing antennas, site, and infrastructure, and
- utilizes the technology already under development for ALMA.

This document describes a proposal to implement the VLA Expansion Project. The result of this project will be, in effect, a new instrument, the EVLA. Because of the size and scope of the project, and because a major part of these improvements can, and should, be implemented quickly to take advantage of parallel development for ALMA, the overall project has been divided into two major phases:

1. **Phase I – The Ultrasensitive Array**: This phase will enhance array performance in all areas *except* resolution. Plans for this phase are well advanced, and are the subject of this proposal. The total cost of implementing this phase is $76.2M – less than one third the (inflation-adjusted) original investment cost of the VLA. After factoring in the anticipated contribution from foreign partners, and re-directed work by NRAO staff to the project, the request to NSF for this phase will be $49.9M.

2. **Phase II – The New Mexico Array**: This phase will add approximately eight new antennas at distances up to ~ 250 km from the array center to provide an enhancement of an order of magnitude in spatial resolution. By connecting these new antennas, plus up to four existing Very Long Baseline Array (VLBA) antennas, to the proposed new correlator with optical fiber lines, a new facility with unprecedented sensitivity and resolution will be created. This second phase may also include further enhancements to the VLA – extended frequency coverage below 1 GHz, enhanced wide-angle capability for improved low-surface brightness imaging, and an 86 GHz capability. Detailed plans for this second phase are under development.

Although the VLA Expansion Project requires no breakthroughs in technology, it does require careful organization and planning. Plans for Phase I are mature, and a start to the project can begin as soon as funds are available. However, many details of Phase II (such as the placement of the new antennas, and the feasibility of implementation of low frequency feeds at the prime focus) must still be worked out before we are ready to start construction. As discussed below, the university community has been involved in the planning process so far, and we intend to expand this involvement.

Finally, we intend to take full advantage of the complementary development of the ALMA project. Much of the new hardware proposed for the EVLA (*e.g.*, the correlator and fiber optics transmission system) is very similar to that which ALMA will employ, and many of the goals for the new on-line computing systems are also similar or identical. We are already working to take advantage of this synergy, with many of the technical staff who will have prime responsibilities in the VLA Expansion Project being heavily involved in the ALMA definition process. Clearly it will be beneficial to continue this parallel development, with ALMA and the VLA Expansion Project proceeding on comparable timescales.

1.2 Key Aspects of the VLA Expansion Project

1.2.1 Impact on the University Community

The NRAO's primary function is to provide world-class radio astronomy facilities to the astronomical community, the core of which consists of those astronomers at U.S. universities. The health of the field depends on continued support of these researchers and regular addition of new PhDs into the discipline. Our user community is large, consisting of nearly one thousand astronomers spread throughout the country from well-known, prestigious research institutions to smaller, undergraduate-dominated teaching institutions like Haverford, Swarthmore, Agnes Scott, and Lafayette Colleges. More than 100 individuals from U.S. universities have received PhDs for work based wholly, or in large part, on data taken with the VLA. A similar number of PhDs based on VLA data have been granted by foreign universities.

Our goals are to serve this diverse community and to involve our U.S. users in making decisions about the future of the discipline. Furthermore, by providing exciting new capabilities, we can work with the universities to ensure a continuing flow of new talent, both technical and scientific, into the field. The VLA has always been a key element in the NRAO's efforts to train the researchers of the future in radio astronomy, via week-long summer schools, summer student programs, and visits by numerous graduate students for terms ranging from a few days to two years. The continuation of this process of training tomorrow's researchers requires an instrument with today's technology. We cannot fulfill these functions with technology that was mature before some of today's students were even born.

Throughout the planning of the VLA Expansion Project we have involved members of the university community in the definition of our goals. In January 1995, about 60 astronomers attended the first workshop on the project; the proceedings of this workshop defined the basic outline of the project as proposed here. In June 1998, we held a second, two-day workshop on the scientific goals of an expanded VLA. This meeting attracted more than 100 astronomers. It focused on the explicit relationship between the science the group wanted to do, and the more detailed ideas we had developed about the technical design.

We intend to continue and strengthen the involvement of the university groups in the VLA Expansion Project. As is usual for NRAO projects, an outside advisory committee will oversee its progress. Some of our studies, dealing, for example, with details of the New Mexico Array, already have university participation; we expect such collaborative efforts to continue. Much of the work is straightforward, so the primary need is for advice rather than technical development. In other areas, such as development of broad-band low frequency feeds and front-ends, there is considerable community experience that can be applied to the VLA.

The primary impact of the VLA Expansion Project on the community will be to provide this group with an instrument with much better sensitivity, spatial and spectral resolution, and spectral coverage, to enable better research. We plan to make the entire process of using the VLA easier, more flexible, much more interactive, and thus more productive. Many of these changes will come from an improved on-line system and associated changes in operation, such as dynamic scheduling and real-time, remote operation utilizing new technologies that provide flexible and powerful interface tools. We also plan to produce an improved data product, including calibrated data and near real-time default images which will be available within minutes to users located anywhere with suitable Internet connection. The details of this product and of the new operations model will be major subjects of discussion with our user community.

1.2.2 Foreign Involvement

Because of its unique capabilities, astronomers from all over the world not only use, but depend upon the VLA for their research. Besides improving the quality of research, foreign involvement in the VLA Expansion Project will promote the advancement of science by

- providing a broad base of intellectual and technical stimulation,
- providing real financial contributions to the instrument for hardware, and
- giving the U.S. a base from which to take part in other new international facilities such as the Square Kilometer Array.

Over the past few years, Mexico and Germany have made significant contributions to the NRAO that have allowed most of the VLA antennas to be outfitted with receivers operating at the

45 GHz band, and have stimulated development of holography and pointing programs that have significantly improved the performance of the antennas and of the array. In addition, contributions from Germany will enable us to equip most of the VLBA antennas with receivers at 86 GHz; this will be a step toward a New Mexico Array (Phase II of the VLA Expansion Project) that could be fully equipped at 86 GHz. Indeed, the VLA's remarkably good performance in the 45 GHz band has suggested that it may be possible to obtain useful observations at 86 GHz; tests with the new German-funded receivers may be undertaken to determine whether this is feasible.

The ALMA collaboration with Europe is the most prominent example of the advantages of relationships with foreign partners. In this case, the international collaboration will produce a much more sensitive and capable array than could be built with U.S.-only funding. We plan to continue this pattern for the VLA Expansion Project by involving other countries in funding and producing the hardware for the EVLA. At this time, we have firm, or nearly firm, commitments from two countries: the Mexican research foundation Consejo Nacional de Ciencia y Tecnología (CONACyT) has just announced a grant of $2M to the project, and an agreement with the Canadian Herzberg Institute for Astrophysics (HIA) for an investment of $10M is very close. This would be used to design and build the VLA Expansion Project correlator, as will be described in later chapters. Again, these partnerships will provide improved VLA performance at a lower cost to the U.S., as well as taking advantage of technical expertise outside the U.S.

The VLA Expansion Project will keep the NRAO and the United States at the center of centimeter wave astronomy by ensuring that the VLA's sound infrastructure is the base on which we build in the future. The even more advanced instruments of the future will require multi-national involvement, and the VLA Expansion Project will build the relationships that will lead to significant benefits to the U.S. from such worldwide efforts.

1.2.3 Public Education and Outreach

There has been a revolution in science education and outreach programs since the VLA Visitor Center was constructed in 1983. As we expand the VLA's scientific capabilities, we must also expand our educational facilities and programs to fully exploit the public visibility and appeal of the world's most famous radio telescope. This expansion will enhance science education and the scientific literacy of tomorrow's leaders and teachers. Using funds requested within this proposal, as well as funds raised from sources outside the NSF astronomy budget, we will build a new Visitor Center, produce effective exhibits that incorporate modern interactive learning techniques, and institute new programs to enhance both formal and informal science education.

1.2.4 Management Planning

To be most effective and efficient, the VLA Expansion Project should be carried out at the same time as the ALMA project. Both could then take financial advantage of shared technologies, including correlator development, fiber optic signal transmission, and software. Indeed, this is already being done on the small scale, where the expertise being developed for the fiber-optic link between the VLA and the VLBA's Pie Town antenna will be applied to the design of ALMA. Those planning the VLA Expansion Project are also working closely with the ALMA design and development effort, and are trying to make the two projects as alike as is practical. The advantages of this approach are obvious, and it should also mean that the instruments are as similar to use as possible for the astronomer.

However, this also implies that the NRAO will have to manage its participation in both projects at the same time. Development of ALMA over the past two years has taken advantage of modern management tools that enable the work effort to be apportioned and tracked throughout the project; the same tools will be used in the VLA Expansion Project. This should prevent significant delays and/or cost overruns, both by the early identification of possible problems and by the proper accounting of time available for each project, as well as for current VLA and VLBA operations. As proposed, the VLA Expansion Project and ALMA will involve separate personnel who communicate regularly with each other by each taking part in the oversight committee work for the other project.

The VLA and the VLBA were both completed on time, and on budget. The VLA Expansion Project is a less demanding project than either of those, as it utilizes an existing site, and retains the current antennas and infrastructure. Chapter 8 of this proposal outlines the top-level work breakdown structure and schedule required to implement the technical development plan for Phase I of the VLA Expansion Project. Understanding the important tasks provides a measure of confidence that the schedule and cost of the this phase are well understood and will be well controlled, when funding is made available.

1.3 Science with the VLA Expansion Project

Radio astronomy plays a unique and valuable role within the discipline of astronomy. Observations taken in the radio bands measure the strength and topology of magnetic fields, provide data on regions completely obscured at optical wavelengths, monitor highly energetic transient sources, and track the formation and evolution of a wide range of astronomical phenomena. The EVLA will enhance the already invaluable role of the VLA as the world's major radio window to the universe. In this section, we list a few prominent examples of key astronomical projects which will be made possible by this instrument.

1.3.1 Science with Phase I – the Ultrasensitive Array

The scientific potential of the Ultrasensitive Array will be tremendous, as projects which are now difficult will become routine, and projects which are currently impractical will become feasible. A short selection of unique programs made possible by the Ultrasensitive Array includes:

- providing accurate positions, sizes, and expansion estimates for up to 100 gamma-ray bursts every year,
- disentangling starburst from black hole activity in the early universe,
- mapping the magnetic fields in individual galaxy clusters,
- looking through the enshrouding dust to image the formation of high-redshift galaxies,
- observing ambipolar diffusion and thermal jet motions in young stellar objects,
- measuring the three-dimensional motions of ionized gas and stars in the center of the Galaxy,
- conducting unbiased searches for redshifted atomic and molecular absorption lines,
- measuring the three-dimensional structure of the magnetic field on the Sun,
- using the scattering of radio waves to map the changing structure of the dynamic heliosphere, and
- measuring the rotation speeds of asteroids.

As with the original VLA, the vast area of "discovery space" opened up by the Ultrasensitive Array makes it likely that the most important discoveries to be made cannot now be anticipated. The greatest impact of the Ultrasensitive Array will thus be measured not by the answers to today's questions, but by the answers to the questions raised by tomorrow's observations.

1.3.2 Science with Phase II – the New Mexico Array

Phase II of the VLA Expansion Project, the New Mexico Array, will enhance the array's resolution by a factor of ten or more, while maintaining the high imaging fidelity which is one of the VLA's most important characteristics. Also, Phase II may extend the continuous frequency coverage of the array downwards to 300 MHz or lower, include significant improvements in low-surface brightness, wide-angle field imaging, and implement an 86 GHz capability.

The addition of up to eight new antennas to the VLA and VLBA will effectively create three new instruments:

- a stand-alone array of 10 to 14 antennas (consisting of eight new antennas, the two VLBA antennas at Los Alamos and Pie Town, and up to four VLA antennas), giving the continuum sensitivity of the current VLA, but with ten times the spatial resolution;
- an array of 37 antennas, comprising the 27 VLA antennas, eight new antennas and two VLBA antennas, which will provide an order of magnitude improvement in *both* resolution and sensitivity over current capabilities, allowing astronomers to image thermal sources with resolutions compatible to the NGST[1]; and
- a continental array, consisting of the eight new antennas, the existing ten VLBA antennas, and some of the VLA antennas. This combination will provide unprecedented sensitivity and imaging capability on the arcsecond-to-milliarcsecond scale from 1 to 50 GHz.

These high resolution, high sensitivity instruments will produce an exciting range of original science, including:

- milliarcsecond imaging of thermal sources, including stellar photospheres, proto-planetary disks, and H II regions,
- imaging the dense centers of proto-planetary disks at resolutions of a few AU,
- mapping the three-dimensional distribution of both temperature and density in nova shells,
- imaging individual compact H II regions in external galaxies as distant as M82,
- tying together the optical and radio reference frames with milliarcsecond precision,
- measuring accurate parallax distances and proper motions for hundreds of pulsars as distant as the Galactic center,
- measuring the velocity and acceleration of the ionized gas within a few tenths of a parsec of the Galactic center, thus giving dynamical information on the gravitational effects of the nearest super-massive black hole,
- imaging extragalactic accretion disks on parsec scales, by observing optical depth effects over factors of ten or more in frequency,

[1] Next Generation Space Telescope

- tracking high-energy particles and imaging central starbursts surrounding active galactic nuclei (AGNs),
- providing < 1 kpc resolution for galaxies at redshifts up to five and beyond, helping to distinguish star formation from AGN activity, mapping the magnetic field strength and structure, imaging H I absorption lines, and probing the surrounding intergalactic medium (particles and fields),
- imaging flares in nearby giant and supergiant stars, and
- monitoring and imaging the full evolution of the radio emission associated with X-ray and other transients.

1.3.3 Synergy with Other Wavebands and Instruments

Just as radio astronomy is not an isolated field, so the VLA is not an isolated instrument. The capabilities of the EVLA nicely complement those provided by major telescopes at other wavelengths.

Two of the main science drivers for the NGST, SIRTF[2], Keck, and ALMA[3], as well as for instruments such as SCUBA[4] and BOLOCAM[5], are the twin evolutionary questions of star formation in the Galaxy, and galaxy formation in the early universe. For star formation, optical and near-infrared observations provide spectacular images and detailed spectroscopy of relatively dust free regions, while millimeter and submillimeter telescopes map out the molecular gas and thermal dust emission. The EVLA in turn will fill out the picture by imaging the most obscured regions in proto-stellar disks where planets might form, mapping out the acceleration regions of thermal jets, and providing the complete spectral information needed to disentangle synchrotron, free-free, and dust emission.

Similarly, optical and infrared instruments are essential to measure redshifts and emission lines in the most distant galaxies, and to trace the detailed morphology of these sources at the wavelengths most often studied locally. Observations by ALMA, SIRTF, and SOFIA[6] will be sensitive to the bulk of the luminosity of starburst galaxies shrouded in dust, and will allow us to follow the evolution of the molecular gas out of which stars are formed. The EVLA will contribute valuable complementary data on the evolution of the ground state of hydrogen, as well as the redshifted low-order transitions of such vital molecules as carbon monoxide. The EVLA will see through the dust to directly image ultraluminous infrared galaxies, showing the relative contributions from active galactic nuclei and star formation, providing an independent dust-free estimate of the star formation rate, and simultaneously measuring the strength and orientation of the magnetic fields. While individual telescopes like the HST[7] have clearly had an enormous impact, multifrequency studies provide much more information than isolated spectral points. The importance of radio data is illustrated by the fact that VLA campaigns are already underway to locate distant galaxies detected at submillimeter wavelengths by SCUBA and to study high redshift quasars found optically by the Sloan Digital Sky Survey, and by a recently submitted proposal for deep VLA imaging of the SIRTF First-Look Survey field.

The connection between radio and high-energy observations is even tighter and more direct, since both trace highly energetic phenomena. One of the major results of the Yohkoh mission was

[2]Space Infrared Telescope Facility
[3]Atacama Large Millimeter Array
[4]Submillimetre Common-User Bolometer Array
[5]Bolometer Array Camera
[6]Stratospheric Observatory for Infrared Astronomy
[7]Hubble Space Telescope

the clear positional coincidence between solar X-ray flares and simultaneous radio events imaged by the VLA. Most target-of-opportunity proposals on ASCA[8] and the RXTE[9] are now triggered by radio observations, and *vice versa*, with the VLA providing sensitive and comprehensive monitoring, as well as imaging, of the jets accelerated by black hole X-ray binaries. The X-ray/radio correlation for active stars is as tight as the far-infrared/radio correlation for star-forming galaxies, with correspondingly important implications for energy loss mechanisms. On larger scales, ROSAT[10], Chandra[11], and the XMM[12] provide vital information on the amount and distribution of hot gas in galaxy clusters, while the VLA traces the equally pervasive magnetic fields and relativistic particles. Similarly, the same active galactic nuclei which emit the gamma-rays seen by INTEGRAL[13] and GLAST[14] are strong radio sources. The VLA provides accurate light curves as well as sensitive probes of both continuum and line absorption in these objects, giving unique information on the accretion disks and any obscuring material, as well as on the active galactic nuclei themselves. Finally, while BATSE[15], Beppo-SAX[16], Swift[17], and HETE[18] find and localize gamma-ray bursts, and the HST and Keck track their optical light curves, find their host galaxies, and measure their redshifts, only the VLA can provide extinction-free statistics on gamma-ray burst afterglows, follow the emission from the initial relativistic fireball to the late sub-relativistic stage, and (through interstellar scattering) directly measure source sizes and expansion rates. Full realization of the potential of X-ray and gamma-ray satellites requires the complementary radio observations that only the EVLA can provide.

1.3.4 The EVLA in Context

There are many powerful radio telescopes operating in the 300 MHz to 50 GHz frequency band. However, none of them can compete with the VLA's *combination* of speed, flexibility, sensitivity, resolution, and operational capabilities. These other instruments are either limited in some key aspects of their capability, or have been designed with a highly specific scientific goal in mind – they have been optimized for performance in some key parameter at the cost of flexibility and capability in others. The most powerful characteristic of the VLA is that it provides outstanding performance in *all* key parameters. It is a unique world facility.

The new scientific opportunities created by the VLA Expansion Project are enormous – a summary is given in Chapter 4, and a more extensive description will be found in Appendix A. The proposed improvements rest on currently available technologies that are well understood and relatively inexpensive. Indeed, much of the development work that will be needed is already underway for ALMA. Now is the time to allocate the reasonable resources needed to create a telescope as fully capable at centimeter radio wavelengths as the NGST, Chandra, SIRTF, and ALMA will be in their respective wavebands.

The EVLA and the SKA

In recent years there has been considerable discussion within the international radio astronomy community about the design of a next generation radio telescope with at least 50 times the collecting

[8] Advanced Satellite for Cosmology and Astrophysics – formerly Astro-D
[9] Rossi X-ray Timing Explorer
[10] Röentgen Satellite
[11] Chandra X-ray Observatory
[12] X-ray Multimirror Mission
[13] International Gamma-Ray Astrophysics Laboratory
[14] Gamma-ray Large Area Space Telescope
[15] Burst And Transient Source Experiment
[16] Sattelite per Astronomia X
[17] Swift Gamma-ray Burst Explorer
[18] High Energy Transient Explorer

area of the VLA. This concept has become known as the *Square Kilometer Array* (SKA). In order to construct a radio telescope with such a large collecting area for less than a billion dollars, it will be necessary to break the cost curve of contemporary instruments by more than an order of magnitude. Studies are underway in a number of countries, including the United States, to develop a cost-effective technology for constructing such large collecting areas, although it is likely that different technologies, and thus different instruments, will be needed to provide the desired capabilities over the wide range of frequencies covered by the EVLA.

In order to obtain sufficient angular resolution to avoid confusion at the high source density expected for nanoJansky radio sources, and to adequately image distant galaxies, overall array dimensions of hundreds to thousands of kilometers, depending on wavelength, will be necessary. Because these are the dimensions of the EVLA, it will constitute a critical first step towards the Square Kilometer Array. Possible next steps would be to extend the real-time operation of the New Mexico Array to the other eight elements of the VLBA, then to add large collecting areas at each of the VLBA and New Mexico Array sites using newly developed technology, and even to construct new sites located on other continents. In this way it will be possible to approach the full capability of the SKA in a deliberate fashion, and at the same time maintain the viability of the user community during the long development and construction period of the SKA, which may extend over several decades.

Furthermore, solutions to challenges posed in handling external radio-frequency interference, multiple-field calibration in the presence of non-isoplanatic screens, non-coplanar imaging (especially in combination with the preceding effects), and imaging with dynamic ranges in the millions can be tested and implemented in the VLA Expansion Project. These are critical problems which will limit the SKA, and which must be solved before an SKA can be built and operated. The EVLA is an essential step towards the SKA.

1.4 Summary of this Proposal

This document describes a proposal and plan for implementing Phase I, the Ultrasensitive Array, of a project for expanding the scientific capabilities of the Very Large Array. A later document will similarly describe a proposal for implementing Phase II, the New Mexico Array.

Chapter 2 summarizes the design goals of the full VLA Expansion Project, and gives a brief scientific justification for each of these major goals.

Chapter 3 describes the design goals of Phase I of the project – the Ultrasensitive Array – and gives detailed descriptions of the planned capabilities of the improved array. The chapter concludes with a detailed overview of the scientific implications of the new instrumental capabilities.

Chapter 4 gives a summary of the key science benefits of the Ultrasensitive Array, and how each is dependent upon the improvements requested in this proposal. A much more extensive survey is provided in Appendix A.

Chapter 5 gives the technical development plan. In general, we have taken a conservative design approach, using well understood technologies to ensure a maximum return for minimum cost.

Chapter 6 discusses computing and data management issues. Since the EVLA will produce data at a rate two or more orders of magnitude greater than that of the VLA, the demands on computing, both in real-time operations, and in off-line processing, will be considerable. We are planning a comprehensive approach to handle these anticipated demands, an approach which will also be used for ALMA and the GBT, as well as other modern instruments.

Chapter 7 briefly reviews the impact the VLA has on education and public outreach, and includes our plans for expanding and improving these vital programs.

Chapter 8 describes the schedule and budget for implementing the Ultrasensitive Array.

Chapter 2

The VLA Expansion Project

2.1 Goals of the VLA Expansion Project

The overall goal of the VLA Expansion Project is to produce the best radio telescope for astronomy in the centimeter and decimeter wavelength bands at reasonable cost and on a timescale of less than ten years. This can be achieved now by incorporating newly available technologies into the sound basic design and existing infrastructure of the VLA, and by expanding the array spatially through the addition of new antennas at locations up to 250 km from the current VLA. This project will create a new instrument, the Expanded Very Large Array (EVLA), whose observational capabilities will be typically an order of magnitude better in all key observational characteristics than those of the current VLA.

The VLA Expansion Project consists of the following major elements:

- new and improved receivers to provide complete frequency coverage from 1 GHz to 50 GHz, and potentially from 300 MHz, or less, to 1 GHz.
- a new correlator and wideband signal processing and transmission system,
- a data management system with streamlined observer access to scheduling, instrument control, data archiving, and data reduction,
- a new on-line computing system and control software,
- addition of new antennas to extend the array's maximum baseline by a factor of ten.

A brief description of each of these major elements is given below.

2.1.1 Full Frequency Coverage from 1 to 50 GHz

The VLA's antennas perform well over the entire frequency range from 300 MHz to 50 GHz. But limitations in the receivers and in the signal transmission system designed over 20 years ago restrict the VLA's tuning to lie within seven narrow frequency bands which are widely spaced across that large frequency range. Only a small fraction of the available information can thus be conveyed to the correlator. Modern receiver and signal transmission technology can eliminate all of these "dead zones" and thus permit full access to the entire spectrum. Implementation of these technologies will then provide vastly wider bandwidths (and hence much improved continuum sensitivity), and will enable studies of all spectral transitions within this frequency range, including those of highly redshifted objects in the early universe.

This component of the VLA Expansion Project comprises implementation of eight observing bands which will allow observing with outstanding sensitivity at any frequency between 1 and 50 GHz. These feeds and receivers will be located at the Cassegrain secondary focus. (An additional component to extend coverage downwards to 300 MHz, or lower, using prime-focus receivers, is under consideration.) Characteristics of these new or improved systems include:

- **Improved sensitivity and coverage in the 1.5 GHz band.** This frequency band is arguably the most critical for attaining optimum performance. The VLA's current performance in this band is significantly degraded at low elevations by scattering of ground radiation by the microwave lens, and by a polarizer designed over 20 years ago. A new horn and polarizer will be installed which will eliminate the lens (thus reducing the ground pickup) and permit high-sensitivity performance from 1 to 2 GHz.
- **Retrofitting the 5 GHz and 15 GHz Bands.** The sensitivity and tuning range of the existing 5 GHz and 15 GHz bands are a factor of three to ten below what can be achieved with modern technology. New receivers and feeds covering the ranges 4–8 and 12–18 GHz will be installed.
- **New observing capabilities at 3 GHz and 33 GHz Bands.** The current VLA has no receivers for these bands, both of which offer exciting science potential. Modern wideband receivers covering 2–4 and 26.5–40 GHz will be installed.
- **Improvements for 10 GHz, 22 GHz, and 45 GHz bands.** Funding for the continuation of the installation of the 45 GHz band, and for beginning the retrofit of the 22 GHz band is already secured. Completion of these projects will require additional funding. The tuning range of the existing 8–9 GHz band will be extended to cover 8–12 GHz.
- **Improved antenna and operational performance.** By improving the antenna control electronics, adjusting panels for higher efficiency, developing techniques to permit better pointing, and employing new feeds with improved performance, the VLA will be able to employ demanding new modes of observing, and to efficiently observe in the 22, 33, and 45 GHz bands.
- **RFI Tolerance and Excision.** The wide bandwidths and frequency tuning range of the EVLA will greatly increase our exposure to radio frequency interference (RFI), especially from elevated sources such as balloons, aircraft, and satellites. The new receivers and transmission system will be designed with particular attention to the extra demands imposed by these signals. Flexible digital filters will be utilized to prevent strong interfering signals from entering the correlator. The new correlator will be designed with high tolerance to strong interfering signals, and will have a sufficiently large number of high-resolution frequency channels to permit detailed removal of data contaminated by narrow-band interfering signals.

2.1.2 A New Correlator and Wideband Signal Transmission System

The VLA correlator is 20 years old, and limits almost every scientific project on the VLA due to its limited total bandwidth (200 MHz), and limited channel capacity (a maximum of 512). All continuum observations are limited by the bandwidth maximum, while spectral line studies are restricted at high frequencies to lines with widths less than 300 km/sec, and at low frequencies to studies of single transitions in individual objects. Spectral line surveys are virtually impossible.

A new correlator, employing the power of modern digital processing, will revolutionize the scientific capabilities of the VLA. Such a correlator would utilize far more bandwidth than can be conveyed by the current waveguide, so a new signal transmission system must also be designed and implemented.

In this most urgent category are two key items:

- A **new correlator**, able to support at least 40 antennas with full polarization processing capability, up to 8 GHz in each polarization and at least 16,384 spectral channels per baseline. Because this correlator will be used for the full EVLA, and for nearby VLBA antennas, it will be designed to handle signals from stations as distant as 500 km.

- A **fiber optic data transmission system** to transmit up to 16 GHz in broadband signals and monitor data, replacing the original waveguide. This transmission system will be extended to nearby VLBA stations as well as to the new antennas which comprise Phase II, enabling a more extended configuration (see Section 2.1.4).

2.1.3 Computing and Data Management

The VLA currently uses on-line computing and monitor and control systems that were designed and built more than two decades ago. These systems are difficult to program, expensive to maintain, and not appropriate for the applications we plan to provide. We will replace these systems with a new, modern on-line computing system, monitor/control system, and associated software. These will enable a much improved user and operator interface with the array, and permit more flexible observing modes and other new capabilities with the new correlator and signal transmission systems.

The EVLA will provide its users with a vastly increased data rate, as well as an unprecedented level of interactive use and number of operational modes. In these characteristics, the EVLA will present similar demands on data analysis and capabilities as other telescopes under construction – notably the Green Bank Telescope (GBT) and ALMA. To provide users with a familiar, and common, means of interaction with all these instruments, we are centralizing computing management for the observatory under an Associate Director for computing, with a broad mandate to oversee and coordinate development of data products and programs dealing with these, and other, telescopes.

2.1.4 Extending the Array – The New Mexico Array

The VLA's maximum baseline of 35 km limits its resolution, while the VLBA's minimum effective baseline of about 300 km limits its sensitivity to extended structures. This "VLA-VLBA" gap critically limits science in the resolution range of a few tens to a few hundreds of milliarcseconds. Our goal is to completely fill this gap by incorporating new and existing antennas into the EVLA. There are two major portions to this component of the VLA Expansion Project:

- **New antennas** to provide baselines now unavailable between those in the VLA and in the VLBA. To maintain VLA-like imaging fidelity, about eight new stations are required, to be distributed at distances up to 250 km from the VLA. In order to match the frequency capabilities of the VLBA antennas, these new antennas will be designed to provide good efficiency in the 86 GHz band.

- **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 of the existing VLA antennas, the proposed new antennas, and the existing nearby VLBA antennas by the new correlator. Modifications to the VLBA electronics will be required to permit the use of the VLBA antennas in a combined array.

The antennas comprising the VLA, VLBA, and the proposed new antennas, can be combined into different independently operating arrays, using the new correlator. For example, the existing VLA could be operated as one array, the eight most distant VLBA antennas as another (using the existing VLBA correlator), and the ten antennas at intermediate distance (eight new and two VLBA) as an entirely independent array with imaging fidelity and continuum sensitivity comparable to the current VLA, but with ten times the resolution.

The new antennas (and nearby VLBA antennas) will not require remote VLBA data recording systems, as all signals will be sent in real-time by optical fiber links to a central site for either real-time correlation (VLA mode) or tape recording (VLBA mode). Weekly maintenance of these new sites will be provided from the Array Operations Center in Socorro, since all proposed antennas will be within three hours' drive. This arrangement will minimize the impact of these new stations on the operating cost of the combined arrays.

2.1.5 Further New Capabilities

Other significant improvements to the VLA's capabilities, not currently among the primary goals of the VLA Expansion Project, are being considered. For these components, further development of feasibility and assessment of scientific viability are required. If these capabilities are recommended by our user community, they would be implemented during Phase II of the project. The three most prominent extra components are:

- **Continuous frequency coverage below 1 GHz.** The VLA's antennas are useful down to approximately 50 MHz. Enabling the VLA to work effectively at frequencies below 1 GHz will require prime focus feeds, which in turn will require modifications of the focus-rotation mounts and the quadripod legs. We plan further studies of a proposed means for implementing coverage of these frequencies.

- **Improved low-resolution performance.** Although the VLA's **D** configuration provides good low-resolution capability, a denser placement of the 27 VLA antennas would result in faster and more accurate imaging on angular scales comparable to the antenna's primary beam. This would be accomplished with new antenna stations which would define a "super compact" **E** configuration with maximum baseline of $\lesssim 250$ meters. Such a configuration will allow fast mosaicing of large fields with much better fidelity and surface brightness sensitivity than can be achieved now. Studies of the optimum placement of antennas, and the resulting performance, will be continued, but it is possible that this component will not be pursued, depending on the performance of the GBT and the 1hT[1].

- **An 86 GHz capability.** The VLBA antennas, and the proposed new antennas comprising Phase II, will be capable of observing in the 86 GHz band. Although the VLA's antennas were not designed for operation at frequencies above $\sim$ 23 GHz, the adjustments made by holographic measurements have resulted in good efficiency in the 45 GHz band, and have encouraged us to consider implementation of an 86 GHz capability. Efficiency tests with an 86 GHz receiver on a VLA antenna will be needed before this component can be seriously considered.

2.2 Implementing the VLA Expansion Project

The VLA Expansion Project will return the Very Large Array to a state-of-the-art telescope with greatly enhanced capabilities, at a cost considerably less than half the original cost of the VLA in

[1] One Hectare Telescope

today's dollars. For many reasons, it is important to start this work as soon as possible.

- There is extensive overlap between technical needs of the VLA Expansion Project and those of ALMA. Technical developments for ALMA are proceeding rapidly, and there is an obvious advantage in applying these to the VLA Expansion Project at the same time.
- The VLA's operational costs are increasing steadily, as older, obsolete components fail and must be replaced – in many cases with difficulty and in all cases with increasing costs. The EVLA will be completely refitted with modern components, so that operational costs may actually be reduced for many years, despite the vast increase in observational capability.
- The proposed changes are extensive and will require many years to implement. By starting soon, we can better space the modifications to minimize the impact on existing operations.
- A healthy future for centimeter wave astronomy requires that major instruments in this field be maintained at the technological state of the art. Current technologies permit major improvements in the scientific capability of the world's premier centimeter wave astronomical instrument. It is vital to the future of the entire field of radio astronomy that we take advantage of this opportunity now.

These considerations, plus the realization that a core subset of the overall project affects all observations in all frequency bands, and are prerequisites to enable other future improvements, drive us to propose an immediate start on this critical core. Thus, as previous noted in Chapter 1, the VLA Expansion Project has been organized into two phases, the **Ultrasensitive Array**, and the **New Mexico Array**.

2.2.1 Phase I – The Ultrasensitive Array

This first phase of the VLA Expansion Project, and the subject of this proposal, consists of:

- a new correlator,
- a new wideband fiber optics data transmission system,
- a new on-line computing system,
- integration of data management with parallel developments for ALMA and the GBT,
- improvements in antenna performance, and
- continuous frequency coverage from 1 to 50 GHz from the Cassegrain focus ring.

2.2.2 Phase II – The New Mexico Array

This second phase of the VLA Expansion Project, for which development is ongoing and for which a funding plan will be developed later, will consist of eight new antennas at distances of 50 to 250 km from the VLA, with dedicated fiber optic communications to permit real-time transmission of signals from these remote stations.

In addition, this second phase may include those items which are the subject of design and testing in Phase I, should these studies and tests demonstrate sufficiently cost-effective improvement.

2.3 Operational Consequences of the VLA Expansion Project

The VLA is an aging instrument, and its operational costs are rising steadily as replacement parts for outmoded, or out-of-stock components become hard to find. Eventually (and probably within ten years) parts of the existing instrument will be unmaintainable without significant redesign. Thus, even in the absence of the VLA Expansion Project, operational manpower will need to be expended on redesign, just to keep the array operating.

We believe that operational costs of the array after completion of Phase I will not exceed current levels, despite the major increase in operational capacity. This is because of the scope of the replacement of aging electronic components. Most of these will be replaced with higher capacity, modern, more reliable components.

Although Phase II of the project will result in a significant increase in the number of antennas and electronics, we believe that the operational expense increase will be far less than proportional to an increase of eight stations in the current VLBA. This is because these eight new antennas, plus two of the nearby VLBA stations, will no longer require tape recorder units at the sites. VLBA data from these stations will flow to, and be recorded at the Array Operations Center in Socorro, thus removing the need for these stations to be manned. Maintenance of these 'local' stations will be done out of Socorro with a fixed crew based there.

2.4 Summary

The VLA Expansion Project will create an instrument of unprecedented astronomical capability in the meter-to-millimeter wavelength band. Although we plan on implementing the project in two phases, it is not necessary that the first phase be completed before the second begins, as consideration of the overall goals of the project has everywhere been taken into account in the proposal for implementation of the first phase.

The remainder of this document is specific to Phase I of the VLA Expansion Project. Preparation of a similar document for Phase II will begin later this year.

Chapter 3

Design Goals for the Ultrasensitive Array

3.1 The Capabilities of the Ultrasensitive Array

The previous chapter outlined the goals of the VLA Expansion Project, and describes why the project has been divided into two phases of roughly equal size. The remainder of this document is concerned specifically with Phase I of the project – the Ultrasensitive Array. In this chapter we describe the technical capabilities of the VLA after implementation of this phase of the project.

The Ultrasensitive Array will have the following characteristics:

- **Frequency Accessibility and Bandwidth**
  - Complete frequency access between 1.0 and 50 GHz, using eight frequency bands, as described in Table 3.1.
  - The ability to independently tune two different frequency pairs anywhere within one, or two, frequency bands, with each pair providing up to 4 GHz bandwidth in each polarization – a maximum total bandwidth of 16 GHz.
  - The ability to observe in a hostile RFI environment, through a combination of linear design and signal processing techniques, including analog and/or digital filtering, flexible frequency and bandwidth selectability, and post-processing algorithms utilizing multi-channel data.
- **Sensitivity**
  - Line and continuum point source sensitivities as shown in Figure 3.1, and listed in Table 3.1.
  - Equivalent surface brightness sensitivities for the four configurations, assuming an object of angular size equal to the synthesized beam, as given in Table 3.2.

Table 3.1: **Frequency Coverage and Point Source Sensitivity of the Ultrasensitive Array.** Assumes dual-polarization observations with 27 antennas.

Band	Freq. [GHz]	Freq. Range [GHz]	T_{sys} [K]	η	Continuum $\Delta\nu$ [GHz]	Continuum rms noise [μJy] 2 min	Continuum rms noise [μJy] 12 hr	Line (1 km/sec) $\Delta\nu$ [kHz]	Line rms noise [mJy] 2 min	Line rms noise [mJy] 12 hr
L	1.5	1.0– 2.0	26	0.50	0.5	36	1.9	5	11	0.58
S	3.0	2.0– 4.0	29	0.62	1.5	21	1.1	10	7.6	0.40
C	6.0	4.0– 8.0	31	0.60	3.0	16	0.82	20	5.7	0.30
X	10	8.0–12.0	34	0.56	3.0	18	0.95	33	5.1	0.28
U	15	12.0–18.0	39	0.54	4.0	19	0.98	50	5.1	0.27
K	22	18.0–26.5	54	0.51	6.0	23	1.2	74	6.1	0.32
K_a	33	26.5–40.0	45	0.39	8.0	21	1.1	111	5.3	0.28
Q	45	40.0–50.0	66	0.34	5.0	46	2.4	150	7.6	0.40

Explanation of Table Entries

η: a general efficiency factor, including both aperture efficiency and correlator losses. Assumes a two-bit, four-level correlator.

$\Delta\nu$: the frequency width, per polarization, used in calculating the noise. For the continuum case, the width assumed is limited by the RFI environment at low frequencies, and by atmospheric opacity at the highest frequencies; for the spectral line case, this width corresponds to 1 km/sec at the central frequency of the band.

rms noise: the root-mean-square (1σ) thermal noise, assuming dual-polarization observations and a data weighting scheme chosen to give low noise with a reasonably small beam size (Briggs' robustness R = 0).

Table 3.2: **Surface Brightness Sensitivity of the Ultrasensitive Array: A-Configuration.** For the **B**, **C**, and **D** configurations, multiply the beam size by 3.2, 10, and 32, and divide the rms noise by 10, 100, and 1000, respectively.

Freq. Range [GHz]	Synthesized Beam size [arcsec]	Continuum rms noise [K] 2 min	Continuum rms noise [K] 12 hr	Line (1 km/sec) rms noise [K] 2 min	Line (1 km/sec) rms noise [K] 12 hr
1.0- 2.0	1.6	11	0.57	3,300	170
2.0– 4.0	0.80	6.3	0.33	2,300	120
4.0– 8.0	0.40	4.8	0.25	1,700	90
8.0–12.0	0.25	5.4	0.30	1,500	84
12.0–18.0	0.17	5.7	0.30	1,500	81
18.0–26.5	0.12	6.9	0.36	1,800	96
26.5–40.0	0.08	6.3	0.33	1,600	84
40.0–50.0	0.06	14	0.72	2,300	120

Assumes the same parameters as in Table 3.1.

Beam size: full width at half maximum for the frequency at the center of the band, assuming the same data weighting as in Table 3.1.

rms noise: the root-mean-square (1σ) thermal noise as in Table 3.1, converted to the surface brightness sensitivity assuming a source whose size is equal to the beam size.

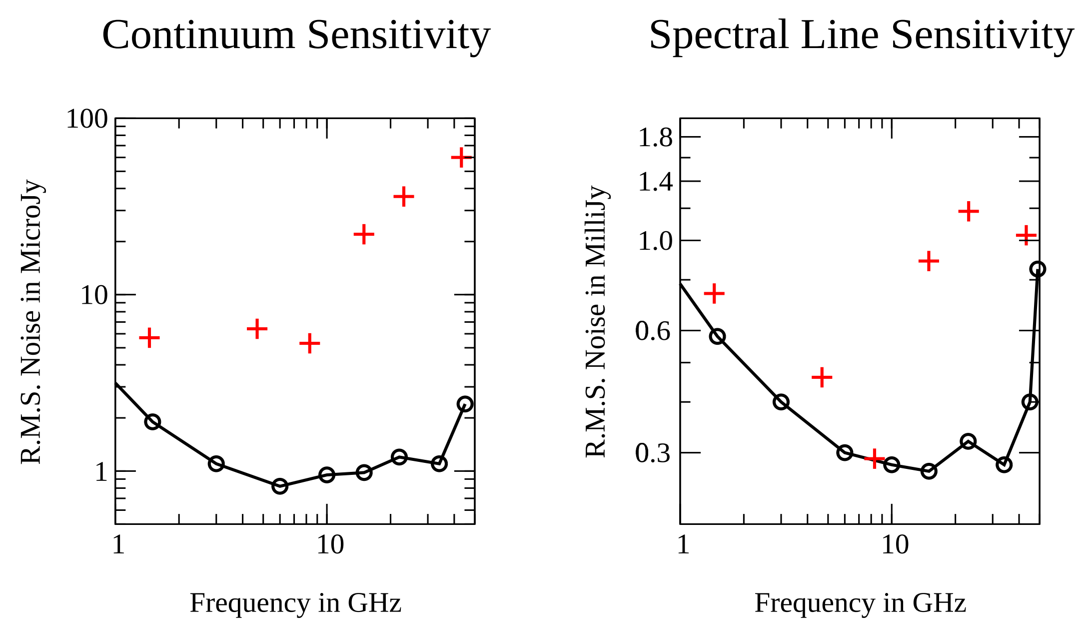


Figure 3.1: The current (+), and projected (o) continuum (left) and spectral line (right) point source sensitivity (1σ in 12 hours) of the VLA after the Ultrasensitive Array is completed. For the continuum plot, the bandwidths of Table 3.1 are assumed. For the spectral line plot, the assumed bandwidth corresponds to a velocity width of 1 km/sec. The width of the '+' symbols demonstrates the approximate range of tuning with the current VLA. The EVLA will be continuously tunable over the entire band.

- **Operations**
  - A flexible, real-time interface between the array and the operations staff, and between the array and the users, allowing them to react quickly to changing observing conditions, and giving them the ability to modify their observing goals in response to information already obtained.
  - A more powerful and flexible operating and computing environment for the operations staff, permitting simpler and more efficient development of new observing modes.
  - A unified end-to-end approach from proposals through scheduling to calibrated data and images. The cover sheet of the original proposal, the schedule as used at the telescope, all monitor data (including antenna pointing results, system temperatures, ionospheric corrections, atmospheric water content, wind speed, antenna repair histories, *etc.*), on-line flags, calibrated $(u,v$ data, default images, the scripts used to calibrate and image the data, and scripts to undo that calibration, will all be stored together in a single, unified archive available from a standard user interface.
  - Real-time distribution of all the above data products to users with access to suitable network bandwidth.
  - Near real-time production of default images for distribution to users, thus enabling their effective interaction with ongoing observing.

- **Correlator**
  - Ability to process four oppositely-polarized pairs of signals, each of 2 GHz bandwidth, from each of 40 stations. Spectral resolution will be a few MHz or better when operating at full bandwidth, with resolutions of 100 Hz or better at the narrowest bandwidths. Bandwidths and resolutions will be flexibly selectable, probably in factors of two, down to some reasonable minimum.
  - Ability to correlate signals from stations located up to 500 km from the VLA.
  - Support for at least ten subarrays, and at least three simultaneously operating observing modes.
  - Highest frequency resolution of ~ 1 Hz (may require a special mode).
  - Full polarization capability.
  - Sustained dump times as short as 10 msec for specified subsets of the integrators.
  - Pulsar gating mode offering at least 32 phase bins.
  - A burst mode, permitting extremely rapid accumulation of data for a short period of time.
  - Careful design for RFI suppression and very high linearity in the presence of strong narrow-band signals.

A correlator design based on the ALMA design will meet these specifications. The correlator group at the Dominion Radio Astrophysical Observatory (DRAO) is developing an alternate design which will also match these correlator requirements, and will offer attractive extra capabilities in the areas of RFI tolerance and tuning flexibility. At the time of writing, an agreement between the NRAO and the Herzberg Institute of Astronomy (HIA) for construction of such a correlator was close. This correlator would form the basis of the Canadian contribution to the VLA Expansion Project.

Table 3.3 presents some of the combinations of bandwidth and frequency resolution that a correlator based on the DRAO design would provide; many other modes would also be possible. The proposed correlator would accept four pairs of oppositely polarized signals, each of 2 GHz bandwidth. Each of these eight baseband channels would be digitally subdivided into 16 sub-bands using 16 finite impulse response (FIR) filters, each with 1024 'taps'. The 128 sub-bands would then have bandwidths individually selectable in factors of two between 125 and 7.8125 MHz wide, with special modes available for stacking the filters to create even narrower bandwidths for a lesser number of sub-bands.

Each sub-band will be processed individually to produce 128 spectral channels, for a total of 16,384 spectral channels. Signals from oppositely-polarized sub-bands operating at the same frequency can be correlated to produce dual or full polarization information; sub-bands may also be tuned to the same frequency to combine the spectral processing capability, resulting in higher spectral resolution at the cost of total bandwidth. In normal operation, the sub-bands will be adjacent, and the total output spectrum will result from digitally combining the individual spectral outputs to produce a seamless wide-bandwidth spectrum. However, these subbands can also be separated and tuned to specific frequencies, with different bandwidths, thus providing a remarkably flexible operational capability.

Recirculation, which will provide more spectral channels and higher spectral resolution at the expense of less total bandwidth, can also be employed in this design. Preliminary studies indicate modes providing up to 262144 total channels, with resolution as fine as 100 Hz, are possible. A special 'RADAR' mode, providing resolutions as fine as 0.16 Hz, is also possible.

An attractive feature of this design is that it is a four-bit processor. Detailed simulations have demonstrated a spectral dynamic range in excess of 55 dB – excellent protection against external RFI.

Table 3.3: Bandwidth per polarization, sub-band bandwidth, and frequency resolution for a few of the possible modes of the EVLA correlator, as proposed by DRAO. In all cases, 16,384 total channels are produced – 128 for each of the 128 subbands. The modes differ in the setups of the FIR filters, and in the number of polarization products which are produced. In this design 1 Hz resolution would be achieved by special-purpose hardware. This design will support recirculation – preliminary estimates indicate up to 262144 total channels in the narrowband modes.

		Frequency Resolution[1]		
Frequency Span (MHz)	Sub-band Bandwidth (MHz)	One Product per Baseline[2] (kHz)	Two Products per Baseline[3] (kHz)	Four Products per Baseline[4] (kHz)
8000	125	488	977	1954
4000	62.5	244	488	977
2000	31.25	122	244	488
1000	15.625	61	122	244
500	7.813	31	61	122
250	7.813	15	31	61
125	7.813	8	15	31
62	7.813	4	8	15
31	31.25	2	4	8
16	15.625	1	2	4

- **Antenna Drive/Control**
  - Stop-and-shoot imaging on 10-second timescales for mosaicing, with on-source integration of at least seven seconds for offset movements less than 30 arcminutes.
  - Continuous raster-scan interferometric observing with rms pointing accuracy of ≤ 10 arcseconds for drive rates of ≤ 2.5 deg/min.
  - Blind pointing accuracy (1σ, calm night conditions) of six arcseconds.
  - Reference pointing accuracy (1σ, best conditions) of two arcseconds.
  - Antenna efficiency exceeding 60% at the lowest six Cassegrain frequency bands, and exceeding 40% for the highest two bands.

3.2 Implications of These Improvements for Quality Science

A telescope with the capabilities described above will revolutionize centimeter wave radio astronomy, since its speed, sensitivity, and flexibility will exceed current capabilities by an order of magnitude or more. In this section, we discuss in broad terms some implications for science with this new instrument.

[1] Frequency separations are before smoothing.
[2] One polarization product per baseline, *e.g.*, RR or LL.
[3] Two polarization products per baseline, *e.g.*, RR and LL
[4] All four polarization products per baseline, RR, RL, LR, LL.

3.2.1 Sensitivity

The major gains in sensitivity come from the increased bandwidth at all frequencies, and from the improved gain and system temperature at high frequencies. The Ultrasensitive Array will be at least a factor of 50 faster than the current VLA for all continuum observations above 2 GHz, and almost a factor of 1000 faster at the highest frequencies. What implications does this have for astronomy?

- **Studying more sources**

  Observations which are difficult now will be routine with the Ultrasensitive Array, leading to much better, more complete, and less biased source samples. This implies a deeper and more reliable luminosity function for every type of source; just as optical observations discovered important populations when extended to low flux densities (*e.g.*, faint blue galaxies) and surface brightnesses (*e.g.*, low surface brightness galaxies), so the Ultrasensitive Array will reveal new types of radio sources which are currently unknown. Studies now restricted to the extreme examples of a given class (*e.g.*, polarization mapping of galaxies, imaging of thermal jets in young stellar objects) will be extended to more typical and more distant or less luminous members, showing which characteristics are truly general and which are simply high luminosity eccentricities. In addition, the increase in the number of detectable sources will permit projects that currently cannot be done at all. The number of detectable sources in a random field will rise by a factor of three at low frequencies, and a factor of ten or more at high frequencies, giving for the first time significant numbers of probes for rotation measure and absorption studies, and allowing many fainter sources to be used for phase-referencing – an important improvement at high frequencies, where atmospheric phase instabilities often limit the sensitivity of the images.

- **Studying sources in more detail**

  In a diffraction limited telescope, increasing the observing frequency has two unavoidable, linked, consequences: an increase in resolution, and a decrease in surface brightness sensitivity. These two effects commonly combine with the telescope's sensitivity limit to prohibit high resolution imaging of extended structures of faint objects. That is, an object easily detectable but barely resolved at a lower frequency could be resolved but is not detectable at a higher frequency. Improving the sensitivity of an array can thus lead directly to higher resolution without increasing the telescope's size. This is important for resolution-limited projects investigating intrinsically small sources such as accretion disks around proto-stars, and polarization studies of extended regions where a Faraday screen has imposed small-scale substructure.

  Similarly, greater instantaneous sensitivity allows finer temporal resolution: the Ultrasensitive Array will detect a 1 mJy source (5σ) in one second, from 2 to 40 GHz. This 'fast' sensitivity is vital for research on variable objects – many sources exhibit flux and spectral index variations on these time scales, including the Sun and the radio counterparts to X-ray transients and gamma-ray bursts. The ability to make useful observations in a very short time, combined with true dynamic scheduling, will allow variable sources to be observed more immediately, more consistently, and over a wider range in frequencies; the greater sensitivity will also permit these sources to be followed for longer times.

  Finally, the improved sensitivity combined with the new correlator will ensure that every continuum observation gives sensitive spectral and polarization information, without losing bandwidth or requiring additional observing time.

- **Detecting new types of sources**

  Improving the sensitivity of the VLA will allow many sources to be detected which are simply too faint to be seen with the current instrument. Obvious examples include comet nuclei, radio-quiet quasars, spiral galaxies as luminous as the Milky Way at $z \sim 0.5$, and Kuiper-belt objects. More speculative but potentially even more interesting are those objects which currently have no known radio counterparts, such as type Ia supernovae. An order-of-magnitude increase in sensitivity, over such a wide frequency range, will undoubtedly permit detection of radio emission from objects we currently think of as radio quiet.

3.2.2 Flexibility and Efficiency

The second major advance provided by the Ultrasensitive Array is an improvement in flexibility and efficiency.

- **Full and flexible access to the entire spectrum from 1 to 50 GHz**

  The current system requires working around instrumental limitations to approach the science: frequencies must be chosen to match the available bands and the restrictions of the local oscillator (LO) chain; bandwidths and spectral resolution must be juggled to fit in a spectral line or get the minimum acceptable frequency coverage. Oftentimes the permitted combinations greatly degrade the science; observers working at high frequencies have to depend on luck for a sufficiently nearby phase calibrator and good enough weather to give useful data.

  The Ultrasensitive Array will eliminate these limitations. By quadrupling the range of available frequencies, and giving roughly equal sensitivity over most of that range, the Ultrasensitive Array will permit astronomers to choose the frequency appropriate to a particular source and scientific problem. The only limitation will be that imposed by the RFI spectrum, rather than the current limitation imposed by the availability of receivers. By providing much wider bandwidths, two fully independent frequency settings (each giving full polarization potential), thousands of spectral points across the band, and the capability to tune around RFI, the Ultrasensitive Array will give observers full and flexible access to the entire spectrum received at the telescope between 1.0 and 50 GHz. The observer will be able to tune the VLA to the proper frequencies for a particular observation and a particular object, permitting, for example, investigations of the transition from an optically thick to an optically thin spectrum, or observations of spectral lines from an extragalactic object of any redshift. Similarly, the nearly equal continuum sensitivity from 1.0 to 50 GHz will allow routine measurement of the full spectral energy distribution, from low frequencies dominated by synchrotron emission to high frequencies dominated by dust.

- **High-fidelity imaging at high frequencies**

  The combination of dynamic scheduling and much-increased sensitivity will make high fidelity imaging much more reliable at the high frequencies, by ensuring such observations are taken in good weather conditions, and by allowing the use of at least ten times as many sources as phase calibrators.

- **Observing spectral lines and continuum simultaneously**

  Retaining spectral resolution over wide bandwidths will make every spectral line project a continuum project as well, and *vice versa*. Since at low frequencies the improvement is primarily in bandwidth rather than system temperature or gain, observations of faint spectral lines will still require long integrations. But with broad bandwidths, each spectral line observation will also cover other transitions, both in emission and absorption, over a huge redshift range, and will provide deeper continuum images than any now available. Continuum observations will automatically measure the shape of the spectrum rather than just a single flux density; spectral line observations will be able to target multiple lines within a single band, *e.g.*, to measure all of the hyperfine lines of ammonia, or to stack adjacent radio recombination lines for sensitivity.

- **Effective spectral line surveys**

  The ability to observe over wide bandwidths while retaining high spectral resolution will make effective spectral line surveys possible for the first time at the VLA. The enormous increase in sensitivity at high frequencies will help as well, making it plausible to search for highly redshifted molecular lines.

- **Operational improvements**

  - *Making the VLA easy to use:*

    Several advances will make the EVLA much easier to use than the current instrument. Scheduling will be based on simple goals such as achieving a certain phase calibration accuracy or reaching a given noise limit, requiring much less expertise than the current command-line system. Dynamic scheduling will make it easier to insert target-of-opportunity observations, and to ensure that programs requiring certain weather conditions (*e.g.*, high-frequency imaging) are more regularly successful, without active user intervention. Since all data products related to a given program will be stored together, the end user will be assured easy access to all the information he or she needs. This includes the original proposal, the schedule used at the telescope, monitor data and telescope histories, and the calibrated *(u,v* data and images created by the pipeline. The scripts that created these pipeline products will also be attached to the data, making it easy to modify and extend them when necessary to improve on the automatic reduction. Finally, with all NRAO telescopes sharing the same "look and feel", it should be easy to move from, say, the GBT or ALMA to the EVLA. Taken together these advances will lead to a significant increase in scientific productivity, and make radio data available to a far larger fraction of the astronomical community.

    The simple availability of an archive of *images* will be a very significant improvement. The current VLA archive consists solely of uncalibrated *(u,v* data, requiring some expertise to process to the stage useful for scientific work. With first-look images together with scripts and a record of the original intent of the observer, the EVLA archive will be far more useful to many more astronomers.

  - *Encouraging interaction with observations:*

    The new on-line system will provide easy and rapid access to the data in real time, and will allow correspondingly quick reaction to changing observing conditions. This can be as important and as trivial as obtaining an excellent continuum image in a few minutes, and noticing that the telescopes are pointing toward the wrong place – a simple check that optical observers take for granted, but which is difficult with the current system at the VLA. More sophisticated responses will include avoiding interference, choosing a better calibrator, updating the pointing and delays as necessary rather than at set intervals, and so forth. The Ultrasensitive Array will allow observers to react in real time, rather than waiting for the data to appear on their desks, long after the observations have been completed.

  - *Reacting quickly to changing observing styles:*
    The use of modern computers, programming languages, and coding practices will make the entire on-line system more responsive, both in the day-to-day operation of the instrument, and in installing and testing new capabilities. New observing modes will be implemented more quickly and more transparently to the user.

3.2.3 Reduction of Systematic Errors

Without reducing systematic errors, the Ultrasensitive Array would simply reach the limit set by these errors faster than the current instrument. Although it will be difficult to eliminate all such errors, the Ultrasensitive Array directly addresses known problems, and provides considerably more flexibility for tackling newly-discovered systematic errors in the future. Some of these improvements include:

- **Spectral improvements**
  - *More stable bandpass shapes:* The bandpasses will be defined by digital Finite Impulse Response filters, rather than analog devices, offering better defined and more stable bandpass shapes.
  - *More spectral channels:* The new correlator will provide much higher spectral resolution and many more channels, even over the widest bandwidths, greatly reducing bandpass closure errors and limiting the spectral 'ringing' due to sharp spectral features (*e.g.*, radio frequency interference or masers). Retaining the full frequency spectrum (instead of replacing the first channel with the spectrum average, as is currently done) will allow a re-sampling of the spectrum and application of any desired smoothing function after the observations, reducing these effects even further.
  - *Better signal transmission:* Replacing the waveguide with a fiber optics system will reduce the so-called '3 MHz' ripple, which dominates the time-dependent part of the frequency response of the present instrument, and will eliminate cross-coupling between signal channels, permitting more stable and accurate calibration of the bandpass and of instrumental polarization. These effects will be further reduced if a digital data transmission system is employed.
  - *Better continuum subtraction:* The new correlator will provide much wider bandwidths for spectral line projects, ensuring ample line-free spectral channels for continuum subtraction. Besides reducing the noise on the estimated continuum, this will allow more accurate subtraction of very distant or extended sources (*e.g.*, the Sun), where the assumption of a linear variation of the visibility with frequency breaks down.
  - *Direct comparisons of the noise statistics:* The combination of wide bandwidths and narrow frequency channels will allow the most direct check possible on the true statistics of the noise, using the large number of line-free spectral channels. This is important for deep searches for faint emission or absorption lines, where non-Gaussian statistics can easily lead to spurious detections.
  - *More accurate deconvolutions:* The new correlator will provide many spectral channels across very wide bandwidths, permitting multifrequency synthesis, and allowing the removal of deconvolution errors due to changes in source structure or flux density across the band. With typical bandwidth ratios of 1.5:1 the *uv* coverage will be greatly improved. Such data will also allow much more accurate calibration of the spatial change of the primary beam with frequency.

- *Unbiased rotation measures:* The rotation measure (RM) gives unique information on the density and distribution of ionized gas within and around radio sources. Rotation measure studies rely on the ν^{-2} frequency dependence of the Faraday rotation, but are generally limited by sensitivity, which determines the accuracy with which the polarization position angle can be measured. In addition, the maximum detectable RM is set by the channel width, while the minimum is set by the total bandwidth. The new correlator, providing narrow frequency channels over very wide bandwidths, will be ideal for RM studies, and will open the door to sophisticated spectropolarimetry as a standard observing mode.
- *RFI removal:* One of the major advances of the Ultrasensitive Array will be to develop an effective, layered approach to finding and removing radio frequency interference (see Section 5.2). This is essential for utilization of the full bandwidth brought from the antennas, and for avoidance of signal compression due to finite dynamic range, which give rise to non-linearities and spurious signals. The four-bit sampling of the DRAO correlator design will provide outstanding immunity to strong RFI – spectral dynamic ranges in excess of 55 dB are anticipated.
- *Wide-field imaging:* The new correlator will permit sensitive, wide-field imaging over the full primary beamwidth for all configurations. This capability is currently lacking because the existing correlator provides too few channels in its wide bandwidth modes to prevent chromatic aberration.

Sophisticated software will be required to take advantage of all these possibilities. Many of the extensions and algorithms mentioned above are already built into AIPS++, and both that project and ALMA are continuing this development.

- **Improvements in calibration**
  - *Avoiding decorrelation at high frequencies:* Observations at high frequencies are vulnerable to atmospheric phase instabilities, especially in the larger configurations, requiring frequent calibration using nearby point sources. The improved sensitivity of the Ultrasensitive Array will allow the use of much weaker and more plentiful calibrators, as well as extending self-calibration to fainter target sources. This will be particularly useful given the flexibility of the correlator and LO system; one can tune a single IF pair to a strong, narrow maser line, and use that to calibrate simultaneous observations of fainter line and/or continuum emission. Dynamic scheduling will also help avoid observing at high frequencies during unsuitable periods, while the high time resolution provided by the correlator and by the improved sensitivity will help recover those data which are taken under adverse circumstances.
  - *Improved pointing:* By improving the 'blind' pointing to six arcseconds (rms), and allowing the use of fainter calibrators for referenced pointing, the Ultrasensitive Array will greatly improve the sensitivity at high frequencies, and eliminate a major source of uncertainty at all frequencies. More accurate and more consistent pointing gives more consistent relative antenna gains across and beyond the primary beam, leading to easier removal of the sidelobes of distant sources, and more accurate imaging of objects within the primary beam.
  - *Measuring time-dependent effects:* The improved sensitivity will allow self-calibration on shorter timescales, as well as offering the prospect of identification and correction of antenna pointing errors, based on the apparent flux variations of background sources. Similarly, time-dependent polarization leakage terms will similarly be easier to measure and remove.

Chapter 4

Science with the Ultrasensitive Array

The Ultrasensitive Array is designed to exploit the unique capabilities of radio astronomy, building on the superb infrastructure of the current VLA to allow exciting new science at moderate cost. The main science drivers may conveniently be split into four key areas:

- measuring the strength and topology of magnetic fields – the Magnetic Universe;
- unbiased surveys and imaging of dust-obscured objects – the Obscured Universe;
- rapid response to and imaging of transient sources – the Transient Universe; and
- tracking the formation and evolution of objects ranging from stars to spiral galaxies and active galactic nuclei – the Evolving Universe.

In this chapter we discuss the importance of these areas, and how the new capabilities provided by the Ultrasensitive Array translate into new and exciting science. Only one or two examples are given here in each area; many more are detailed in Appendix A. These examples can only hint at the true potential of this instrument. As with today's VLA, the breadth and flexibility of the Ultrasensitive Array will undoubtedly produce exciting discoveries over the entire range of modern astronomy, answering questions we do not yet know to ask. It is intended not to perform a single, particular experiment, but to provide an essential tool for a wide variety of inquiries.

4.1 The Magnetic Universe

Electromagnetism is one of the four fundamental forces in the universe, and the only one other than gravity to operate on large scales. Yet magnetic fields are, with dark matter, one of the major unknowns in modern astronomy. We know they exist; we believe they are important, even dominant, in contexts as diverse as solar flares, the formation of stars, and the support of the gas between galaxies in clusters. But for most sources even basic questions of field topology and strength are still unanswered, because magnetic fields are very difficult to observe directly. Radio data are, in principle, ideal for these sorts of measurements, providing direct probes ranging from Faraday rotation to synchrotron emission to Zeeman splitting. In practice however current instruments are hampered by a combination of poor sensitivity, inadequate spectral resolution, narrow bandwidths, and spotty frequency coverage. The Ultrasensitive Array is designed to remove or greatly reduce all of these limitations, by providing

- **Excellent sensitivity** – 0.8 μJy, vs. current 10 μJy:
  required both for high-resolution polarization imaging of individual sources, and to allow the use of numerous faint background sources as probes of the field along the line-of-sight.
- **High spectral resolution** – at least 16,384 channels, vs. current 512 channels:
  essential to track the expected rapid changes of polarization percentage and polarization angle with frequency, *e.g.*, for Faraday rotation and Zeeman studies.
- **Wide bandwidths** – maximum 8 GHz, vs. current 0.1 GHz in dual polarization:
  needed to improve the sensitivity, and to allow the measurement of polarization properties over a wide range in frequencies in a single observation.
- **Complete frequency coverage** – 100% coverage from 1 to 50 GHz, vs. current 30%:
  necessary because many magnetic effects are strongly frequency dependent. For instance, the critical frequency for gyroresonance scales directly with the magnetic field strength; tuning up and down in frequency allows one to match (or derive) the conditions in the specific sunspot or other region of interest.

These improvements will make the Ultrasensitive Array the best instrument in the world for measurements of magnetic fields throughout the universe.

4.1.1 An Example: Clusters of Galaxies

The space between galaxies in clusters is filled with turbulent hot gas, relativistic particles, and magnetic fields. The magnetic fields in particular are of great interest, as they may play an important role in galaxy and cluster evolution, as well as in cluster dynamics; in addition, even relatively weak fields can have profound effects on energy transport within galaxies/clusters.

Radio observations provide the only means of directly measuring these fields, primarily through synchrotron emission and Faraday rotation. However, current instrumentation severely limits these studies. We know that some clusters have significant magnetic fields, and (from rotation measure [RM] studies) have some idea of their distribution and topology in a few key sources. But the details are far from clear. Do all clusters have large-scale fields at some level, or are such fields confined to those with known (bright) radio halos? At what redshift do such fields 'turn on', and how do they evolve? RM studies currently are based almost entirely on sources embedded within the clusters; are the magnetic fields thus observed created or heavily influenced by the sources themselves? What is the magnetic field topology *away* from such powerful radio sources, and are there strong fields without relativistic particles to 'light them up' via synchrotron radiation?

The Ultrasensitive Array will be ideally suited to answering these questions, allowing Faraday rotation studies of individual clusters, detailed imaging of faint cluster halos, and extensive searches and high-resolution RM imaging of radio sources at high redshift, which may be associated with the youngest clusters known. These projects are discussed further in Appendix A; here we briefly outline the first.

Faraday rotation gives an independent measure of the magnetic field and ionized medium along the line-of-sight, and has the advantage that it can be measured against strong background sources as well as any radio-emitting cluster members. The number of useful sources is limited by the sensitivity (requiring reasonable detections of the *polarized* emission, at high enough resolutions to avoid beam depolarization) and the spectral resolution (to avoid polarization angle wraps within a channel, while maintaining broad enough bandwidths to detect even low RMs). With major advances in both areas, the Ultrasensitive Array will bring about a revolution in these studies.

At the moment, RMs can be measured toward one or two background sources in a given cluster. Combining these for many galaxy clusters shows clearly that a magnetic field is present (Figure 4.1), but cannot yet determine whether the fields detected are caused by strong radio galaxies in the cluster, or are intrinsic to all clusters. By contrast, the Ultrasensitive Array can provide RMs toward more than 20 background sources within 0.2 Abell radii of *each* of more than 80 Abell clusters.

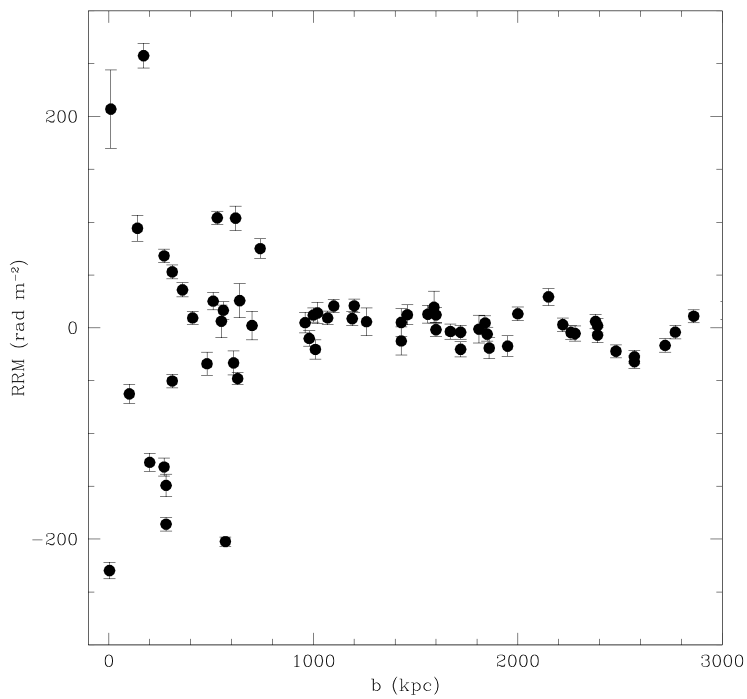


Figure 4.1: The rotation measure (RRM) vs. impact parameter (b) for radio sources near, within, and behind Abell clusters (Clarke 1999; references appear at the end of Appendix A). Note the clear increase in the width of the RM distribution at small radii. This plot can only be made currently by combining data from *all* clusters (22, in this particular plot); the Ultrasensitive Array will provide higher-quality measurements, toward more sources, in *individual* galaxy clusters.

The Ultrasensitive Array will similarly advance RM imaging of embedded sources, which provides the only observational measurement of the detailed magnetic field strength and structure within individual clusters. Virtually every source that can now be imaged in total intensity will give extended RM maps with the Ultrasensitive Array (cf. Figure 4.2). By combining significant background studies with improved imaging of the cluster sources themselves, the Ultrasensitive Array will finally answer the question of whether magnetic fields exist in all clusters, and if so at what level, and with what spatial topology.

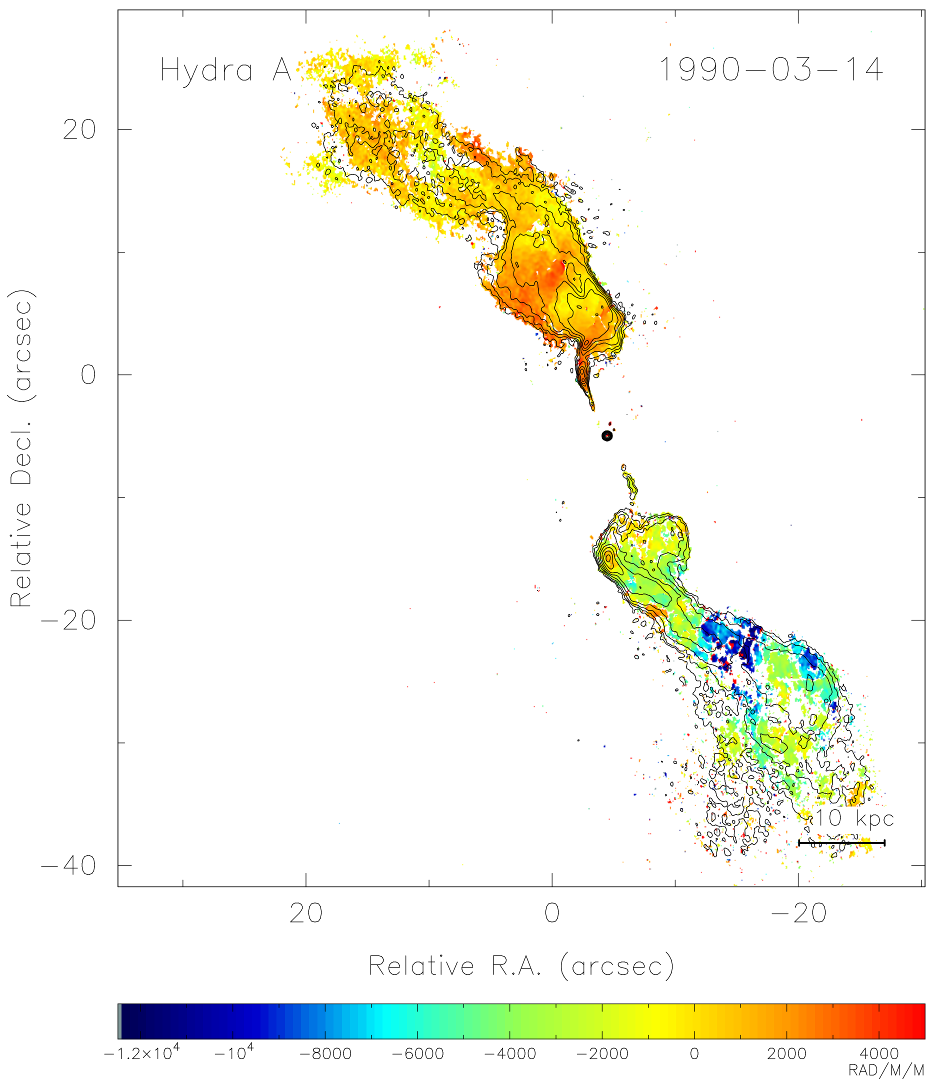


Figure 4.2: The rotation measure structure of Hydra A at 0.3 arcsecond resolution (Taylor & Perley 1993). The colors indicate RM from −12,000 to 4000 radians/m^2; the contours represent the 8.4 GHz radio continuum. The Ultrasensitive Array will allow similar RM mapping of sources which are an order-of-magnitude fainter — basically every radio galaxy which can currently be imaged.

4.2 The Obscured Universe

Properly accounting for propagation effects is among the most basic and the most difficult problems in astronomy. Line-of-sight processes can modify or even completely redirect or eliminate the emitted radiation, introducing important biases, and precluding the direct observation of many interesting sources. Star formation is perhaps the clearest example. The dusty envelopes of protostars shield the central regions from view even at millimeter wavelengths, while extinction is one of the major uncertainties in optical derivations of star formation rates as a function of redshift. Submillimeter measurements of the dust itself can yield estimates of the total luminosity, but the obscuration still makes it difficult to determine the source of that luminosity, especially in galaxies which may harbor both young stars and active galactic nuclei. Ideally one would instead observe at frequencies where the intrinsic emission is strong but not significantly scattered or absorbed, and where any absorption which is present can easily be quantified and accounted for.

Radio frequencies satisfy all of these criteria. Many interesting sources, from H II regions to jets around black holes, produce copious amounts of thermal dust, free-free, and/or synchrotron emission; the resulting radio photons can be seen even through dust thick enough to completely extinguish optical radiation; and the primary absorption processes which do occur, free-free and synchrotron self-absorption, leave clear spectral signatures over ranges of radio frequencies which are quite easy to observe. However, current radio studies are restricted to narrow-band observations of the closest and most luminous sources. The Ultrasensitive Array is designed to lift these restrictions and permit the unbiased surveys and imaging which radio data allow, providing

- **Much-improved spatial resolution:**
  through increased surface brightness sensitivity, and the corresponding ability to image at higher frequencies where many sources are intrinsically fainter.

- **Access to many more and much fainter sources:**
  due to a factor of 5–30 improvement in continuum sensitivity.

- **Unbiased absorption line surveys:**
  based on the combination of complete frequency coverage (eliminating redshift biases), wide bandwidths (allowing wide velocity coverage), simultaneous high spectral resolution (ideal for the detection of narrow absorption lines), and the fact that radio emission is not affected by dust extinction.

- **Access to the entire radio spectrum, from 1 to 50 GHz:**
  essential to distinguish the wide range of absorption and emission processes, to cover observing bands where different sources may be optically thin, and to allow absorption line surveys of both molecular and atomic species over the widest possible range of redshifts.

4.2.1 An Example: Young and Proto-stellar Objects

One of the major results of star formation studies has been the clear association between accretion disks and outflows. The details of this relationship however remain a mystery. How are the jets formed and collimated? Are they always accompanied by accretion disks, and *vice versa*? How does the mass of the system influence this relationship, and how do binaries differ from isolated protostars? These, together with the problem of how to form planets, are among the most important questions in star formation studies today. The Ultrasensitive Array will supply crucial information for these studies:

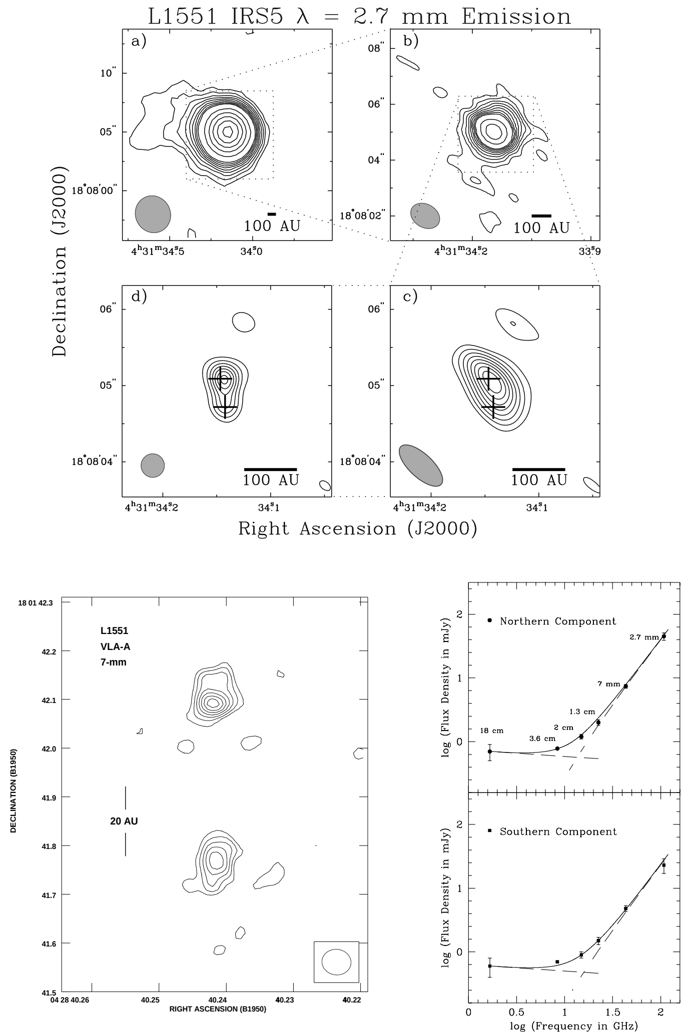


Figure 4.3: Dust emission from L1551 IRS5. Upper: BIMA images at 110 GHz with increasing angular resolution (Looney *et al.* 1997), showing that L1551 is composed of two circumstellar disks located within a flattened circumbinary structure embedded in an approximately spherical large-scale envelope. Lower: VLA images at 45 GHz with 50 milliarcsecond (7 AU) resolution (Rodríguez *et al.* 1998) clearly resolve the individual dust disks surrounding the members of the proto-binary system. The spectral decomposition shows that the dust dominates the emission – and is optically thick – down to $\sim$ 22 GHz, below which optically-thin free-free emission takes over.

- *Spectral energy distributions from 1 to 50 GHz:*
  Disentangling thermal dust, free-free, and synchrotron emission in young stellar objects (YSOs) requires accurate, high-resolution data over a wide range of frequencies, from a few to a few hundred GHz (cf. Figure 4.3). While ALMA will be the premier instrument for dust and molecular studies, the Ultrasensitive Array is essential for observing the densest dust, the ionized gas, and the relativistic particles (*e.g.*, Wilner, Reid, & Menten 1999[1]). Currently the VLA can laboriously detect some tens of sources, and image a handful of those. The Ultrasensitive Array will increase this by a factor of at least a thousand, while also providing continuous frequency coverage from a few to several tens of GHz, at resolutions sufficient to resolve proto-planetary disks for nearby systems (50 mas at 45 GHz, corresponding to ~ 7 AU at 150 pc — somewhat smaller than Saturn's orbit).

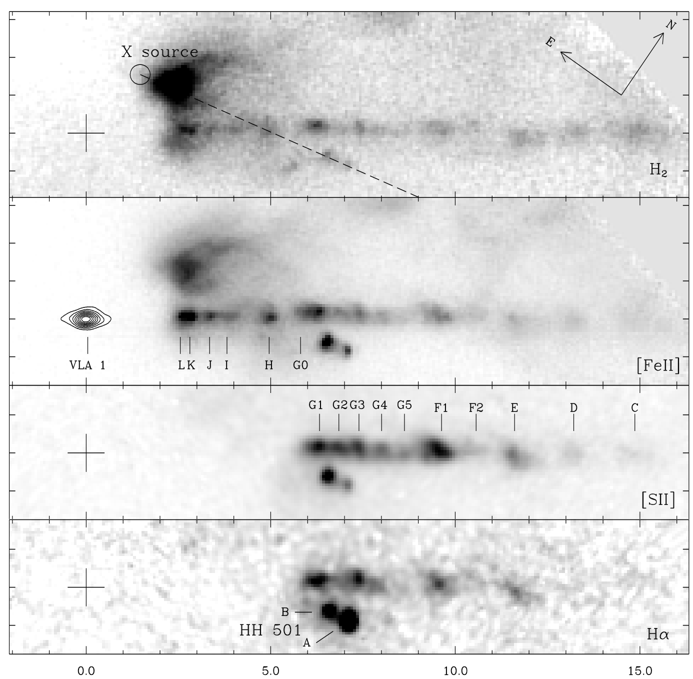


Figure 4.4: The thermal jet in HH 1–2, combining VLA 8.4 GHz (*contours*) with HST optical and near-IR (*greyscale*) data. The [Fe II] panel in particular shows the radio emission from the thermal jet (VLA 1) extending about an arcsecond, while the [Fe II] seen by HST picks up several arcseconds out, and extends to ~ 10 arcseconds. The Ultrasensitive Array would give higher resolution and fill in the missing emission, allowing us to follow the jet continuously from the origin to the working surface (the Herbig-Haro objects). Courtesy L. Rodríguez, S. Heathcote, & B. Reipurth (1999).

- *Deep imaging of known jets:*
  VLA images typically show a thermal jet extending perhaps an arcsecond from the star, only reappearing in the near-IR several arcseconds out (Figure 4.4). The Ultrasensitive Array,

[1] References appear at the end of Appendix A.

with its $\sim$ 30-fold improvement in high-frequency sensitivity, will fill in this missing gap, linking the radio to the near-IR/optical jet, and tracing the jet all the way from its origin to the working surface (the Herbig-Haro objects – also radio sources). This innermost part of the jet traces the recent history (tens of years) of the outflow, while the near-IR, optical, and molecular data record the history of the past hundreds and thousands of years. The Ultrasensitive Array is essential to provide the first complete data sets on the full temporal evolution of these outflows.

- *Temporal variations in outflows:*
  The Ultrasensitive Array will also directly measure variations in the flow rate and possibly the direction of numerous outflows. Moving knots have been detected a few hundred AU from the exciting star in the HH 80-81 jet (Martí, Rodríguez, & Reipurth 1998); this result required multi-epoch observations, separated by several years, of one of the brightest outflows in the sky. Are these enhancements in the flow periodic? Are these flow variations the rule or the exception? The Ultrasensitive Array could provide the answers, detecting proper motions of 300 km/sec at kiloparsec distances with only a month between the observations.

4.2.2 An Example: Quasar Absorption Line Systems

Dust obscuration prevents optical studies of quasar absorption line systems from seeing the highest column density systems: $N(\mathrm{H} + \mathrm{H}_2) \geq 10^{22}$ cm^{-2} corresponds to a V-band extinction of more than 6 magnitudes, assuming a Galactic dust-to-gas ratio. These high column density systems are thought to contain most of the neutral baryonic matter in the universe, and are the best tracers of the dense, (pre-)star-forming interstellar medium in nascent galaxies. The Ultrasensitive Array will provide, for the first time, the simultaneous high spectral resolution, wide bandwidths, high sensitivity, and excellent interference rejection needed to conduct *unbiased* spectral line surveys over a large range of redshifts. Here we describe two such surveys, which together would determine the evolution of the cosmic neutral baryon density from $z = 0$ to 3, without the uncertainties due to dust obscuration inherent in optical studies.

- *Redshifted H* I *21cm Absorption:*
  In 200 hours, the Ultrasensitive Array could survey the redshift range $0 \leq z \leq 0.4$ to optical depths corresponding to $N(\mathrm{H\,I}; 5\sigma) \sim 2 \times 10^{20}\,\mathrm{cm}^{-2}$ (for a spin temperature of 100 K) toward each of the $\sim$ 55 1.5 mJy background sources expected in a VLA primary beam (45 arcminutes FWHM at 1 GHz). Ultraviolet studies with the HST indicate about one high column density absorption system ($N \geq 10^{21}$ cm^{-2}) per unit redshift in this range. Hence we expect at least 22 systems to be detected at $\geq 5\sigma$ in such a survey. Note that this is a *lower limit* to the number of expected systems, due to the dust bias inherent in optical studies. Moreover, since all the sources surveyed would be within 45 arcminutes of each other, these data could also be used to constrain large-scale structure in the universe by studying the correlation between absorption systems as a function of redshift and source angular separation.

- *Redshifted Molecular Absorption:*
  Searches for molecular absorption line systems are extremely difficult with the current VLA due to the correlator and the limited bandwidth: the VLA at the moment is limited to a 50 MHz bandwidth at 43 GHz with eight spectral channels (dual polarization), implying a total velocity range of only 300 km/sec (Figure 4.5). By contrast, the Ultrasensitive Array could survey the frequency range 26 to 50 GHz with a velocity resolution of 50 km/sec to a noise level of 0.05 mJy/channel in under 24 hours. This corresponds to the 5σ detection of 10% absorption toward 2.5 mJy sources, of which there are $\sim$ 7 per square degree. Possible

lines include the ground-state rotational transitions of CO at redshifts between 1.3 and 3.4, and of HCN and HCO^+ at redshifts between 0.7 and 2.3.

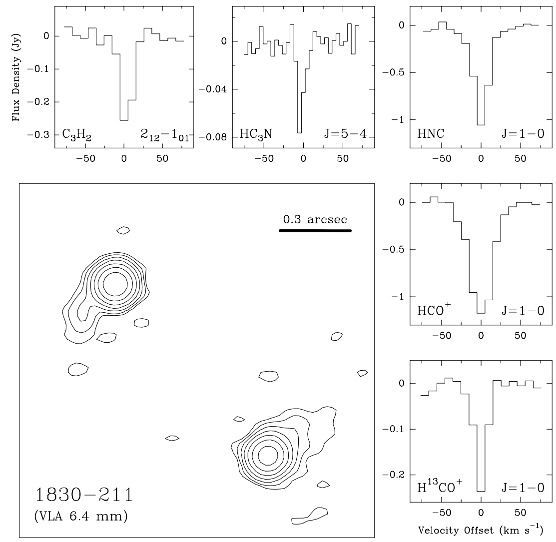


Figure 4.5: The contour plot shows a VLA image of the 'Einstein ring' radio source PKS 1830−211 at 43 GHz with a resolution of 0.1 arcseconds. The source redshift is 2.507. The spectra show molecular absorption by gas in the lensing galaxy, as observed with the VLA toward the southwest radio component. Zero velocity corresponds to a heliocentric redshift of 0.88582 (Carilli, Menten, & Moore 1999). These observations were possible only because the redshift was already known, and the redshifted lines happened to fall within the VLA's current observing bands; even so correlator limitations forced each line to be observed separately. The Ultrasensitive Array could observe all these lines at once, at higher spectral resolution, even if the absorption redshift were not known beforehand.

In addition to simply measuring the evolution of the cosmic baryon density, observations like these will provide estimates of the microwave background temperature (Wiklind and Combes 1996), the abundances of important species like deuterated molecules and molecular oxygen, and basic physical constants, such as the fine structure constant and the nucleon mass (Drinkwater *et al.* 1998), all as a function of redshift. The Ultrasensitive Array will play a dominant role in such studies, due to its high sensitivity, high resolution, continuous frequency coverage, and wide field-of-view, combined with the natural interference rejection afforded by an interferometer.

4.3 The Transient Universe

Rapid change is the hallmark of small and energetic sources, from solar flares to accreting black holes to gamma-ray burst sources. These objects are interesting both in themselves, as exemplars of extreme physics, and for their impact on their surroundings, most obviously as important sources of mechanical energy. Their rapid evolution however makes them very difficult to study, with important changes occurring on timescales as short as seconds, requiring a rapid response and excellent sensitivity.

Radio observations are very important for these transient sources. Synchrotron radiation offers a direct tracer of the high-energy particles created in shocks, and the corresponding radio photons can be seen even through very dense dust and gas. Those effects which do modify the radio spectrum, such as free-free opacity and scintillation, are frequency dependent, and may be inverted to derive interesting source parameters (*e.g.*, size scales and the density of the surrounding medium). Radio emission also tends to be long-lived compared to optical or higher energies, tracking the entire evolution of the sources rather than simply the initial outbursts. Finally, radio telescopes offer many practical advantages, with the ability to observe day or night in almost any weather, and with fields-of-view large enough to search for targets based on quite poor initial positions.

The VLA is already the world leader in these sorts of studies, but has significant limitations. Although the VLA's rapid, high-sensitivity imaging capability remains unequalled, for many classes of sources only the strongest (and generally the most unusual) examples can be observed in any detail, or over a significant fraction of their life cycles. Images of sources such as gravitational lenses and X-ray transients can currently be made only during that quarter of the time that the VLA is in its largest (**A**) configuration. And while the instrument in principle could respond quickly to alerts from other telescopes and monitoring programs, in practice scheduling these sorts of 'triggered' observations is at best difficult, and often impossible. The Ultrasensitive Array is designed to remove these constraints and take advantage of the full power of the VLA, by

- **Retaining all the advantages of the current instrument:**
  including a wide field-of-view, the ability to observe over three-fourths of the sky on any given day, and the resolution needed both to resolve nearby sources, and to filter out confusing large-scale emission.

- **Enabling dynamic scheduling of the array:**
  allowing a rapid response to new transients, and simple, consistent, and regular monitoring of these sources as they evolve.

- **Giving a factor of 5–30 improvement in continuum sensitivity:**
  permitting less biased samples of transient sources to be followed throughout their entire evolution (rather than just the initial outburst), and allowing imaging at much higher frequencies. The latter is important both to better characterize the spectral energy distribution, and for higher spatial resolution – in particular, any source which can currently be imaged at low frequencies in **A** configuration, could be imaged at higher frequencies in **B** configuration as well, effectively doubling the useful imaging time available on the array.

- **Providing complete frequency coverage from 1 to 50 GHz:**
  allowing the observer to choose the most interesting frequency for a particular source, *e.g.*, to track scintillations in gamma-ray burst sources at different Galactic latitudes.

With these capabilities the Ultrasensitive Array will revolutionize the study of transient radio sources.

4.3.1 An Example: Gamma-ray Burst Sources

The study of gamma-ray burst sources (GRBs) has undergone a renaissance since the launch of the Italian-Dutch satellite BeppoSAX and the subsequent discovery of long-lived "afterglows" at X-ray (Costa *et al.* 1997), optical (van Paradijs *et al.* 1997) and radio (Frail *et al.* 1997) wavelengths. We now know that GRBs are the most violent explosions (10^{52}-10^{54} erg) in the cosmos, driving relativistic shocks into their surroundings with bulk Lorentz factors $\Gamma_\circ \simeq 300$; and it is thought that they may announce the births of black holes. But many questions still remain. What is the true range of GRB energies, and what are their progenitors? Are GRBs spherical outflows or collimated jets? How do GRBs and the material surrounding them affect one another? Radio studies play a critical role in answering these questions, and the new capabilities of the Ultrasensitive Array are essential to make these studies possible.

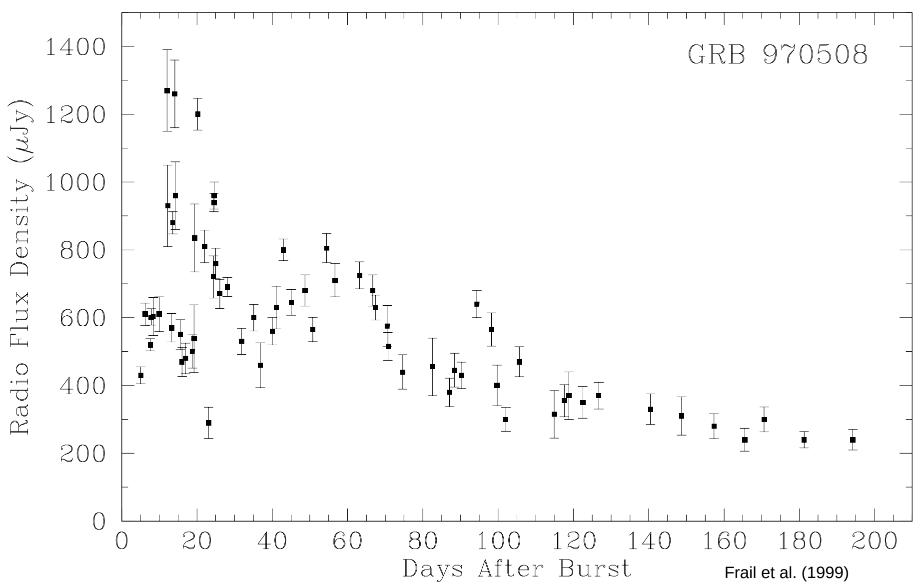


Figure 4.6: 8.46 GHz light curve of the radio afterglow from GRB 970508 (Frail *et al.* 1999). The flux density fluctuations at early times are the result of refractive interstellar scintillation, an interference effect produced by the intervening ionized gas along the line of sight. This scintillation provides a direct measurement of the angular size of the expanding fireball (see text for details). At late times (>100 days) the radio light curve undergoes the same power-law decay seen at X-ray and optical wavelengths.

The VLA has been at the forefront of radio observations of GRBs, making the first discovery of a radio afterglow from GRB 970508 (Figure 4.6) and making all subsequent radio afterglow discoveries in the northern hemisphere. But this impressive beginning is only a hint of what is possible. The Ultrasensitive Array will find and follow the evolution of as many as 100 GRBs a year (compared to the current one or two), in greater detail, over a wider range of frequencies, and for longer times than any current afterglow observations. Here the excellent sensitivity and responsiveness of the Ultrasensitive Array is the key, since even the strongest radio afterglows peak at around 1 mJy. These data will make fundamental contributions in several areas:

- *Monitoring the complete evolution of the source:*
  Radio observations are particularly important in constraining theoretical models of GRBs, because the radio emission is observable throughout all the major phases in the light curve. For instance, the most robust estimates of the total energy and the geometry come from radio observations at late times, when the blast wave has slowed to sub-relativistic speeds and the entire radiating surface is visible. In providing detailed and long-lasting light curves of many dozens of GRBs each year, the Ultrasensitive Array will make a major contribution to our physical understanding of these sources.

- *Sizes and expansion rates:*
  GRB afterglows are only a few microarcseconds in diameter; surprisingly, such diameters can actually be measured by radio telescopes, thanks to refractive interstellar scintillation (RISS). Well-sampled data taken at the right frequency (which depends, for example, on the Galactic latitude) can be used to measure GRB sizes and expansion rates, and have already provided the only *direct* demonstration that GRBs and their afterglows originate from relativistic shocks (Figure 4.6). Such measurements are currently limited to a few of the stronger radio afterglows; the Ultrasensitive Array will extend this to provide sizes and expansion velocities for dozens of GRBs every year.

- *Jets, rings, or spheres:*
  RISS can in principle determine not only the size but also the geometry of the radio afterglow, at least to the extent of settling one of the major outstanding questions: are GRBs jets or spherical outflows? This requires very well-sampled and low-noise radio light curves, and the Ultrasensitive Array is ideally suited to providing them. Additional constraints on the geometry come from the intrinsic linear polarization, which can in principle be followed for much longer times at radio wavelengths; the evolution of the polarization fraction and orientation should then reflect the shift from highly beamed to more isotropic radiation. Current instruments are simply not sensitive enough to measure afterglow radio polarizations. The Ultrasensitive Array by contrast can detect (5σ) 10% polarization in the $\sim 500\,\mu$Jy afterglows seen now, in under 10 minutes.

- *Dust-free samples:*
  There are now several afterglows which have only been detected at radio frequencies, and several others which show clear signs of reddening (Taylor *et al.* 1998). This raises the possibility that optical studies may miss a substantial fraction of the afterglow population, and particularly those GRBs born in dense, star-forming regions. Radio afterglows can be detected regardless of dust extinction, and the Ultrasensitive Array will provide a large enough sample that such biases can be rigorously checked.

- *Imaging the host galaxies:*
  Any model of GRBs must be consistent both with the positions of the GRB within their host galaxies, and with the properties of the host galaxies themselves; for instance, models based on the explosions of massive stars ("hypernovae") predict an association with the disks of actively star-forming galaxies. Currently this work is the domain of optical studies, and is limited by the small number of optical afterglows and the possibility of optical obscuration. The Ultrasensitive Array will be able to detect the radio emission from host galaxies out to $z = 1$ or beyond in a few hours, giving extinction-free estimates of the host galaxy's star formation rate, and providing sub-arcsecond measurements of the position of the GRB within the galaxy.

4.4 The Evolving Universe

The study of the formation of structured, separable objects – planets, stars, galaxies, and galaxy clusters – is among the most active areas of research in astronomy today. It is also among the most difficult, because the physical processes involved are both fundamental and complex, ranging from the accretion of matter to the dispersal of angular momentum and magnetic fields. Star formation, for example, involves such diverse phenomena as accretion disks, dusty envelopes, jets, and ambipolar diffusion. A combination of detailed observations over the widest possible range of wavelengths is required to disentangle the complex physics. In this context, the unique capabilities outlined in the previous sections make radio observations particularly valuable. Radio data probe physical phenomena known to be important but difficult otherwise to observe (*e.g.*, magnetic fields and cosmic rays) and give extinction-free measurements of the material from which these objects form (*e.g.*, the neutral and ionized gas). The VLA has begun to realize some of this potential, but the Ultrasensitive Array is essential to take full advantage of these possibilities, and to provide radio data of similar quality to those which will be obtained by instruments like the NGST, SCUBA, and ALMA at other wavelengths. The Ultrasensitive Array will provide three key improvements:

- **5−30 times better continuum sensitivity**
  allowing the Ultrasensitive Array to observe a much wider range of sources, at higher resolution, with simultaneous polarization information. Molecular gas and synchrotron emission will be detectable in galaxies like Arp 220 (if they exist) at redshifts of 5 or beyond, while closer to home, observers will be able to image complete, dust-free samples of supernova remnants and individual H II regions as far away as the M81 group.

- **Complete frequency coverage from 1 to 50 GHz**
  yielding reliable spectral decompositions of thermal dust, free-free, and synchrotron emission in young stellar objects, with simultaneous sub-arcsecond imaging; and, at high redshifts, providing unique constraints on the relative contributions of star formation and active galactic nuclei.

- **Excellent spectral resolution over wide bandwidths**
  allowing efficient, unbiased searches for emission and absorption lines, and accurate rotation measure estimates, even in standard continuum observations.

4.4.1 An Example: Star Forming Galaxies at High Redshift

Studying dusty, star-forming galaxies at high redshift is one of the main science drivers for the NGST, SIRTF, and ALMA. The Ultrasensitive Array will provide critical, complementary information, ranging from emission-line studies of low-order transitions of CO, to high-resolution dust-free imaging of both star formation and magnetic field structures, to the possible detection of dust emission in galaxies at redshifts of 10 or beyond.

Redshifted CO Emission Lines

Carbon monoxide (CO) is a major coolant of dense molecular gas in active star-forming regions, and a very useful molecule to observe: the CO luminosity provides a robust tracer of total molecular gas mass, while the peak line brightness gives a direct estimate of the gas temperature. Despite initial concerns that CO might not exist in the early universe due to low metallicity, luminous CO-emitting galaxies have been detected out to $z = 4.7$ (Figure 4.7; see also Ohta *et al.* 1996 and Omont *et al.* 1996), including the first two dusty SCUBA galaxies which have been observed ($z = 2.6$ and 2.9; Frayer *et al.* 1998, 1999). These detections are extremely important; while continuum emission may result from a number of processes, including star formation and accretion around massive black holes, CO unambiguously indicates the presence of massive amounts of molecular gas.

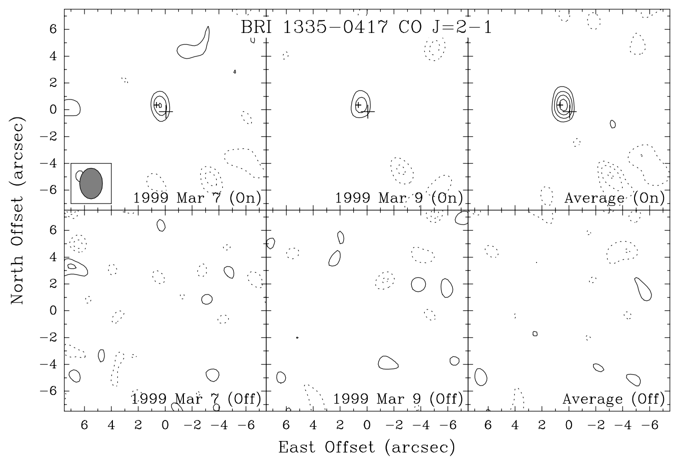


Figure 4.7: CO (2−1) emission at $z = 4.4$, as seen with the VLA in BRI 1335−0417 near 43 GHz (Carilli, Menten, & Yun 1999). The implied molecular gas mass is $M(H_2) \sim 10^{11} M_\odot$. Millimeter observations give a line-width of 420±60 km/sec (Guilloteau *et al.* 1997), but the maximum bandwidth currently available at the VLA is 50 MHz (dual polarization), corresponding to 350 km/sec at 43 GHz. The authors were therefore forced to use two independent tunings in continuum mode, on (*top*) and off (*bottom*) the line, and correct the observed flux density difference upwards for the missing velocities. The Ultrasensitive Array will cover 8 GHz – 56,000 km/sec – at a velocity resolution of $\sim$ 7 km/sec (assuming the DRAO WIDAR correlator).

While ALMA will be the ideal instrument for studying CO emission from relatively nearby galaxies, the low-order transitions are redshifted to centimeter wavelengths by z of a few (Figure 4.8). Spectral energy distributions for the recent submillimeter-detected sources suggest dust (and presumably gas) temperatures of about 50−100 K, implying that the best CO transitions to study are $J = 6 \rightarrow 5$ ($E_J = 155$ K) and lower. For relatively low redshifts, observing multiple transitions with ALMA and the Ultrasensitive Array will both confirm the individual detections and give a direct indication of the excitation conditions. This last is especially interesting since the cosmic microwave background temperature ($T_{\rm CMB} = 2.7\,[1 + z]$) becomes high enough to affect the population of the lower J levels at redshifts of only a few. At the highest redshifts, $z \geq 10$, all the key transitions will have redshifted into the VLA bands, and the Ultrasensitive Array can detect CO in galaxies like Arp 220 (thus most SCUBA-detected submillimeter sources) out to the edge of the universe (Figure 4.9).

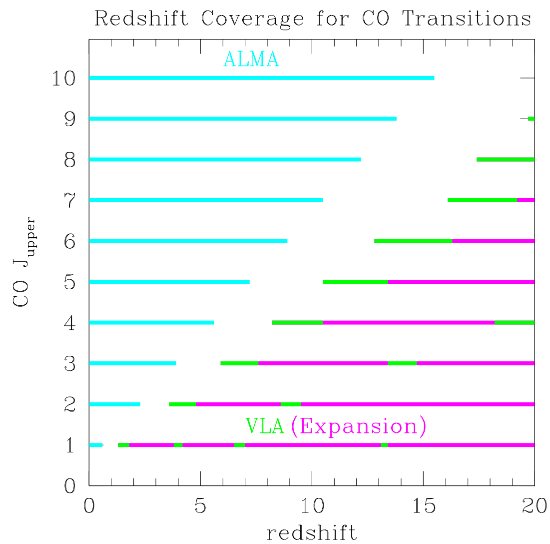


Figure 4.8: Redshift coverage of different CO rotational transitions covered by ALMA (magenta) and the Ultrasensitive Array (cyan). The Ultrasensitive Array will give a continuous redshift coverage, unlike the current VLA (green), and the new IF system and new correlator will provide 160 times the spectral bandwidth – large enough even for a redshift search. The gap between the two is caused by strong atmospheric absorption between 50 and 70 GHz. It is not yet clear whether ALMA will have 30−50 GHz receivers, which would extend its coverage for the $J = 1 \rightarrow 0$ transition (for instance) to $z = 2.8$.

Radio Continuum Emission

In addition to the spectral line studies outlined above, the Ultrasensitive Array will provide critical information on three of the most important broad-band emission processes:

- *Radio synchrotron emission* results when relativistic particles spiral around magnetic field lines, and hence probes both the cosmic ray electrons and the magnetic fields. Long observations with the Ultrasensitive Array can detect this emission from 'normal' galaxies (star formation rates of $10\,M_\odot$/year) out to $z = 3$, and from ultra-luminous infrared galaxies ($100\,M_\odot$/year) out to $z = 5$ (Figure 4.10). Similar emission from active galactic nuclei (AGNs) will also be detectable, to $z \sim 5$ for typical Seyferts, and out to virtually any redshift for more radio-loud systems.

- *Free-free emission* from thermal electrons (H II regions) dominates the integrated spectra of local star-forming galaxies between 40 and 120 GHz (*e.g.*, Condon 1992). The Ultrasensitive Array can detect this emission from galaxies with star-formation rates as low as $40\,M_\odot$/year out to $z \sim 2$ (5σ in 200 hours).

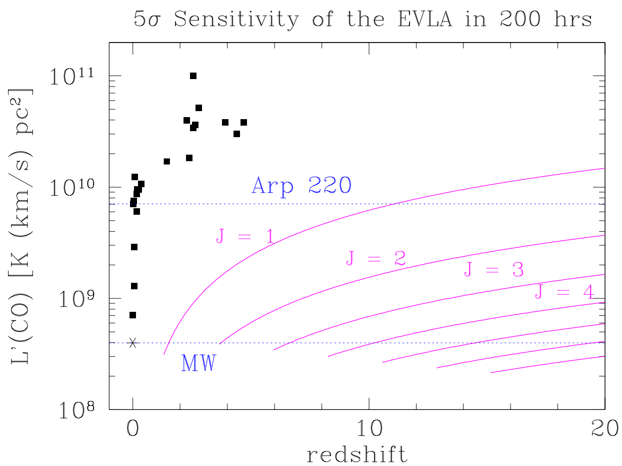


Figure 4.9: Detecting CO emission from high-redshift galaxies with the Ultrasensitive Array. The y-axis is the CO luminosity, which is proportional to the CO mass. Filled squares represent current measurements; horizontal lines show the CO luminosities of the Milky Way and Arp 220, which are independent of redshift and (roughly) of the transition, up to $J \sim 5$. The curved magenta lines show the 5σ sensitivity of the Ultrasensitive Array after 200 hours of integration, labeled by the rotation levels before the transition (*i.e.*, $J = 1$ refers to the $J = 1 \rightarrow 0$ line). Gas-rich galaxies like Arp 220 (thus most SCUBA-detected submillimeter sources) should be detectable at all redshifts. Galaxies with CO luminosity comparable to the present day Milky Way will be detectable to $z \geq 8$.

- *Thermal emission from dust* dominates the observed luminosity of the dustiest and most rapidly star-forming galaxies. At 45 GHz the 'negative K-correction' for the dust emission spectrum more than offsets the distance losses in the redshift range of $4 \lesssim z \lesssim 30$, so that a galaxy with a star formation rate of $100\,M_{\odot}$/year will have a flux density of only $0.5\,\mu$Jy at $z = 4$, rising to $3\,\mu$Jy at $z = 10$, and $10\,\mu$Jy at $z = 20$. The Ultrasensitive Array will reach a 5σ sensitivity of $3\,\mu$Jy in 200 hours, sufficient to detect such galaxies at $z \geq 10$.

These observations will complement the work of near-IR and optical telescopes, which study the starlight from these galaxies, and of ALMA, which will delineate the thermal continuum emission from warm dust (for $z < 10$), and the molecular line emission. In particular, the radio data will provide

- *Estimates of the massive star formation rate, unbiased by dust extinction,* via any or all of the three emission mechanisms.
- *Constraints on the temperature and density of the interstellar medium*, from the free-free emission.
- *Magnetic field strengths and geometries,* based on minimum-energy arguments and polarization imaging of synchrotron sources.

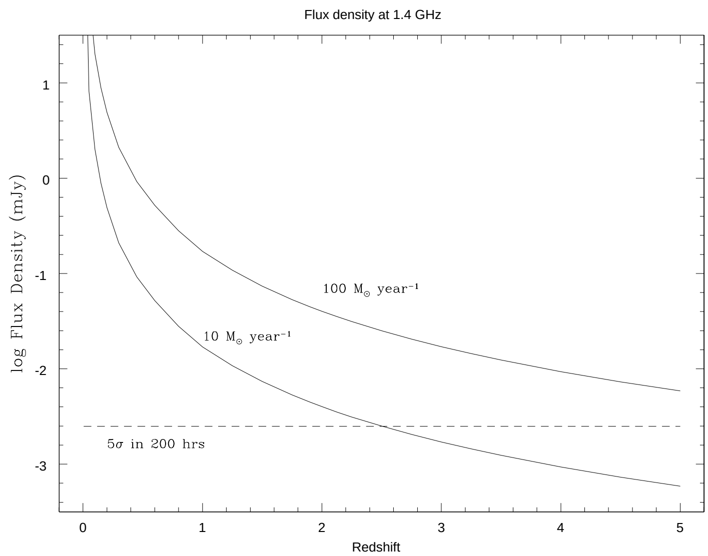


Figure 4.10: The solid lines show the expected 1.4 GHz continuum flux density of star-forming galaxies as a function of redshift; the dashed line represents the 5σ limit of the Ultrasensitive Array in 200 hours. Note that the in-beam source confusion in the **A** and **B** configurations is more than an order of magnitude below this limit.

- *Identification of possible AGN components,* from spectral index studies and high-resolution imaging.
- *Sub-arcsecond imaging and astrometry,* showing the distribution of the star formation without any worries about extinction, and providing the accurate positions needed for follow-up at optical and other wavelengths.
- *"Photometric" redshift estimates,* particularly when combined with ALMA data to allow fitting the spectral energy distribution over three orders of magnitude in frequency (cf. Carilli & Yun 1999).

Radio observations alone cannot solve the problem of galaxy formation and evolution; but neither can optical or millimeter data. Our best hope of understanding these complex and fascinating processes is to combine sensitive, high-resolution observations across the entire spectrum. The VLA Expansion Project will ensure that radio observations play their proper role in this endeavor, and that scientists have access to the unique information radio data can provide.

4.5 Summary

Radio observations offer a unique access to fundamental physics, measuring the strength and topology of magnetic fields, looking through dense dust layers to the cores of star-formation regions and accretion disks, and probing the high-energy particles associated with extreme sources ranging from black holes to cosmic explosions. The richness and complexity of these phenomena demand a flexible and sensitive instrument. That instrument must make useful images in seconds, while also being able to integrate for hundreds of hours for maximum sensitivity. It must provide sub-arcsecond resolution for small sources like stellar cores, but also map large fractions of a degree for big objects like galaxies. For maximum sensitivity to synchrotron radiation, it should operate at low frequencies; but for optically-thick sources and thermal emission, it must also work well up to several tens of GHz. Wide bandwidths are essential for spectrophotometry and spectral line surveys, but those bandwidths must be observed with high spectral resolution to retain sensitivity to high rotation measures and narrow lines. The utmost sensitivity is of course needed as well, to allow detailed polarization and imaging studies, and to allow detection of even the the least luminous and most distant sources. Finally, the ideal telescope should be responsive and easy to use, so observations can be driven by scientific goals rather than technical details. The Ultrasensitive Array, with order-of-magnitude advances in frequency coverage, spectral resolution, flexibility, and sensitivity, will build on the superb foundation of the VLA to achieve all of these goals, and allow astronomers full access to the unique information radio data can provide.

Chapter 5

Technical Development Plan

5.1 Overview

This chapter presents a detailed technical plan for implementing Phase I of the VLA Expansion Project, the Ultrasensitive Array. It should be kept in mind that this plan is continuously evolving. The plan described in this chapter reflects the approach that the correlator would adopt the ALMA design, that the signal transmission is analog, and that considerable analog and/or digital filtering of the signal will take place in the antennas. Some or all of these may change as development continues.

There are five principal components of Phase I:

- New or upgraded receivers at the Cassegrain focus providing continuous frequency coverage from 1.0 to 50 GHz in eight frequency bands.
- A new wide bandwidth fiber optic signal transmission system, including associated Local Oscillator (LO) and Intermediate Frequency (IF) electronics to carry signals with 16 GHz total bandwidth from each antenna to the correlator.
- New electronics to process eight channels of up to 2 GHz bandwidth each, including digital filters to define the bandpass and center frequency of each signal channel.
- A new wide bandwidth full polarization correlator, providing at least 16,384 spectral channels per baseline. The correlator will provide full polarization capability for four pairs of input signals of up to 2 GHz bandwidth each.
- A new real-time control system for the array, new monitor and control hardware for the electronics system, and improved antenna control electronics.

The design for the Ultrasensitive Array will draw heavily on development that is currently underway for ALMA. Both instruments will utilize a fiber optic system to transmit 16 GHz of noise bandwidth over a few tens of kilometers to a special wide bandwidth correlator system. New synthesizers are being developed for the ALMA Local Oscillator system and modern options for the design of the ALMA monitor and control system are being investigated. The ALMA design will include FIR (Finite Impulse Response) filters to select and shape the bandpasses. In all of these areas, the Ultrasensitive Array will follow the development being done by the ALMA project. Many of the design approaches can be directly transferred to the Ultrasensitive Array, and some modules or sub-modules may be directly interchangeable between the two projects. The largest cost savings will be in the years of engineering time that will not be expended in going from the top level design concept to the detailed design.

5.2 Design Considerations Imposed by Radio Frequency Interference

One of the primary design criteria is to be able to observe in a hostile environment of radio frequency interference (RFI). The centimeter wavelength bands are being increasingly filled by wireless communication: cell phones, pagers, aeronautical navigation and traffic control, satellite broadcast, and many other services. Terrain shielding, which for decades helped isolate radio observatories from RFI, is becoming less relevant as interference from broadcast and communication satellites, balloons, and airplanes increases. A modern broad-band radio astronomy system needs to have greater sensitivity and bandwidth to do the new science, but also has to work amidst a growing forest of strong and potentially debilitating artificial signals.

Our goal is to design a system that can function with strong man-made signals in the receiver passband and will not corrupt visibility measurements due to spurious intermodulation products. To provide the necessary dynamic range to enable handling of strong signals (both man-made and natural, in both the spatial and frequency domains), the entire signal transmission system must be designed with extremely linear response. This goal will be accomplished by a layered approach, each layer avoiding or removing RFI which cause non-linearities in the subsequent electronics.

At the top layer, this will be accomplished by using the minimal amount of amplifier gain, with careful design for linear response, before the first opportunity to insert filters for suppression of the strongest RFI signals. Since it is both difficult and expensive to build a transmission system entirely free from intermodulation problems, most of the analog processing of the IF signals must be done at the antennas.

The next layer of RFI filtering will consist of a digital FIR filter. This filter will follow a multibit sampler and be reconfigurable in software by loading tap weights into the filter memory. The FIR filter can be used to place rejection notches or bandpass edges where needed and could be dynamically reconfigured to adjust to a changing RFI environment.

The final layer of RFI filtering will be in the digital cross-correlator itself, after the worst of the RFI has been removed by filtering or tuning. With 16,384 or more spectral channels available for every baseline, weaker, narrow-band RFI can be removed during post-processing and data editing.

In addition, total power measurements will be available at several places in the system in order to monitor RFI.

5.3 Phase II Design Considerations

Phase II of the VLA Expansion Project, the New Mexico Array, calls for building and outfitting perhaps eight new 25 meter diameter antennas to fill in the gap between the baselines available at the VLA and those available from the VLBA. This second phase may also include other improvements to the VLA's capabilities, such as extending complete frequency coverage below 1 GHz to 300 MHz or lower, improving the low surface-brightness sensitivity of the array through construction of a more compact configuration, and implementing an 86 GHz capability. These components will be studied in detail over the next several years.

The budget and timescale of Phase II will be addressed in a future proposal. However, in all aspects of design of the Ultrasensitive Array, the needs of this second phase will be considered, so that this expansion will not require re-engineering. A relevant example of this is in the design for the new correlator. This includes a maximum separation of 500 km from the VLA – sufficient for the New Mexico Array antennas as well as the Pie Town, Los Alamos, Fort Davis and Kitt Peak antennas of the VLBA.

5.4 The Receiver Suite

A major goal of the Ultrasensitive Array is to allow observing over the entire frequency range from 1 to 50 GHz. This can be accomplished by installing eight receivers and feeds around the Cassegrain feed ring, as described below.

5.4.1 The Cassegrain Receiver Suite

During Phase I we will modify or replace most of the Cassegrain system receivers currently installed at the VLA and introduce new receivers for the 3 and 33 GHz bands. The bandwidth presented to the correlator will increase by a factor of between 10 and 80. Table 5.1 summarizes the frequency coverage of the proposed Cassegrain receiver suite.

Table 5.1: Proposed VLA Cassegrain Observing Bands

Band code	Freq. Center (GHz)	Freq. Range (GHz)	BW ratio	Action	Maximum Bandwidth	T_{sys} (K)
L	1.5	1.0 – 2.0	2.0	Modify	2×1 GHz	26
S	3.0	2.0 – 4.0	2.0	New	2×2 GHz	29
C	6.0	4.0 – 8.0	2.0	Replace	2×4 GHz	31
X	10.0	8.0 – 12.0	1.5	Modify	2×4 GHz	34
U	15.0	12.0 – 18.0	1.5	Replace	2×6 GHz	39
K	22.0	18.0 – 26.5	1.5	In Progress	2×8 GHz	54
Ka	33.0	26.5 – 40.0	1.5	New	2×8 GHz	45
Q	45.0	40.0 – 50.0	1.25	In Progress	2×8 GHz	66

Details on each of these bands follow:

- C-band (4–8 GHz) and U-band (12–18 GHz) – Replace

  The existing C-band and U-band receivers are still housed in the original VLA dewar and have long runs of waveguide to the room temperature polarizers attached to their feeds. Modern receiver design and new cryogenic amplifiers will reduce T_{sys} by a factor of 1.6 at C-band and nearly a factor of three at U-band.

- L-band (1–2 GHz) and X-band (8–12 GHz) – Modify

  The existing L-band and X-band receivers are already attached directly to the feed, eliminating the connecting waveguide. The current L-band receiver has a reasonable system temperature at zenith, but T_{sys} is severely degraded at elevations below 30° by scattering of ground radiation into the feed horn by the microwave lens. In addition, the receiver performance begins to deteriorate at frequencies below 1300 MHz, just where the best performance is needed to detect the weak redshifted H I lines. This receiver will be rebuilt with a new horn and polarizer which will reduce the ground pickup and permit high sensitivity observations from 1 to 2 GHz. The X-band receiver will be modified to increase its front-end bandwidth to cover 8–12 GHz.

- S-band (2–4 GHz) and Ka-band (26.5–40 GHz) – New

  Currently, the VLA cannot observe in these bands; these will be new capabilities for the array.

- Q-band (40–50 GHz) – In Progress

  From 1991 to 1995, thirteen VLA antennas were equipped with 45 GHz band receivers using funds provided by the Universidad Nacional Autónoma de México (UNAM). These receivers have proved to be a valuable research tool both for spectral line and continuum studies. Despite the fact that the array is only partially outfitted, this band is one of the most heavily used of the VLA observing bands.

  With the help of funds from the Max Planck Institut für Radioastronomie, and the NSF MRI program, a project has been started to fabricate 17 new 45 GHz receivers over the next two years. Six receivers were installed in 1999 and six more will be installed in 2000. Ultrasensitive Array funds will be needed to complete this project in late 2001.

- K-band (18 – 26.5 GHz) – In Progress

  Construction has begun for this part of the Ultrasensitive Array. Twelve of the new K-band receivers have been installed on the VLA. Under good observing conditions, T_{sys} for these receivers is about 55 K compared to the old receivers with T_{sys} of about 160 K. Four more are budgeted for installation by the end of 2000. Ultrasensitive Array funds will be needed to complete this installation.

The proposed arrangement of these eight Cassegrain feeds around the secondary feed circle is shown in Figure 5.1. Modern wide bandwidth feed horns are quite large, especially in their length. Mounting the S-band and L-band feeds will require modifications to the vertex room, as shown in Figure 5.2.

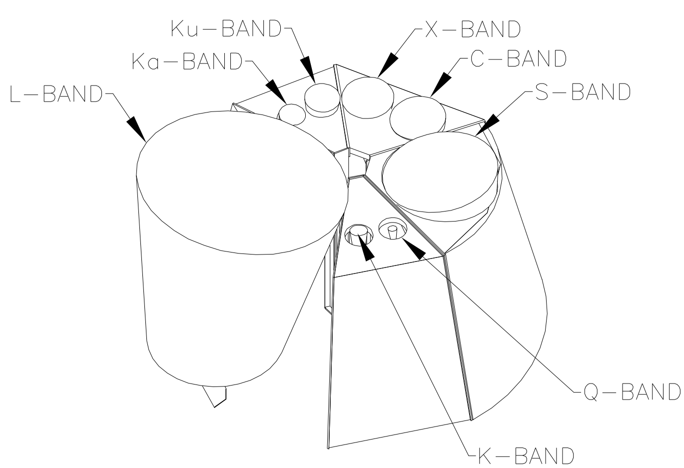


Figure 5.1: Continuous frequency coverage from 1 to 50 GHz from the Cassegrain feed ring can be accomplished with this arrangement of the feeds, without requiring any changes to the existing subreflector. The fit is tight, due to the size of the L-band feed. The high frequency feeds are arranged on the elevation axis to permit compensation of quadripod sag by rotation of the subreflector. All feeds except L-band are housed in a segmented feed cone.

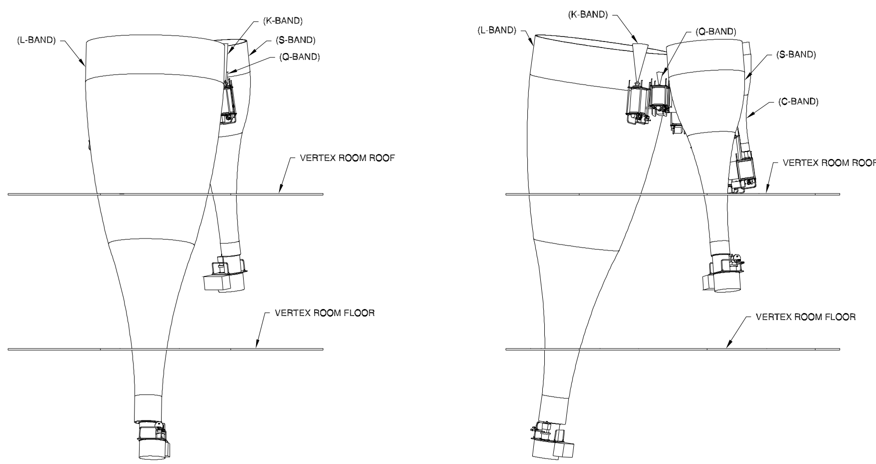


Figure 5.2: Two elevation views of the Cassegrain feeds, as seen from different azimuths. The two horizontal lines are the existing roof and floor of the vertex room. The L-band receiver will be mounted in a special housing below the floor. The six highest frequency receivers will be above the roof, within the segmented housing shown in Figure 5.1.

5.4.2 Other Aspects of the Receiver Plan

Dichroic operation of the array is not specifically a part of the current proposal. However, the electronics will permit simultaneous tuning in two different bands, and the feed arrangement shown in Figure 5.1 has been chosen to allow future implementation of a dichroic system utilizing band pairs whose feeds are located approximately opposite on the feed ring (*e.g.*, K and Q bands could be paired with X-band, Ka and U-bands with S-band). This could be implemented using dichroic reflectors as is done on the VLBA for geodetic observations.

In Phase I of the VLA Expansion Project, observations below 1 GHz will continue to be provided by the existing narrowband 327 and 74 MHz systems. There are no plans to widen the spectral response of these two existing systems. However, the availability of a much more flexible correlator will allow use of much wider bandwidths with the existing 327 MHz system. We expect to expand from the current 3.1 MHz to 25 MHz or more, resulting in a factor of about three improvement in sensitivity.

5.5 Electronics System

The design of the upgraded electronics system will offer unprecedented flexibility in tuning and bandwidth selection. Key aspects are:

- At the antenna IF, there will be two independently tunable polarization pairs, with filter bandwidth selection from 4 GHz down to 16 MHz in steps of factors of two. Each polarization pair can be placed anywhere in the front-end bandpass. The independent pairs can be placed within the same band, or in two different bands for dichroic operation. For the narrower bandwidths, an FIR filter will enable flexible removal of RFI.

- The two pairs of 4 GHz-wide signals will be split into four pairs, each of 2 GHz width. After digitization, a combination of an eight-way matrix switch and eight FIR filters will enable independent and flexible selection of eight frequencies and bandwidths from anywhere within these four input pairs, for presentation to the correlator. This will allow, for example, selection of eight different spectral transitions from within a single input IF polarization, or four (R,L) pairs of frequencies, with different bandwidths, from one or both pairs of input signals. This selectability will also enable flexible avoidance of RFI signals which are within the IF. The frequency selectability of these eight output signals will be limited by bandpass sampling considerations.

The very wide IF bandwidth and the continuous frequency coverage planned for the VLA Expansion Project require that most of the electronics equipment in the antenna and the central electronics building be replaced. The total IF bandwidth from each antenna will increase from the current 200 MHz to 16 GHz. The only practical way to transfer this much bandwidth is via a fiber optic system; the existing waveguide transmission system will be decommissioned.

A key decision for the electronics system is whether to transmit the IF signal in analog or digital form on the fiber optic system. This has many implications for the overall electronics design. The costs and benefits of the two systems are being studied in detail for the ALMA project, and the current baseline plan for ALMA is for a fully digital system. Such a system has many attractive advantages, particularly in stabilizing the signal transmission system, and thus removing an important source of errors. However, there are concerns about cost, complexity, and RFI generation at the antennas, which must be addressed before a decision can be made on the transmission system for the VLA Expansion Project. In this proposal we present a plan using an analog system. However, it is possible that the implementation will change to full wide-band sampling at the antenna and digital transmission if these concerns are suitably addressed.

Several factors lead to the current design concept:

- The large front-end bandwidth requires a high IF frequency (8–12 GHz) to avoid design of single-sideband (SSB) mixers with high image rejection.
- The design should be compatible with the existing VLA electronics to permit continued observing during the transition from the old system to the new.
- Very flexible filtering for RFI avoidance or removal should be available at the antenna, before high gain is applied to the signals.
- The design must allow for future operation with the antennas of the extended New Mexico Array, and for possible expanded low-frequency capabilities.

The system block diagram for the antenna electronics is shown in Figure 5.3, and a brief description follows.

Signals from the seven high frequency feeds (3 GHz band through 45 GHz band) follow the top signal path. There are two separate LOs, permitting flexible frequency selection. The bandwidth at this point is 4 GHz for each of the four signals (two (R,L) pairs). After the band-select switch and IF downconversion, these four high frequency signals enter the BW Selection module. Here, the full 4 GHz bandwidth signals are either passed through, or are each split into two 2 GHz wide signals. The full bandwidth signals pass straight to the IF transmitter module. If the 2 GHz wide mode is chosen, then one 2 GHz signal is directed to the IF transmitter, the other to the tunable LO (middle box in the IF Converter column) for possible further processing.

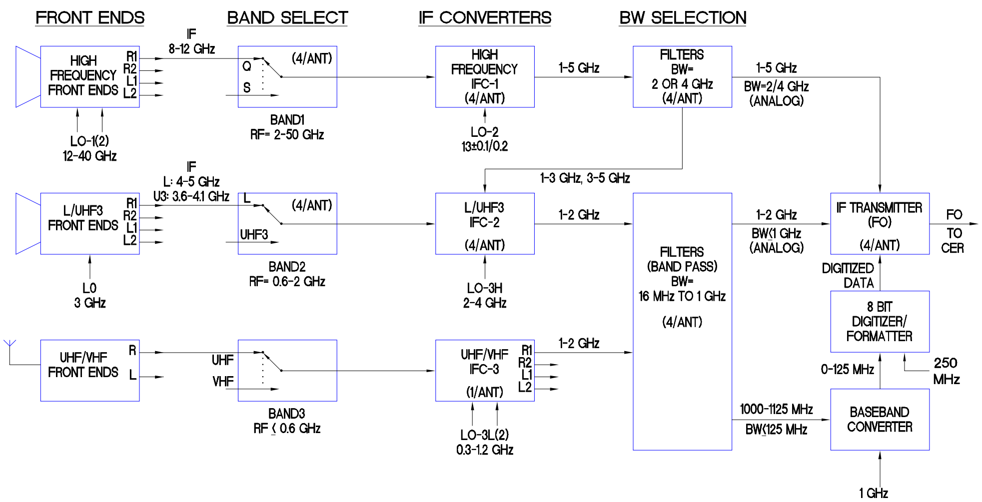


Figure 5.3: A block diagram showing the key components of the proposed Ultrasensitive Array antenna electronics. Signals from the high frequency feeds (3 GHz through 45 GHz bands) enter through the upper left box, from which three bandwidth options for transmission to the control building are available, as described in the text. The 1.5 GHz and the upper UHF bands utilize the middle path, leading to two transmission options. Low frequency bands (below 600 MHz) will use the bottom path.

If the intended final bandwidth is 1 GHz or less, the 2 GHz wide signals are routed to a tunable frequency converter (middle box in the IF Converter column in the figure). The signals then proceed to the analog filter bank for further filtering. This filter bank has seven selectable bandwidths, from 1 GHz to 16 MHz, in steps of factors of two.

From this filter bank, signals with bandwidths greater than 125 MHz will pass straight to the IF Transmitter, for analog transmission through the fiber optic line to the central electronics. For signals with bandwidth less than or equal to 125 MHz, there will be two options – either the same analog path, or an 8-bit digital path. The latter path is intended to preserve high dynamic range in digitizing for low frequency signals which are heavily contaminated by RFI.

Signals from the 1.5 GHz and future UHF3 bands (nominally defined as 600 to 1100 MHz) will enter the electronics through the middle horizontal path in the figure and, after initial frequency conversion and band selection, enter the same filter bank described above.

Signals from the low-frequency systems (currently the 327 and 74 MHz system, and any future prime-focus systems below 600 MHz) will follow the bottom path.

The central electronics block diagram (Figure 5.4) shows the final stages of signal processing prior to presentation to the correlator. This figure shows the signal path after having been received by the fiber optic receiver (left side). The four analog signals from each antenna (each of bandwidth between 16 MHz and 4 GHz in steps of two) are split into an upper and lower half in the “Demux” module shown in the figure. If the input bandwidth is 2 GHz or less, then only one of these halves

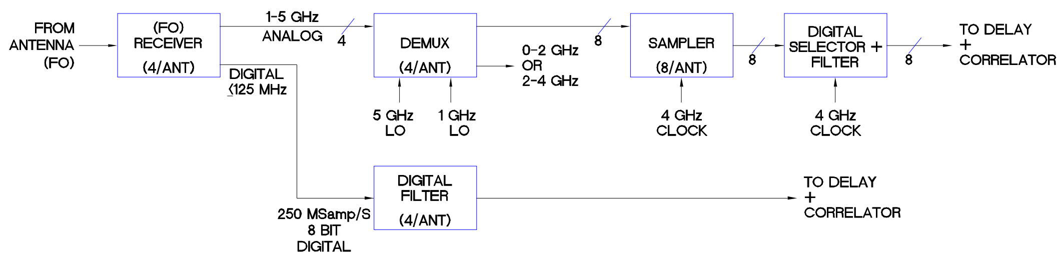


Figure 5.4: The block diagram of the Central Electronics Room IF Signal Path

carries the signal. Each of the resulting 2 GHz-wide signals is sampled, then passed to a cross-bar digital selector module which will permit very flexible selection of final frequency and bandwidth for the eight IFs to be sent to the correlator. The details of this cross-bar selector are yet to be worked out, but the goal is to allow the user to select any eight frequency/bandwidth outputs from the eight inputs. Because the correlator will have a 4-bit processing capability, the output from the samplers and digital filter blocks must also be four bits.

5.6 The New Correlator

The proposed correlator for the VLA Expansion Project described below is based on the ALMA correlator design concept. If this approach is followed, most of the chip and board designs can be taken from ALMA, so minimal funds are needed for engineering development.

However, it is possible that an alternate design, being developed by the correlator development group at the Dominion Radio Astrophysical Observatory in Canada, will be adopted. This correlator would constitute the Canadian contribution to the project, providing the design is acceptable to the NRAO, and the necessary agreements between the NRAO and the HIA be successfully completed.

The ALMA-based correlator design is based on the following specifications:

- Lag correlator design
- 125 MHz system clock rate

- 40 antennas (to allow future inclusion of New Mexico Array antennas)
- 8 IFs per antenna (maximum total bandwidth per antenna = 16 GHz)
- 4 Giga-sample/sec sampler clock rate
- 2-bit, 4-level input bit stream for wide bandwidth use
- 4-bit, 16-level input bit stream for narrow bandwidth use
- 1024 channels per baseline, single polarization, within a 2 GHz bandwidth
- 4 product pairs (RR, RL, LR, LL) possible for polarization
- 500 kilometer maximum antenna delay range (for future inclusion of New Mexico Array and nearby VLBA antennas)
- 5 msec maximum transmission delay
- Gating capabilities for pulsar observing with $\lesssim 20\,\mu$sec time resolution
- Up to 32 bins for pulsar timing
- Sustained data dump times of 10 msec
- A high-resolution (1 Hz) mode for bistatic radar experiments

The last analog IF stage of the electronics system will deliver four dual-polarization signal pairs to drive four pairs of samplers. Eight FIR filters will select the frequency and bandwidth to be passed to the correlator. The correlator chip accepts both polarizations from an antenna pair and can be internally reconfigured to distribute its 256 lags to yield 64 channels at full polarization (four polarization products), or 128 channels for just the two parallel polarization products, or 256 channels for just one of the parallel polarization products. Auto-correlation spectra for each antenna, for each polarization product, will also be available.

The wide bandwidth 4 Giga-sample/sec samplers will probably be direct copies of those developed for ALMA. A 2 GHz bandwidth FIR filter like that used in ALMA will be located after the samplers to provide flexible bandpass definition and center frequency. If the design concept changes to digital IF transmission from the antenna, the 2 GHz bandwidth FIR filters may be located at the antenna to avoid sending very high bit rates over the fiber.

A very useful characteristic of the ALMA correlator design is the capability of trading numbers of channels for bits of sampling. Thus, it will be possible to obtain 4-bit sampling (16 levels) in exchange for a maximum bandwidth of 500 MHz (per quadrant), rather than 2-bits over 2 GHz. This capability will be exploited for the VLA Expansion Project correlator, since the lower frequencies (3 GHz band and lower) have both narrower total bandwidths and more RFI. The extra bits of sampling should greatly assist in RFI mitigation, as well as improving sensitivity.

For very narrow bandwidths, 125 MHz or less, there will be 6-bit or 8-bit sampling with a low speed FIR filter. This filter has not yet been designed, but it may draw on studies for the ALMA FIR filter.

There are several areas in which the VLA Expansion Project correlator may deviate from the ALMA correlator. At the VLA, pulsar observations are important, so a method of gating the correlator multiplications synchronously with the period of the observed pulsar is necessary. This gating must be done prior to the long term accumulators. Gating for the purpose of RFI excision may also be needed.

Fast dump times from the correlator are needed for solar observations and for observing modes involving continuous imaging which could be used in surveys. Dump times of 10 to 20 msec may be needed in some cases. This should be no problem for the correlator, but the sustained effective dump rate will be limited by the capability of the post-correlator processing system and the archiving system.

Channel spacings as fine as 1 Hz are desired for bistatic planetary radar experiments. This will require an additional set of narrow IF filters or it may be done using the FIR filter. Again, this should not present a problem for the correlator design.

5.7 Antenna Control Electronics

The antenna control unit, servo electronics, encoder electronics interface, and focus rotation mount controller will be integrated into a single computer chassis. This RFI-shielded chassis will contain a high-speed processor board, monitor and control interface, and all digital and analog interface cards required for antenna control. This will provide fully flexible, software-based monitoring and control of the servo system, focus-rotation mount system and other industrial equipment. This approach will provide two benefits over the current hardware architecture.

- It significantly simplifies future modifications to the antenna hardware.
- It allows each antenna's drive system to be more finely tuned to optimize performance.

An additional benefit is that the algorithms modeling antenna acceleration and deceleration can be implemented locally in the antenna to improve tracking performance. The cost of this portion of the Ultrasensitive Array will be approximately $8K per antenna, which is substantially lower than the annual cost of maintaining the obsolete hardware currently in the system.

Chapter 6

Data Management and Computing

6.1 Introduction

Computing for the EVLA, as for all telescopes, will cover a range of activities from proposal submission and tracking, through array scheduling and observing, to data reduction and analysis. The EVLA will provide the user with unprecedented levels of interaction with the telescope and observing, as well as an unprecedented data rate – up to three orders of magnitude higher than that of the VLA. The EVLA will not be alone in these characteristics, as ALMA and the GBT will also provide the user with similar capabilities and data rates. These common characteristics suggest a unified approach to telescope and data management. Such an approach, besides making operations and maintenance simpler and more cost effective, will result in commonality of the user interface with these diverse instruments, thus improving efficient use and ease of operations.

For the EVLA, the NRAO plans to bring together the separate groups that have been working in these areas across the Observatory. Existing technologies will be reused where possible, and experience and development work that is common to various NRAO telescopes, such as the EVLA and ALMA, will be shared.

In this chapter, we describe first the data management philosophy that will be adopted. Then we discuss how this translates into principal requirements. System requirements are discussed next, then we discuss deployment issues. Finally, we explain the changes that will be needed to the Array Operations Center infrastructure to support the large increase in data volume.

Although this proposal is for funding for the Ultrasensitive Array, the computing plan presented in this chapter is crafted for the entire EVLA.

6.2 Data Management

The EVLA will mark a major advance in the management of data associated with a synthesis array. By managing data flow throughout, use of the telescope will be simplified, making possible more flexible and powerful scientific and testing programs.

The main goals of data management in the EVLA will be to:

- Simplify user access,
- Improve the data products,
- Archive all data products,

- Provide uniform access to all data products.

It is important to note that the users of telescopes are not limited to astronomers. Those who need access to the telescope include observers, operators, engineers, data analysts, and programmers. The data management goals must satisfy the requirements of all classes of users.

The NRAO is in the process of forming a more centralized management of computing, specifically devoted to satisfying these requirements for all NRAO telescopes.

The EVLA will use a computing environment derived from current Observatory practice. Elements of the system will come directly from the current VLA system, the VLBA, and AIPS++. Basic techniques derived from these systems as well as from the GBT and 12-Meter telescopes are being incorporated into the design. The computing systems of all NRAO telescopes will be more closely aligned, and thus all will be more productive.

As much as possible, the EVLA, the VLBA, the GBT, and ALMA will share scheduling, analysis, data formats, user-interfaces, development environments, software, and interferometer software models. The advantages of similar scheduling, observing, and analysis tools include better data quality control, more features, better maintenance and development, and streamlined, uniform scientific data paths.

6.2.1 Observer Access

Observer access to the EVLA will have the following attributes:

- Data submitted by the observer will be maintained and carried through the entire computer system. This will include proposal cover sheets, telescope schedules, and information entered during reduction.

- The telescope scheduling will be primarily goal-based rather than detail-oriented. Thus, rather than specifying the detailed sequence of the movements of the array, the observer will specify a set of goals: *e.g.*, determine the phase stability, determine bandpasses to a given fractional rms, or generate an image of a specified object to some specified sensitivity. Although this approach is similar to that used for optical telescopes, the application to radio telescopes requires considerable development and we expect that it will be accomplished in stages, with early stages requiring some human guidance. This area is one where interests directly align with ALMA, and indeed with many other radio telescopes. But, scheduling will be possible in several different formats, including the current format, and other formats and styles yet to be devised. Users will be able to schedule observations in the same environment (AIPS++) as the data reduction. This allows simulations of observations to be carried out prior to observing, as the AIPS++ simulator will accept goal-oriented schedules.

- Interaction with the EVLA will be possible from any remote location with adequate, secure Internet access. The experience and technology for this capability has been gained from the operation of NRAO's 12-Meter telescope over the last few years.

6.2.2 Data products and the archive

In many cases, the data archived from the EVLA will permit scientific results to be obtained directly without further data reduction. Initial calibration and imaging will be accomplished using a pipeline implemented in AIPS++. "Default" images will be produced using heuristics driven by the information in the schedule. The processing actions will be recorded in a repeatable, documented script that will be part of the standard data product. In addition to original and calibrated data, and default images, the archive will include all ancillary information, such as observer logs, and data from monitoring instruments such as temperature, dew point, wind speed and direction, GPS and phase stability monitors.

In many cases, the default image will suffice for the scientific purpose, but for the most demanding observations, some further analysis will be necessary. In all cases, observers will be able to remove the default calibration, and process their data according to their own methodologies. Continuing research into and development of the imaging techniques needed to improve the EVLA's data products will be an important part of the activities of the NRAO's new centralization of computing. .

The astronomer will be able to retrieve any of the data products stored in the archive. This will be possible both from a Web interface and from AIPS++ so that astronomy can be carried out using the large archive of observations.

Development of an in-house archiving facility requires a considerable effort. We intend to draw extensively on the experience of other observatories for this development.

6.3 Design Requirements for the EVLA

6.3.1 Principal Requirements

Scheduling

Both fixed and dynamic scheduling will be used to allocate time on the EVLA. Many activities such as radar mapping experiments and maintenance must be scheduled in advance for specific times. Dynamic scheduling will enable the best use of much of the remaining array time. The observations themselves may be conducted using goal-oriented observing plans, interactive graphical user interfaces (GUIs), or detailed observing plans, including the script files currently in use.

Support of goal-oriented observing is needed for a number of reasons:

- The current observer interface via the VLA's scheduling program "Observe" is too low-level and very often requires an observer to provide more information than what is necessary for a successful observational program. It thus acts as an impediment to new users who are not familiar with nuances of the observing system.
- Dynamic scheduling requires that the goal of a given set of telescope operations be recorded, so that in dynamic allocation, the necessary accommodations can be made.
- The calibration and imaging pipeline requires some information about the reasons for various operations (*e.g.*, this next set of observations should be used to determine the amplitude calibration).

Observing

The style of observing for which the VLA on-line system was originally designed will continue to be supported. It is based on the assumption that nothing changes quickly (once a minute or so) and some things change only very slowly (once per observing program, perhaps). Some new styles and modes of observing will be developed. Thus the planned control system must provide flexibility for this development.

Anticipated new modes of observing and schedule that the new system will support include:

- All current observing modes,
- Enhanced capabilities in mosaicing, fast-switching, and sub-array modes,

- Total power measurements and on-the-fly mapping,
- User monitoring of current observations on timescales of minutes,
- Goal-oriented scheduling,
- Interactive and remote observing, and
- Dynamic scheduling of observations.

Observers should be able to learn enough about the course of their current observations to be able to alter planned observations in a few minutes. The operations staff should be able to easily choose which observational program should be done, given the current atmospheric transparency, wind, phase coherence, ionospheric delays, and any number of other conditions.

Interferometer Model

The long baselines and high sample rates required by the EVLA demand an accurate interferometer model. For this, the VLBA correlator model is ideal. In fact, using nearly the same code will be highly advantageous for future maintenance and model upgrades for both instruments.

The accuracy levels required from the model are largely driven by the following goals:

- Increasing the accuracy of VLA absolute source position measurements,
- Source-to-source phase referencing,
- Observing on the long New Mexico Array baselines in the 45 GHz band,
- On-the-fly mosaicing at 50 GHz, and
- Fractional-sample delay tracking at a sample rate of 4 Giga-sample/sec.

Uncertainties in modeling the wet component of the atmospheric delay will cause fringe delay residuals which are a substantial fraction of the sample interval of 250 picoseconds. In order to minimize post-correlation fringe fitting, an improved wet atmosphere mapping function will have to be developed.

The fundamental requirements on EVLA model precisions and update rates to the correlator and antenna are given in Table 6.1. These are the values required for sidereal model tracking. The lobe rotator model update interval of 50 milliseconds is based on an error limit of no more than $0.5°$ of phase at 50 GHz. This error is the amount of phase deviation due to the unmodeled second order and higher derivatives of the phase model over 50 milliseconds. The delay precision in Table 6.1 of 15.625 picoseconds (1/16 sample time) holds the band center phase error to less than $5.6°$.

As well as meeting the precision and update rate requirements, the EVLA model must provide model accountability information to the data archive. The observers must be able to reconstruct precisely what delays, phases, and rates were used during their observations. This capability is currently implemented on the VLBA and has proven to be extremely valuable.

Array Control

Elements of the existing control system will gradually be replaced over the course of the project. To minimize shutdowns of the instrument, the EVLA computing system must work with the existing hardware. The system must therefore be built to control and operate, in order of priority:

Table 6.1: **Timing Requirements for M&C and Correlator Data**

Data Type	Requirement
Antenna Monitor Data Rate	1700 bytes/sec/antenna
Average Antenna Command Data Rate	1300 bytes/second/antenna
Pointing Command Rate	20 Hz
Pointing Command Precision	1 arcsecond
Lobe Rotator Phase/Rate Update Interval	50 millisec
Lobe Rotator Phase Precision	0.5° of phase
Delay Model Update Interval	50 millisec
Delay Model Precision	15.625 picosec
Scan Reconfiguration Time	1 sec
Correlator Maximum Sustained Output Rate	600,000 complex visibilities/sec (4 Mbytes/sec)
Maximum Spectral Channels per baseline	32,768 channels (262,144 bytes)

- The existing VLA antennas, monitor and control system, and correlator,
- The EVLA antennas, monitor and control system, and correlator,
- The New Mexico Array and VLBA antennas.

The EVLA computing system will be designed to facilitate development of new instrument control languages incorporating elements suitable for dynamic allocation of array time. Dynamic scheduling is an essential feature for future operation of the EVLA, the GBT, and ALMA. A simple version of dynamic scheduling is under development at the VLBA. A unified approach to this kind of time allocation is desirable, and will be directed by the NRAO's centralized computing management. .

The new system must be accessible for operational, maintenance and diagnostic purposes from the VLA control building, the antennas, other buildings at the VLA site, the Array Operations Center (AOC) in Socorro, and across the Internet. Network bandwidth for these purposes will be provided within the VLA site and to the AOC. The user interfaces will be built to allow wide access at reasonable bandwidth, but some remote functionality may be limited.

The system must archive all primary and ancillary data products and provide for access and distribution of these data to investigators and staff. Experience with the VLA and VLBA shows that wide-ranging archive analysis tools are essential. Good investigative tools will reduce personnel needs and increase data quality.

The array control system for the EVLA must be simple for the novice and must permit detailed control by the sophisticated. Accommodation of both simple and complex applications will require careful design.

Operations

A wide variety of tasks is required to operate a large interferometer. Operations staff require a complete and well-integrated tool suite to test, control, monitor, maintain, calibrate, and manage the instrument. Such a tool suite must cover allocation of observing time on the array, construction of observing control files, observation monitoring, array status, maintenance, and queries of archival data stores. Interfaces to low-level devices, major subsystems, and high-level array control are also needed. If such extensive user interface and data store systems are well designed and integrated, there will be significant benefits in data quality and quantity.

Many of these systems must be accessible remotely. Users and staff must be able to use and maintain the system across the Internet. EVLA operations, located in the VLA control building, must have priority access to the array control system and the archive. Operations staff must be able to restrict access to the control system for (at least) commands and primary data products.

Plans to move some VLA Operations to the Socorro Array Operations Center are being considered. These plans have potential benefits in efficiency, workforce retention, and cross-training with the VLBA. However, such a move must not result in a decrease in data quality or reliability.

Standard data products

For most projects, the goal for calibration and imaging is that soon (*i.e.*, minutes) after the end of observing or a designated section of observing, the observer should be provided with default images of the sources that were observed. Information on the calibration and imaging strategies to be employed will be either supplied by the user in the form of a script, or derived from the goal-oriented observing schedule specified by the observer or the operations staff. The strategies will be drawn from a small fixed menu of possibilities, each possessing few parameters. The allowed strategies will include *a priori* amplitude and phase calibration, and referenced calibration. Self-calibration and deconvolution will be available in limited forms.

The data archived from the array will include:

- Proposal cover sheet,
- Observing schedule and operator log,
- Original, un-calibrated visibility data,
- Monitor data and data from ancillary instruments,
- Flagging information,
- System configuration information,
- Derived calibration information,
- Default images,
- Interferometer model accountability data, and
- Repeatable, documented processing script in AIPS++.

Data processing will be implemented in AIPS++ in a calibration and imaging pipeline. The pipeline must have access to current and historical information about the array, such as antenna positions, recent monitor data, geometric models, observing control files, and calibration data. The visibility data must be flagged for validity using documented criteria. Some derived calibration information, such as self-calibration solutions for VLBI phased array observations, will be passed back to the control system.

The processing must be done in a standard software system (AIPS++) that is available to the observer at his or her home institute. A repeatable processing script will be made available, together with the original data, images, and calibration data. All information used in the processing must be part of the standard data product.

Archiving

Data products for each project will be archived in a system with many Terabytes of available storage. Retrieval by anyone will be possible once a proprietary period has passed. A large variety of ways of searching the archive by keyword will be supported. Searching by content will also be supported.

Radio Frequency Interference

Self-generated radio frequency interference within the array must be minimized. High-speed digitizers, embedded controls, communications within the antenna, computers, and other digital devices will all be shielded.

6.3.2 System Requirements

Array Control

Control of the EVLA will be shared among electronics, embedded microprocessors, general purpose computers, and real-time and off-line software. Proper distribution of functionality between these domains requires careful analysis of timing, flexibility, cost, and complexity. Only a collaborative design environment will promote good hardware, computing, and software tradeoffs and prevent a fragmented architecture, duplication of effort, and an overly complex system.

The control system must allow for the growth of the instrument over several decades. The software must be designed in such a way as to allow the computer hardware to be upgraded, to track technology and performance, without major modification. This is not maintenance but rather continued development. A structure designed for this environment is vital. Software will be an essential part of achieving the required flexibility in antennas, correlators, receivers, communications, interference suppression, calibration, and user interfaces. The interfaces to the equipment must be very modular and capable of some degree of location independence.

Antenna Monitoring and Control

The EVLA requires computer control and debugging of remote antennas. The VLBA was designed for just such conditions, relying entirely on the computer system for everything except critical human and machine safety systems. Unless something has to be repaired, the Socorro VLBA operator has almost all the information and control that a site technician has. This policy has been very successful, and will be extended to the EVLA.

The EVLA electronics and the monitor and control system will contain few switches, none which can override computer control, except for safety-critical systems. All indicators will have their information content available over the monitor and control system. The device state, including the state of controllable attributes, will be accessible, except in extreme cases such as entire software downloads. No separate, privileged, interface to the electronics will be developed. All monitor and control capabilities needed to test and support a device should be available over the standard monitor and control interface.

To meet these goals, a monitor and control architecture design, and software support to electronics, must be available during prototyping. Electronics and software engineers must work together on their subsystems early in development.

The antennas will each have about 1000 monitor and control points distributed among about 100 devices. The monitor rate required within the antenna is low, as is the rate needed to configure the entire antenna within a specified one-second scan interval. Specific timing requirements will depend on array-wide design choices that have not yet been made. Control points with requirements below one millisecond, such as lobe-rotator rates, will probably be hardware-synchronized, and there will likely be telescope heartbeats on timescales about one second.

Devices will be allowed to have a wide range of complexity. Sensors, switches, and other devices with simple I/O requirements may be connected through a standard interface to the monitor and control system. More complex devices may have embedded controllers.

Communications within an antenna can be simple and of low bandwidth. Most devices require only a few bytes for monitor and control. Monitoring rates of any individual point are not high, none more than 20 Hz. It is practical to use a polled rather than an event driven communications model. Such a system can be implemented on simple controller chips, and most NRAO telescopes use this model. It is easily ported to different computing platforms, which speeds prototyping and development.

Computing Standards

Observatory coding, documentation, and version-control standards will be adopted. Some formal design methodologies may also be adopted, but a mix of design methods may be used. Tools to support these methods will be purchased. Methods, languages, and operating systems will be chosen to meet standards-based computing goals, promote code sharing among different NRAO projects, and work toward a more unified feel in NRAO systems. System design and coding practices must emphasize modularity, maintainability, and testability. Unit testing software will be developed wherever possible and the computing system will adhere to project-wide testing strategies and standards. In a system with a long projected lifetime, more personnel time will be devoted to expanding the system than to developing it.

Correlator

The EVLA correlator is assumed to be either a modified ALMA correlator, or the DRAO design described in prior chapters. In either case, delivery and performance requirements make it likely that some or all of the correlator-control system will be built by the EVLA team.

Real-Time Systems

One of the best commercial real-time operating systems offered today is used throughout the Observatory, and will be incorporated into the EVLA. The vendor is committed to standards-based computing and is among the leaders in tool offerings and CPU platform breadth. Designs using this environment maximize both portability and cost effectiveness.

Embedded microprocessor systems in custom devices will benefit from the same standards-based approach. They too will require development for many years after construction ends. A real-time kernel and implementation language may be selected for at least some of the antenna-embedded systems, and design, coding, and documentation standards will be applied.

User Interfaces

User interfaces are needed for most of the requirements expressed in this document. Ideally, a single user-interface system will be employed to allow end-to-end observability and control of the array from the array site and from Internet-based locations. Remote observing and maintenance capabilities will be built in from the start. The user interfaces should be as platform-independent as possible.

Technology Transfer

The EVLA computing system will build on those of other NRAO telescopes and on NRAO software packages, such as AIPS++. The new centralization of data management will facilitate the necessary sharing of people, knowledge, and technology. Not only will the EVLA benefit from this interaction, but so will the other NRAO telescopes, ALMA, the GBT, the 12-Meter, and the VLBA.

Fundamental observing techniques and reduction algorithms have been developed over the past 25 years of experience with the VLA. Many of the strategies will be transferred to the EVLA.

The VLBA, the 12-Meter, and the GBT use computing systems based on open architectures. After ten years, they are still well supported by the commercial world with upgrade paths available. The EVLA will also use this strategy. The GBT uses AIPS++ as part of its user interface and in its data analysis system. The GBT and AIPS++ projects have also pioneered the use of object-oriented software methodologies in the Observatory. Designs and software from these projects will be incorporated into the EVLA computing system.

Technology Stance

Mainstream computing techniques and off-the-shelf components can satisfy the requirements in most cases and will be used to maximize the supportable lifetime of the system. Current computing power permits a conservative approach using only a few emerging technologies.

Computing Platforms

Operating system and CPU architecture independence will be pursued wherever possible. Just as a real-time operating system gives a measure of CPU and bus independence, so do some operating systems, languages, and interfaces promote platform independence. User interfaces will require special efforts, since they will be used remotely. Minimizing platform requirements will promote broad use of the system and increase its portability. Complete platform independence is not presently possible.

Computing Infrastructure at the Array Operations Center

The EVLA will require some changes in computer operations at the Array Operations Center in Socorro to cope with the increased data volumes, which will regularly exceed 50 GB. A thorough redesign of our current Local Area Network infrastructure is essential if we are to handle this load.

Two related changes are required:

- We will use centralized disk space instead of disks local to individual workstations. Specialized file servers are already available with sufficient disk space to replace all our current external disks. We expect that developments in these file servers will keep up with increasing disk space demands.
- We will upgrade the AOC's Local Area Network to a switched 1 Gbit/second optical-fiber network, allowing a dedicated bandwidth of more than 100 Mbyte/second to each client. In comparison, our current local Ultra SCSI disks reach only 20 MB/sec. Upgrading to optical fiber will permit centralization of data, and free us from the current necessity of locating data with each CPU.

Computing Infrastructure at the VLA Site

The existing computing infrastructure at the VLA site must also be upgraded to accommodate the data rates and sophisticated analysis tools which will be needed to manage, operate, and use the EVLA. We will implement an architecture similar to that for the AOC. The control system described below is independent of these planned changes.

6.3.3 Design

Control System Architecture

The EVLA control system will be designed around three coordinated control domains. Functionally, these domains may be divided into four control blocks: one for each domain plus a master array controller. Real-time coordination of the work done both within and across domains is required. This coordination can be achieved either by designing a highly synchronous system, or by using independent controllers linked by a pervasive time system. The control building systems can be made synchronous as needed, but coordination of the control building equipment and the antennas hinges on the nature of the communications along the VLA arms.

The design delineated here is based on a central array-control computer which communicates with antenna controllers over a commercial network. Figure 6.1 shows an example of such an architecture. The antenna control domain is in the upper left. The antenna controller will use industry standard equipment and protocols to communicate with the array controller in the central control building. The antenna will have network ports to enable control terminals for engineering activities. It will be possible to monitor and control the telescope from these local terminals without the network to the Control Building, although archival data will not be available under these conditions.

The antenna controller will communicate with custom NRAO devices in the antenna over a local communications bus. Devices such as receivers, antenna servos, and filters will all use this common "fieldbus". This fieldbus will use a simple, master-slave, address-mapped, serial communications protocol. It could be an updated version of the bus used in the VLBA, the GBT, and in NRAO's Orbiting VLBI station, or it might be based on a commercial bus controller like CAN (Controller Area Network). Off-the-shelf components will be connected to the antenna controller through its backplane.

The array controller will coordinate the antennas, the correlator, the archive system, and model generation. Communications among equipment in the control building, such as the wideband samplers and the array controller, will probably use the same fieldbus used in the antennas. The independent control domains will be linked by the array controller through two networks. There will be one network for the antennas and one for the correlator, archive, and model functions.

A separate network will support the other mission-critical functions: operations, archive access, and independent controllers such as the VLBA and pulsar systems. Traffic in this domain will not affect array control. We expect to accomplish this separation of traffic with a single switched network. The final decisions on network architecture will be made when the design is more complete.

The Archive Server will distribute data to Internet-based users. The network bandwidth to the VLA site will be increased as costs permit and use of this feature expands, with a goal of allowing real-time transport of visibility data to any user with a connection adequate for handling the correlator data rate.

Timing

The exact methods of distributing timing and control have not been selected. Indeed, the fundamental timing cycles have not been chosen. Since the LO chain in the antennas must be linked with the master LO in the control building, we can only say that precise coordination will be possible, but no more.

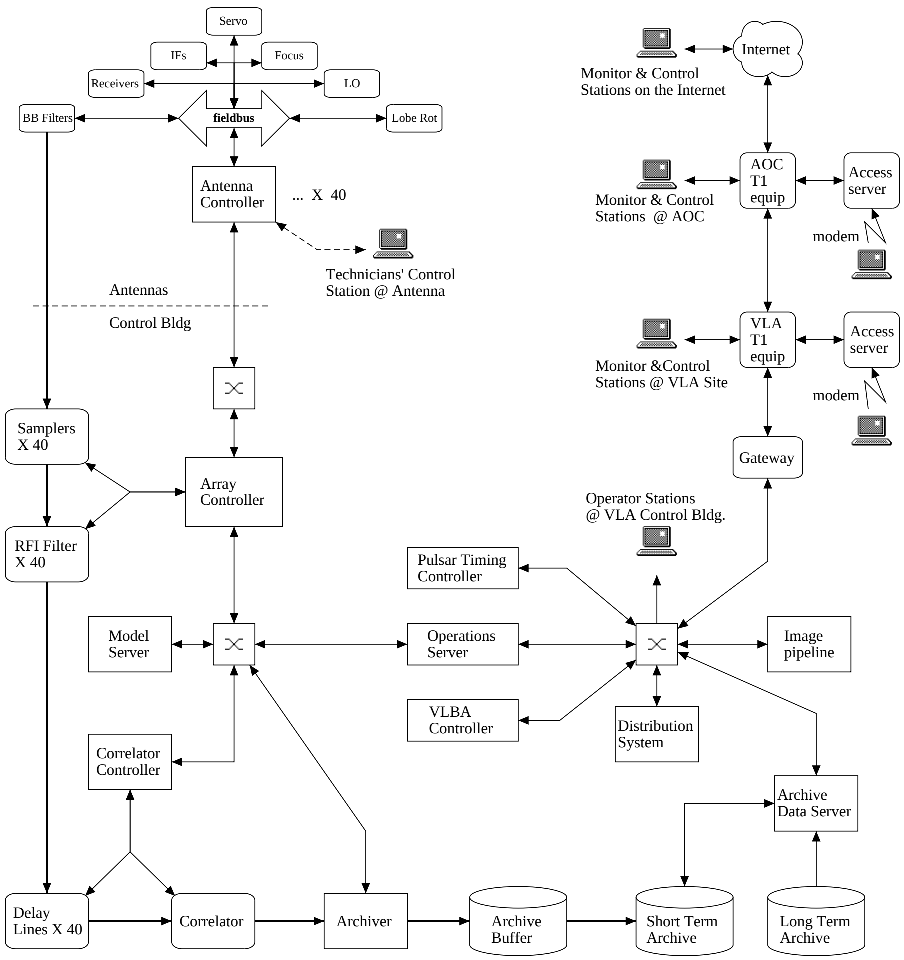


Figure 6.1: **Conceptual Diagram for the On-Line Computing System.** The Antenna Controller in the upper left of the figure configures and controls the antenna and all local equipment, receiving instructions from the Array Controller below it over a fiber optic network. The Array Controller directs and coordinates the antennas, correlator, model system and archive systems, manages scans and subarrays, tracks system state, and is the array control system's interface to the Operations Server. The Operations Server block to the right of the Array Controller will span several computer systems which will contain all the array management software: observing control files, array time-allocation software, array access control, maintenance data, and system configuration. The servers will redistribute monitor data from the array to investigators, operators, and the archive, and will route commands into the array from users and operators. The Archiver (bottom) must take the visibility data out of the correlator, save it and ancillary data in a high-speed Archive Buffer, and then write it to a slower Short Term Archive. The Archive Data Server will distribute archival data, array monitor data, visibilities, calibration, logs, pointing parameters, and other useful data, to investigators, operators, engineers, and technicians. Monitor and Control Stations, shown as monitors, may be in different locations. The Gateway secures the system from unauthorized Internet access.

External Systems

Control devices which are not built as part of the EVLA will be accommodated through the operations network. The VLBA back-end controller and the pulsar timing engine are examples of such equipment.

6.3.4 Deployment

The deployment strategy for the EVLA computer system will follow standard practice. The system requirements and high-level design will be completed and reviewed. While this work is proceeding, the team will evaluate selected technologies and tailor current work to the needs of the EVLA. After the detailed design is complete, the first major milestone will be the completion of a system to run the array in a selected, simple way; for example, as one continuum subarray. The system's capabilities will then be expanded until it has most of the functionality of the present control system. This effort will probably be directed at the hybrid array, but depends on the exact transition strategies employed. After this goal is reached, effort will be devoted to the expansion of the EVLA's capabilities.

The responsibility of minimizing array downtime during construction of the EVLA will largely rest with the computing system. Once the antennas are upgraded, they will no longer be accessible by the current control system. Control of the hybrid array imposes a very early delivery target on the system. If a temporary loss of array flexibility is to be avoided, the computer system must have capabilities near those of the present system. This will be a challenging goal to meet on the four-year timescale between the beginning of the project and the delivery of the first modified antenna. Planning for and implementation of the transition from the present system to the new computing system is ongoing.

Existing systems and work-in-progress will be incorporated into the EVLA. VLBA systems such as time allocation, investigator databases, and proposal management will be used. The VLBA operations management system (OMS) was designed to be extendable to the VLA. OMS is now in early testing and will be well advanced when it becomes time to accommodate the EVLA's needs. A new correlator controller based on VLBA technology has been under development for several years. This controller will replace one of the VLA's central control computers, the array processor, and the correlator's embedded controller. It has a straightforward network interface which the new system will use for running the existing correlator. The VLA waveguide-based monitor and control system is now being connected to a controller based on VLBA technologies. This system is being developed as a test environment for the EVLA system and will be used to make the VLA antennas and control equipment present an EVLA-style interface to the new system.

Chapter 7

Education and Public Outreach

7.1 A New Education and Public Outreach Program

Beyond the central role the VLA plays in modern astronomical research and technology development, there is another goal: the stimulation and inspiration of the intellect and imagination of the general public, particularly students of all ages, who visit the VLA site. The unparalleled grandeur and visual appeal of the VLA, in combination with modern exhibits and highly-focused education programs, has the potential to significantly enhance public understanding and support of science, astronomy and radio astronomy.

As we bring the VLA itself back to the state-of-the-art, we will also upgrade and expand our educational facilities and programs to present the exciting science of today, and opportunities for the next decade made possible by the EVLA. The EVLA, with its new capability to answer fundamental questions about the Universe that excite the imaginations of millions, will have an even greater ability to enhance science education and to promote science literacy among non-scientists, including tomorrow's political and business leaders and teachers.

Across the nation, museums, science centers, and observatory visitor centers are increasingly popular destinations for tourists and families. At other observatories, visitor centers are the foci not only of informal science education but also of programs that are integrated into formal curricula in K–12 schools. Many of these visitor centers have been expanded in recent years and others plan expansions in the near- to medium-term future. Astronomy remains among the most popular of the sciences with the general public, and is effectively used as a "draw" for a wide range of science education efforts.

As the world's most famous radio telescope, featured in movies, TV commercials, science magazines, textbooks and frequent news coverage, the VLA is the public's premier image of radio astronomy. Every year, the VLA draws tens of thousands of tourists from all 50 states and dozens of foreign countries, and also hosts field trips from numerous schools at all educational levels. The VLA is within a day's drive of at least eight metropolitan areas, on a high-use, well-maintained highway (U.S. 60) that also provides access to numerous regional scenic and recreational destinations. In 1998, more than 24,000 visitors signed an unattended guest book. Tourism experts contend that the actual number of visitors, including those who do not sign the book, may be as much as three times higher. The VLA Visitor Center may be already serving more than 70,000 tourists annually.

With its unique combination of global fame and ready accessibility, the EVLA can become one of the premier tools for utilizing the special inspiration of astronomy for promoting science and science education at all levels. We intend to exploit this potential by designing a new education and outreach program centered on new facilities and expanded programs. Recently, we have begun a project to acquire funds for the construction of a new Visitor Center (NVC) which would be an order of magnitude larger than the existing facility. We are approaching private and corporate sources, State and local governments, foundations and NSF divisions outside the Math & Physical Sciences directorate. As part of the EVLA proposal to the NSF we request funding to develop exhibits for the NVC, and to seed the new educational programs to be conducted at the VLA site.

The three main goals of this initiative are: (a) to make the VLA Visitor Center a cornerstone of science education and outreach in New Mexico and the Southwest; (b) to enable every child in New Mexico to explore the New Visitor Center at some stage of their schooling, particularly focusing on children who live in rural areas and/or reservations, outside the urban centers where educational advantages are concentrated; and (c) to produce a dynamic facility capable of showcasing the new and exciting science results from the EVLA as they occur.

To design the new facilities and programs, and to measure the impact and effectiveness of our new education and outreach programs, we will assemble an advisory committee including NRAO personnel and outside experts in educational methodology, K–12 curriculum, museum and science-center exhibit development and educational evaluation. This committee will report to the VLA Director on a regular basis.

7.2 A New Visitor Center

The current VLA Visitor Center, constructed in 1983, is the centerpiece of our educational and public-outreach efforts. It is small – only 1,500 square feet – and the present suite of displays is dated and does not adequately address visitors' misconceptions about radio astronomy or reflect the dramatic astronomical discoveries of the past decade. The last significant upgrade to the Visitor Center's exhibits was in 1989. Like the VLA itself, the Visitor Center and its exhibits have fallen behind the state-of-the-art in content and educational methodology.

The size of the existing visitor center building limits its utility for the expanded educational facilities we plan. Accordingly, we have begun to identify the requirements for a larger facility, a New Visitor Center (NVC), including:

- a 5000–10000 sq.ft. exhibit space for astronomy/radio astronomy/engineering displays, including hands-on exhibits and a ∼10–person slide/video viewing area,
- an education space (including a configurable classroom with lab desk and a teacher library/resource area),
- a ∼150-person auditorium for lectures and video presentations,
- a gift shop and small cafeteria,
- a small observatory area for amateur astronomy/star parties,
- infrastructure space (offices, lobby, bathrooms, etc.), and
- adequate (and visible) RFI-shielding.

The Albuquerque architectural firm Stevens, Mallory, Pearl & Campbell are graciously donating time to help the NRAO develop a conceptual design for the NVC, including an overall concept, floor plan, site plan and first-order cost estimate. Initial estimates of the floor space required to meet our requirements suggest a building of greater than 15000 sq.ft., i.e. an order of magnitude larger than the existing facility. A building of this scale will cost \$3–5 M. At present we are refining the conceptual design to provide an accurate cost estimate for the building, which will then be used as the target for the funding effort beginning summer 2000. It is important to note here that no NSF funds are being requested to build the NVC; all construction funds are being sought from external sources.

The NVC will be the origin for a set of walking trails leading to (a) the center of the VLA, (b) a nearby pad occupied in every VLA configuration, (c) the VLA Cafeteria and Control Room, and (d) the Antenna Assembly building. As part of this project we hope to re-open the VLA Cafeteria to provide lunches for K–12 classes visiting the site, general visitors and NRAO staff.

Based on estimates received from colleagues at other major visitor centers and science museums throughout the Southwest, we believe that a small entrance fee in combination with revenues from a large, well-stocked gift shop will make the NVC self-supporting, assuming a staff of four to six tour guides, educators and assistants. We are already engaged in collaborative efforts with the other institutions in the Southwestern Consortium of Observatories for Public Education (SCOPE), and will continue to draw upon their experience in maintaining self-supporting outreach efforts.

7.2.1 New Displays and Enhanced Content

Since the VLA Visitor Center opened, there has been a revolution in approaches to science education and outreach programs. Today's exhibits at places such as Arecibo Observatory's new visitor center, Lowell Observatory, or the Adler Planetarium, are interactive, inquiry-based learning experiences that engage visitors of all ages. They use proven methodology to effectively stimulate the visitor to build new understanding on the basis of their everyday experience.

We will design displays for the NVC that will incorporate the best techniques and methods for making the visitors' educational experience effective and enjoyable. This will mean first determining the specific, "take-home" messages we wish to convey, then in consultation with our advisory committee, producing effective display hardware and software. These "take-home" messages will emphasize the science done by the EVLA as well as the instrument itself. We feel that a strong unifying theme can be built around the concept of non-optical imaging. Since we know that radio observations are, to the public, one of the most poorly-understood aspects of astronomy, emphasizing non-optical imaging can not only show its value to astronomy but also to other disciplines such as medicine and engineering that may be more familiar to visitors. This theme has numerous connections to formal curricula at the pre-college and college level in addition to its value to informal science education. This theme would be augmented by exhibits and programs on basic astronomy and current research at the VLA and VLBA.

Our new exhibits will include digital audio-visual displays and a wide variety of interactive displays that will be prototyped and tested to ensure that they convey their intended messages. Particular care will be taken to address visitors' common misconceptions about radio astronomy and to build new concepts upon their existing everyday knowledge.

The NVC will be carefully radio-frequency-interference–shielded to avoid interference with the VLA. Some of this shielding will be highly-visible, and a number of displays will explore the effects of RFI on a precious natural resource – the radio spectrum.

We will work with other observatories and science centers to expand the audience for our educational efforts. Such cooperative ventures will include producing both permanent and traveling displays for other facilities, showing traveling displays from other facilities, joint design and production of educational materials, cross-links among Web sites, and multi-observatory tour programs for groups visiting the Southwest.

The \$0.5 M funding requested for Education and Public Outreach (EPO) in this proposal will be used to design and develop the themes to be presented in the NVC, test them with focus groups, and prototype some representative displays. The information gained from these efforts will be used to produce an overall design for the suite of exhibits. During this process we will involve educators, museum specialists, exhibit developers and independent evaluators to review and guide our efforts. Our partners in the SCOPE collaboration will provide much of this expertise.

7.2.2 New Educational Programs

Schools and universities in the Southwest also have made the VLA a popular location for field trips. Elementary and secondary schools from New Mexico and surrounding states bring their classes to show them this famous research facility. In addition, we regularly host college classes in astronomy, physics, engineering and other disciplines. Both the research programs and the technical complexity of the instrument itself provide exciting, real-world links that can help enrich the classroom curriculum.

Across the nation, observatory visitor centers and science museums increasingly are the focus of active educational programs that utilize the hands-on aspects of displays as well as recent research results to enhance the excitement, appeal and effectiveness of both informal and formal science education. We intend to develop such programs to increase the use of the EVLA in such efforts.

Such efforts will include:

- Regular guided tours for the general public,
- Expanded tour program for schools,
- Curriculum materials and lesson plans developed around the science of the EVLA and the Visitor Center displays,
- Web-based educational programs, such as virtual tours of the EVLA and interactive exercises built around EVLA data,
- Teacher workshops.

Such programs will require adding staff members. Other observatories operate such programs and we can learn from their experience as we expand into these areas. One particular area we plan to expand is guided tours; while the public demand for guided tours of the VLA is high, we presently have only a limited ability to meet this demand.

In 2000 we plan to add an education officer to the VLA site, who will expand our guided-tour program, and more importantly begin to make connections with the New Mexico education scene. We have adopted as a goal for the NVC and its programs that every child in New Mexico, during the course of his/her education, would visit the NVC and take part in one of the educational programs.

7.2.3 Supporting the New Educational Facilities and Programs

Buildings and displays must be maintained and regularly updated, and the staff to run the new programs must be supported. To do this, we will operate a retail store at the NVC and charge for some of the new educational services.

A retail store not only provides revenue but also can serve as a means of extending the reach of the educational programs. As at other observatories, the store will sell books and educational materials related to astronomy and science, in addition to tourist souvenirs. Taken home by a tourist or student, the books and materials sold in the store can reinforce, over the long term, the educational experience of the visit to the EVLA. Based on sales figures from other observatories in the Southwest, a store can provide sufficient revenue to support the educational program.

In addition, nominal fees for guided tours and other services will support the educational and outreach staff required to provide those services. This is also a practice parallel to that at some other observatories. The NVC, state-of-the-art interactive exhibits, and expanded educational programs will provide an improved learning experience for students and the public that will well justify the fees charged. With a modest effort at advertising and marketing the NVC and its services, revenues can be expected to grow.

7.2.4 Integration with the NRAO EPO Effort

The construction of a NVC and implementation of new programs as part of the EVLA project takes place at a time when NRAO is expanding its EPO effort across all of its sites. In particular, at the NRAO Green Bank site we are in the process of developing exhibits and constructing a new Science Education Center. EPO staff in New Mexico and Charlottesville are closely following that effort as relevant experience for our NVC plans. Over the next few years NRAO plans to develop standard programs and products in support of its EPO efforts which could be used and expanded by the visitor centers at our sites. This experience will also serve when a visitor center and education programs are required for ALMA.

7.3 Summary

As the VLA, with its technology of the 1970s, is behind in its ability to produce the quality and amount of science that modern technology would enable, the educational and public outreach facilities and programs are also behind in their capabilities to use the appeal of a world-class scientific instrument to enhance scientific literacy. As the Expanded Very Large Array brings the VLA back to the forefront, we will also bring our educational efforts into a new era of excitement and effectiveness, with a New Visitor Center and expanded educational and outreach programs at the VLA site.

This educational and public outreach plan will produce a facility and a program that is not unusual in size for major observatories and science centers in the region. It will allow the NRAO to fully exploit the public appeal of the EVLA to fulfill our mission to help produce a scientifically literate society.

Chapter 8

Schedule and Budget

8.1 Ultrasensitive Array Implementation Schedule

Implementation of the Ultrasensitive Array is currently planned to proceed in two stages. Stage One will last seven years, from CY2001 to 2007, during which the new correlator, the LO and IF systems (both in the antennas and in the Control Building), and the linking fiber optic systems will all be installed. Much of the software development will take place during this time.

Stage Two will last six years, CY2004 to 2009, overlapping the first stage. During this stage, all of the new wideband receivers will be fabricated and installed, with the exception of the 22 GHz and 45 GHz receivers which are currently underway and should be finished in Stage One. The exact start of the Stage Two work will be determined by the available funding. If this work could begin earlier, there would cost savings by shortening the overall length of the project.

Stage One will begin with a two-year Design and Development phase to prototype and debug the new equipment and to begin the quantity production of the electronics modules. The development of the control software and the Monitor and Control system and the installation of the fiber optic cable will be emphasized during the early years. This will ensure that these systems will be ready in some form when the first of the upgraded antennas are released for operation.

After the first two years, the time scale for the project will be set by the need to move antennas through the Antenna Assembly Building for overhaul. The required tasks include:

- New feed cone installation and vertex room rebuild,
- Normal preventive maintenance and retrofits,
- Azimuth bearing replacements (approximately one out of every six antennas), and
- Installation of new antenna electronics.

Allowing five antennas to have an 8-week overhaul and one antenna to have a 12-week overhaul (for the azimuth bearing replacement), work on six antennas can be completed per year. This will be a tight schedule and may involve working two shifts per day. With 28 antennas, and adding a few months for startup and cleanup, this part of stage one will take five years. During that time there will be typically one to three antennas out of the observing array for retrofits and evaluation.

A fundamental requirement is that the VLA should continue to function as a user instrument while the enhancements are introduced. The impact of this on cost and schedule will require a detailed transition plan.

The current plan for the VLA Expansion Project correlator will utilize a design being developed at the DRAO in Canada, with Canadian funds covering the cost of the correlator and associated equipment. Implementation of this plan will require a formal agreement between the NRAO and the HIA. Negotiations towards this goal are ongoing.

The alternate plan for the correlator would utilize a design based on the ALMA correlator design. This has the advantage of cost savings in chip design. There may also be cost savings resulting from quantity purchases, production efficiency, and shared debugging tasks. The large quantity chip purchase for the ALMA correlator is scheduled to occur in mid 2002, and the first quadrant of the correlator is scheduled for delivery in mid 2004. The final quadrant would be delivered in late 2006. A similar schedule would be followed for the VLA Expansion Project correlator.

In stage two, four new cryogenic receivers, for the 3, 6, 15, and 33 GHz bands, will be added to the array. The existing 1.5 and 8 GHz receivers will be modified and upgraded. The 22 GHz receiver installation, which is currently underway and 55% complete, and 45 GHz receiver installation, which is currently underway and 85% complete, should be finished in stage one.

A total of 180 cryogenic receivers will need to be fabricated or rebuilt. If design and prototyping can be done in the first years of stage two, we will need to fabricate about 30 cryogenic receivers per year. This will require a three-fold increase in the production rate of a normal VLA receiver retrofit program, where 9 to 12 receivers are built each year. About 800 new LO/IF/FO modules will have to be built.

A draft schedule for the project running from 2001 through 2009 is shown in Table 8.1. This assumes that the prototyping phase begins in 2001. The major tasks are listed together with an estimate of the duration of those tasks. Milestones, a detailed task list, and the task dependencies will be established as part of the design phase.

Since the normal VLA and VLBA maintenance and upkeep must be continued throughout EVLA Project, about 40 people will be temporarily added to the NRAO staff for that period.

8.1.1 Transition Plan

A key goal for the implementation of the Ultrasensitive Array is to impact as little as possible the scientific viability of the VLA. However, it must be recognized that this is a major project, and some, perhaps significant disruption of observing efficiency will likely take place. Always, the goal will be to make these disruptions of as short a duration as possible. A detailed and flexible transition plan is being prepared at this time.

8.2 Project Cost and Funding

8.2.1 Budget

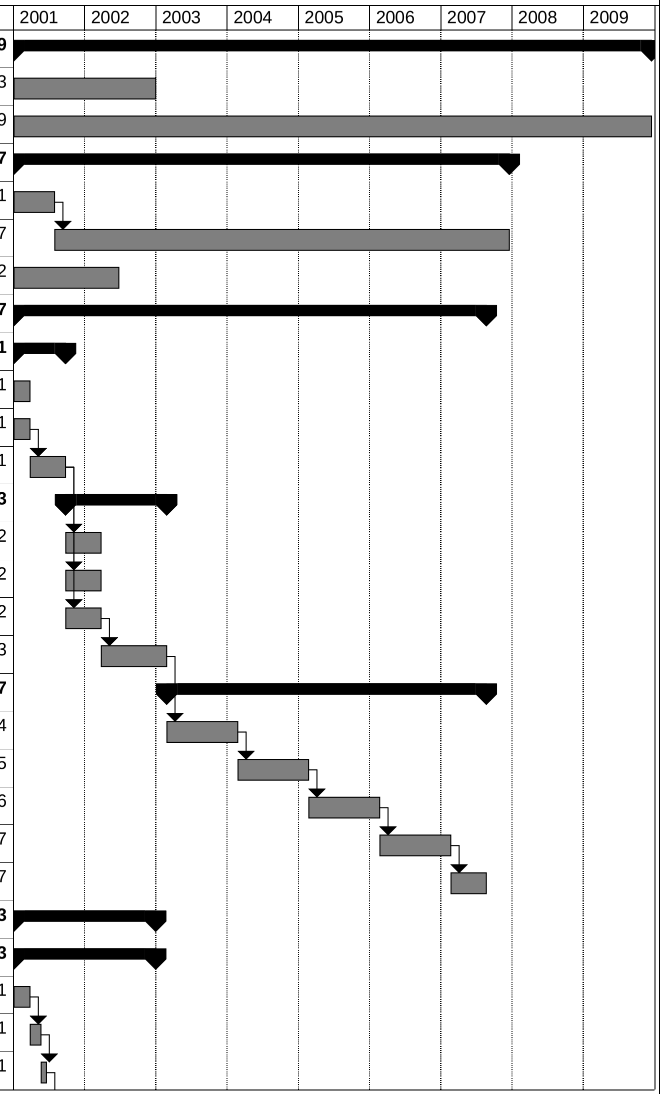
An estimated budget for the Ultrasensitive Array is given in Table 8.2, with the first column corresponding to the work breakdown structure (WBS) categories presented with the schedule. The costs include materials, services, contracts, travel, wages and benefits. The total project cost for the Ultrasensitive Array is given in the last column. Budgets are shown separately for Stage One, Stage Two, and the sum of both phases.

Table 8.3 shows anticipated funding for the project. This includes both future NSF funding and external funding. In addition, progress towards some of the goals of the Ultrasensitive Array project has already been accomplished. For example, a grant from the Mexican CONACyT funded thirteen 43 GHz receivers for the VLA while an NSF-MRI grant, in conjunction with the MPIfR, funded twelve additional receivers. This previous external funding plus previous NRAO Research

Table 8.1: A draft schedule for implementation of Phase I of the VLA Expansion Project.

NRAO VLA Expansion Project

ID	WBS	Task Name	Duration	Start	Finish
1	**1**	**Project Management**	**467 wks**	**Thu 01/04/01**	**Wed 12/16/09**
2	1.1	Purchase Test/Lab Equipment	104 wks	Thu 01/04/01	Wed 01/01/03
3	1.2	Project management	467 wks	Thu 01/04/01	Wed 12/16/09
4	**1.3**	**External Production**	**363 wks**	**Thu 01/04/01**	**Wed 12/19/07**
5	1.3.1	Production Plan	30 wks	Thu 01/04/01	Wed 08/01/01
6	1.3.2	Manage Contracts	333 wks	Thu 08/02/01	Wed 12/19/07
7	1.3.3	Purchase Production test equipment	77 wks	Thu 01/04/01	Wed 06/26/02
8	**2**	**System Integration and Testing**	**346 wks**	**Thu 01/04/01**	**Wed 08/22/07**
9	**2.1**	**System Design and Interfaces**	**38 wks**	**Thu 01/04/01**	**Wed 09/26/01**
10	2.1.1	Interface Specifications	12 wks	Thu 01/04/01	Wed 03/28/01
11	2.1.2	Performance Specifications	12 wks	Thu 01/04/01	Wed 03/28/01
12	2.1.3	System Level Design	26 wks	Thu 03/29/01	Wed 09/26/01
13	**2.2**	**System Prototype**	**74 wks**	**Thu 09/27/01**	**Wed 02/26/03**
14	2.2.1	Power supply modules	26 wks	Thu 09/27/01	Wed 03/27/02
15	2.2.2	A rack	26 wks	Thu 09/27/01	Wed 03/27/02
16	2.2.3	B rack	26 wks	Thu 09/27/01	Wed 03/27/02
17	2.2.4	System test	48 wks	Thu 03/28/02	Wed 02/26/03
18	**2.3**	**Installation and commissioning**	**234 wks**	**Thu 02/27/03**	**Wed 08/22/07**
19	2.3.1	#2 - #7	52 wks	Thu 02/27/03	Wed 02/25/04
20	2.3.2	#8 - #13	52 wks	Thu 02/26/04	Wed 02/23/05
21	2.3.3	#14 - #19	52 wks	Thu 02/24/05	Wed 02/22/06
22	2.3.4	#20 - #25	52 wks	Thu 02/23/06	Wed 02/21/07
23	2.3.5	#26 - #28	26 wks	Thu 02/22/07	Wed 08/22/07
24	**3**	**Civil Construction**	**104 wks**	**Thu 01/04/01**	**Wed 01/01/03**
25	**3.1**	**FO Cable**	**104 wks**	**Thu 01/04/01**	**Wed 01/01/03**
26	3.1.1	Cable system design	12 wks	Thu 01/04/01	Wed 03/28/01
27	3.1.2	Order cable, materials	8 wks	Thu 03/29/01	Wed 05/23/01
28	3.1.3	Construct splice stations	4 wks	Thu 05/24/01	Wed 06/20/01



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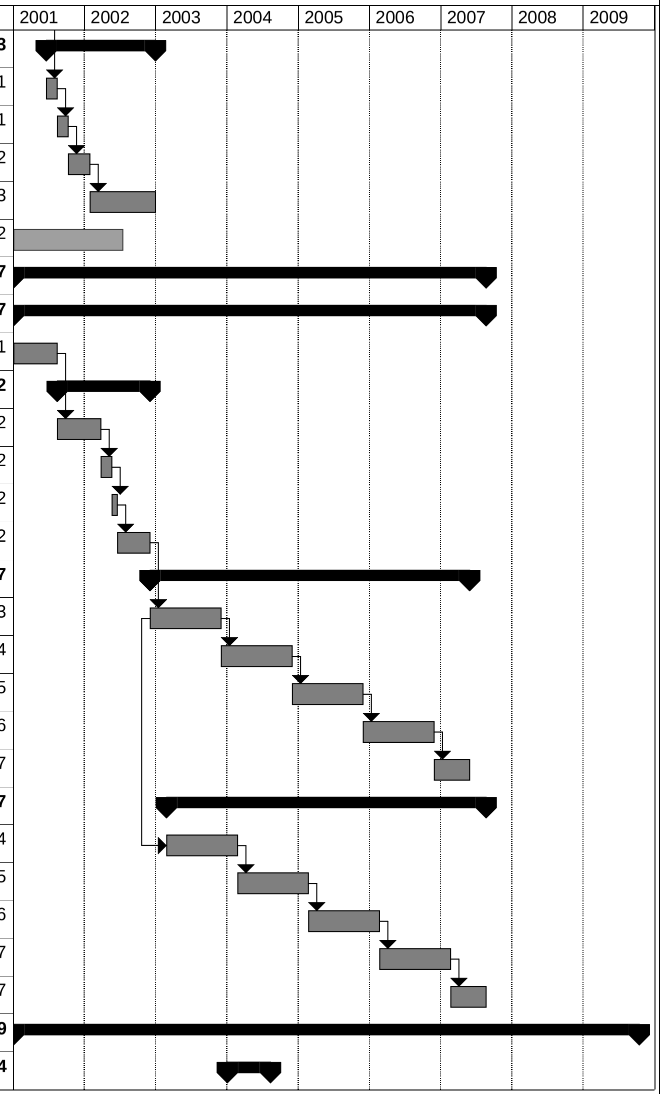
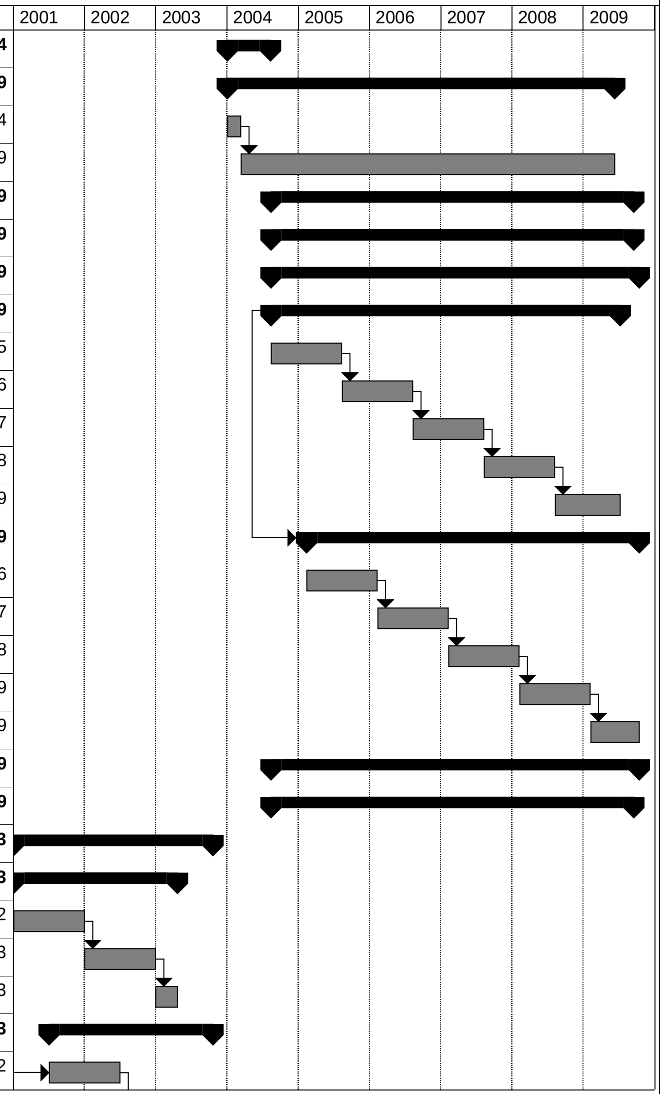
NRAO VLA Expansion Project

ID	WBS	Task Name	Duration	Start	Finish
29	**3.1.4**	**Install cable**	**80 wks**	**Thu 06/21/01**	**Wed 01/01/03**
30	3.1.4.1	Center => D	8 wks	Thu 06/21/01	Wed 08/15/01
31	3.1.4.2	D => C	8 wks	Thu 08/16/01	Wed 10/10/01
32	3.1.4.3	C => B	16 wks	Thu 10/11/01	Wed 01/30/02
33	3.1.4.4	B => A	48 wks	Thu 01/31/02	Wed 01/01/03
34	3.2	Wye Comm cable	80 wks	Thu 01/04/01	Wed 07/17/02
35	**4**	**Antenna, Mechanical**	**346 wks**	**Thu 01/04/01**	**Wed 08/22/07**
36	**4.1**	**Feed Cone**	**346 wks**	**Thu 01/04/01**	**Wed 08/22/07**
37	4.1.1	Design	32 wks	Thu 01/04/01	Wed 08/15/01
38	**4.1.2**	**Prototype**	**68 wks**	**Thu 08/16/01**	**Wed 12/04/02**
39	4.1.2.1	Fabricate	32 wks	Thu 08/16/01	Wed 03/27/02
40	4.1.2.2	Assemble mock-up	8 wks	Thu 03/28/02	Wed 05/22/02
41	4.1.2.3	Install on test antenna	4 wks	Thu 05/23/02	Wed 06/19/02
42	4.1.2.4	Evaluate RF performance	24 wks	Thu 06/20/02	Wed 12/04/02
43	**4.1.3**	**Fabricate**	**234 wks**	**Thu 12/05/02**	**Wed 05/30/07**
44	4.1.3.1	#2 - #7	52 wks	Thu 12/05/02	Wed 12/03/03
45	4.1.3.2	#8 - #13	52 wks	Thu 12/04/03	Wed 12/01/04
46	4.1.3.3	#14 - #19	52 wks	Thu 12/02/04	Wed 11/30/05
47	4.1.3.4	#20 - #25	52 wks	Thu 12/01/05	Wed 11/29/06
48	4.1.3.5	#26 - #28	26 wks	Thu 11/30/06	Wed 05/30/07
49	**4.1.4**	**Installation**	**234 wks**	**Thu 02/27/03**	**Wed 08/22/07**
50	4.1.4.1	#2 - #7	52 wks	Thu 02/27/03	Wed 02/25/04
51	4.1.4.2	#8 - #13	52 wks	Thu 02/26/04	Wed 02/23/05
52	4.1.4.3	#14 - #19	52 wks	Thu 02/24/05	Wed 02/22/06
53	4.1.4.4	#20 - #25	52 wks	Thu 02/23/06	Wed 02/21/07
54	4.1.4.5	#26 - #28	26 wks	Thu 02/22/07	Wed 08/22/07
55	**5**	**Cassegrain Receivers**	**458.4 wks**	**Thu 01/04/01**	**Fri 10/16/09**
56	**5.1**	**Rcvr Prototype**	**32 wks**	**Mon 01/05/04**	**Fri 08/13/04**



NRAO VLA Expansion Project

ID	WBS	Task Name	Duration	Start	Finish
81	**5.2**	**Feed Prototype**	**32 wks**	**Mon 01/05/04**	**Fri 08/13/04**
106	**5.3**	**Cryogenics**	**284 wks**	**Mon 01/05/04**	**Fri 06/12/09**
107	5.3.1	System analysis	10 wks	Mon 01/05/04	Fri 03/12/04
108	5.3.2	Procure and install	274 wks	Mon 03/15/04	Fri 06/12/09
109	**5.4**	**L-band**	**266 wks**	**Mon 08/16/04**	**Fri 09/18/09**
122	**5.5**	**S-band**	**266 wks**	**Mon 08/16/04**	**Fri 09/18/09**
135	**5.6**	**C-band**	**270 wks**	**Mon 08/16/04**	**Fri 10/16/09**
136	**5.6.1**	**fabricate**	**256 wks**	**Mon 08/16/04**	**Fri 07/10/09**
137	5.6.1.1	#2 - #7	52 wks	Mon 08/16/04	Fri 08/12/05
138	5.6.1.2	#8 - #13	52 wks	Mon 08/15/05	Fri 08/11/06
139	5.6.1.3	#14 - #19	52 wks	Mon 08/14/06	Fri 08/10/07
140	5.6.1.4	#20 - #25	52 wks	Mon 08/13/07	Fri 08/08/08
141	5.6.1.5	#26 - #30	48 wks	Mon 08/11/08	Fri 07/10/09
142	**5.6.2**	**install**	**244 wks**	**Mon 02/14/05**	**Fri 10/16/09**
143	5.6.2.1	#2 - #7	52 wks	Mon 02/14/05	Fri 02/10/06
144	5.6.2.2	#8 - #13	52 wks	Mon 02/13/06	Fri 02/09/07
145	5.6.2.3	#14 - #19	52 wks	Mon 02/12/07	Fri 02/08/08
146	5.6.2.4	#20 - #25	52 wks	Mon 02/11/08	Fri 02/06/09
147	5.6.2.5	#26 - #28	36 wks	Mon 02/09/09	Fri 10/16/09
148	**5.7**	**X-band**	**270 wks**	**Mon 08/16/04**	**Fri 10/16/09**
161	**5.8**	**Ku-band**	**266 wks**	**Mon 08/16/04**	**Fri 09/18/09**
174	**5.9**	**K-band**	**146 wks**	**Thu 01/04/01**	**Wed 10/22/03**
175	**5.9.1**	**fabricate**	**120 wks**	**Thu 01/04/01**	**Wed 04/23/03**
176	5.9.1.1	#17 - #22	52 wks	Thu 01/04/01	Wed 01/02/02
177	5.9.1.2	#23 - #28	52 wks	Thu 01/03/02	Wed 01/01/03
178	5.9.1.3	#29 - #30	16 wks	Thu 01/02/03	Wed 04/23/03
179	**5.9.2**	**install**	**120 wks**	**Thu 07/05/01**	**Wed 10/22/03**
180	5.9.2.1	#17 - #22	52 wks	Thu 07/05/01	Wed 07/03/02



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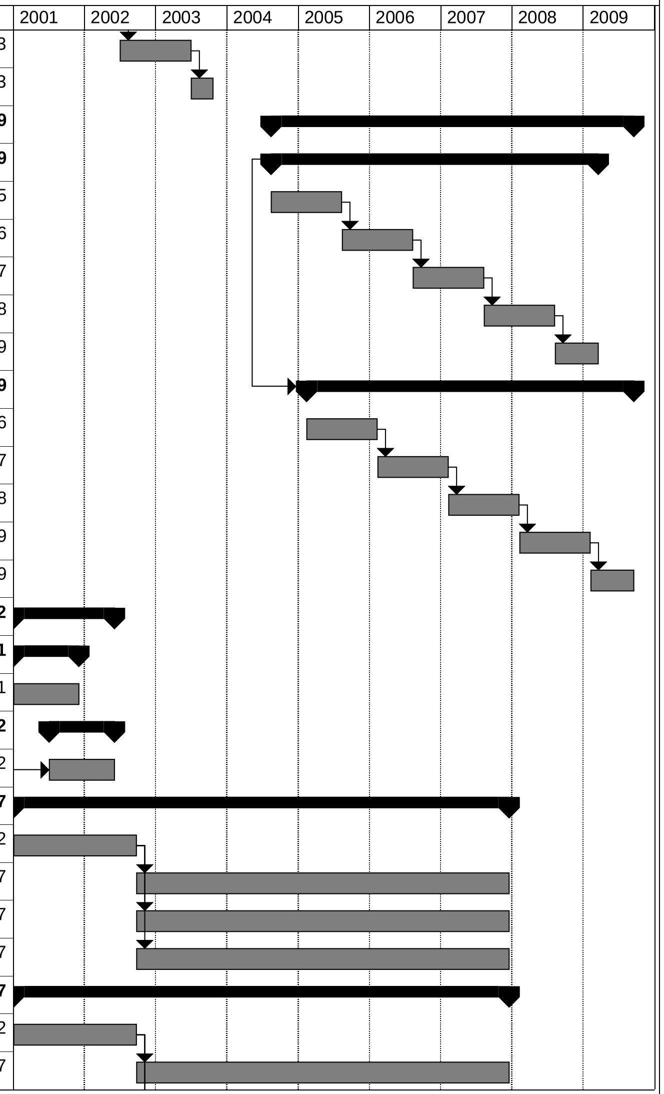
NRAO

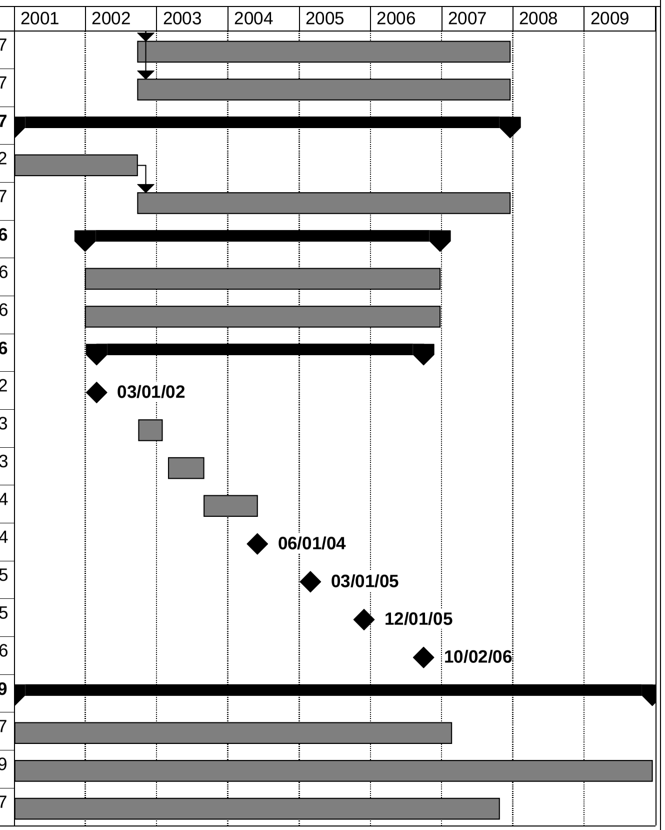
VLA Expansion Project

ID	WBS	Task Name	Duration	Start	Finish
181	5.9.2.2	#23 - #28	52 wks	Thu 07/04/02	Wed 07/02/03
182	5.9.2.3	#29 - #30	16 wks	Thu 07/03/03	Wed 10/22/03
183	**5.10**	**Ka-band**	**266 wks**	**Mon 08/16/04**	**Fri 09/18/09**
184	**5.10.1**	**fabricate**	**240 wks**	**Mon 08/16/04**	**Fri 03/20/09**
185	5.10.1.1	#2 - #7	52 wks	Mon 08/16/04	Fri 08/12/05
186	5.10.1.2	#8 - #13	52 wks	Mon 08/15/05	Fri 08/11/06
187	5.10.1.3	#14 - #19	52 wks	Mon 08/14/06	Fri 08/10/07
188	5.10.1.4	#20 - #25	52 wks	Mon 08/13/07	Fri 08/08/08
189	5.10.1.5	#26 - #30	32 wks	Mon 08/11/08	Fri 03/20/09
190	**5.10.2**	**install**	**240 wks**	**Mon 02/14/05**	**Fri 09/18/09**
191	5.10.2.1	#2 - #7	52 wks	Mon 02/14/05	Fri 02/10/06
192	5.10.2.2	#8 - #13	52 wks	Mon 02/13/06	Fri 02/09/07
193	5.10.2.3	#14 - #19	52 wks	Mon 02/12/07	Fri 02/08/08
194	5.10.2.4	#20 - #25	52 wks	Mon 02/11/08	Fri 02/06/09
195	5.10.2.5	#26 - #30	32 wks	Mon 02/09/09	Fri 09/18/09
196	**5.11**	**Q-band**	**74 wks**	**Thu 01/04/01**	**Wed 06/05/02**
197	**5.11.1**	**fabricate**	**48 wks**	**Thu 01/04/01**	**Wed 12/05/01**
198	5.11.1.1	#26 - #30	48 wks	Thu 01/04/01	Wed 12/05/01
199	**5.11.2**	**install**	**48 wks**	**Thu 07/05/01**	**Wed 06/05/02**
200	5.11.2.1	#26 - #30	48 wks	Thu 07/05/01	Wed 06/05/02
201	**6**	**LO System**	**363 wks**	**Thu 01/04/01**	**Wed 12/19/07**
202	6.1	Design and Prototype	90 wks	Thu 01/04/01	Wed 09/25/02
203	6.2	LO Reference	273 wks	Thu 09/26/02	Wed 12/19/07
204	6.3	LO Distribution	273 wks	Thu 09/26/02	Wed 12/19/07
205	6.4	LO Phase Correction	273 wks	Thu 09/26/02	Wed 12/19/07
206	**7**	**FO System**	**363 wks**	**Thu 01/04/01**	**Wed 12/19/07**
207	7.1	Design and Prototype	90 wks	Thu 01/04/01	Wed 09/25/02
208	7.2	LO Transmission	273 wks	Thu 09/26/02	Wed 12/19/07



NRAO VLA Expansion Project

ID	WBS	Task Name	Duration	Start	Finish
209	7.3	IF Transmission	273 wks	Thu 09/26/02	Wed 12/19/07
210	7.4	M/C Transmission	273 wks	Thu 09/26/02	Wed 12/19/07
211	**8**	**IF System**	**363 wks**	**Thu 01/04/01**	**Wed 12/19/07**
212	8.1	Design and Prototype	90 wks	Thu 01/04/01	Wed 09/25/02
213	8.2	IF System Production	273 wks	Thu 09/26/02	Wed 12/19/07
214	**9**	**Correlator**	**260 wks**	**Tue 01/01/02**	**Mon 12/25/06**
215	9.1	Samplers production	260 wks	Tue 01/01/02	Mon 12/25/06
216	9.2	Digital Filter production	260 wks	Tue 01/01/02	Mon 12/25/06
217	**9.3**	**Correlator Production**	**239.2 wks**	**Fri 03/01/02**	**Mon 10/02/06**
218	9.3.1	Order Custom Chips	0 days	Fri 03/01/02	Fri 03/01/02
219	9.3.2	Order Parts 1st Quarter	89 days	Tue 10/01/02	Fri 01/31/03
220	9.3.3	Assemble 1st Quarter	131 days	Mon 03/03/03	Mon 09/01/03
221	9.3.4	Test 1st Quarter	197 days	Mon 09/01/03	Tue 06/01/04
222	9.3.5	Deliver 1st Quarter to VLA	0 days	Tue 06/01/04	Tue 06/01/04
223	9.3.6	Deliver 2nd Quarter to VLA	0 days	Tue 03/01/05	Tue 03/01/05
224	9.3.7	Deliver 3rd Quarter to VLA	0 days	Thu 12/01/05	Thu 12/01/05
225	9.3.8	Deliver 4th Quarter to VLA	0 days	Mon 10/02/06	Mon 10/02/06
226	**10**	**On-line Computing, Monitor - Control**	**467 wks**	**Thu 01/04/01**	**Wed 12/16/09**
227	10.1	Control Computer	320 wks	Thu 01/04/01	Wed 02/21/07
228	10.2	Software Development	467 wks	Thu 01/04/01	Wed 12/16/09
229	10.3	M/C System	355 wks	Thu 01/04/01	Wed 10/24/07



Equipment funds offsets the total cost of the project. Also, future contributions are expected from Canada and Mexico to help with this project. Finally, NRAO operational funds which would normally go towards incremental improvements and design changes to the VLA will be redirected in support of this project. The difference between the total cost of the project and these other sources of funding gives the amount of new funding requested from the NSF to support this project.

The personnel requirements for the overall project are shown in Table 8.4. The numbers listed are the work-years needed for each WBS level one activity for the nine year duration of the project. The redirected NRAO staff and the necessary new hires are listed separately. During the peak years, 2003 – 2007, sixty people will be working on the project at any time, with forty of them being new hires.

The approximate distribution of cost during the lifetime of the project is shown in Table 8.5. A matching funding profile is shown at the bottom of the Table. The actual distribution of the foreign contributions is uncertain at this time. Budgets are shown separately for Stage One, Stage Two, and the sum of both stages.

8.2.2 Budget Assumptions

Cost Estimation

The costs of the project elements are based on the design concept given in Chapter 5 and are generally made on a bottom-up basis. The lowest level functionally corresponds to a physical module in the existing VLA or a block in the system block diagram. Material and labor costs are estimated at the module level based on VLA and VLBA experience. For the more expensive modules, the costs are calculated based on the major components within the module.

The costs of receivers, feeds and cryogenics are based on similar VLA or VLBA items actually built. The cost of fiber optic cable is based on catalogue prices and estimated contractor costs per 1000 feet of installation.

The amount of the project construction that will be contracted out and the amount that will be done by the NRAO staff is not yet decided in detail. However, for the purpose of this cost estimate, the following assumptions are made:

- Fabrication of sub-modules, cables, wiring harnesses, PC boards (including mounting chips and components), and much of the machine shop work will be contracted out.
- Final assembly, tuning, and testing of modules will be done by the NRAO staff.
- Back-plane wiring and final testing of bins and racks will be done by the NRAO staff.
- Underground fiber optic cable installation will be contracted out. Fiber installation within the antenna and terminations of fibers will be done by NRAO.
- Feed cone fabrication will be contracted; feed cone installation on the antennas will be done by NRAO.

Other assumptions made in constructing the budget and schedule are:

- Major purchases will be done in late 2002. Approximately 20% of the hardware will be assembled, tested, and delivered each year from early 2003 through 2007.
- Most modules will be built in multiples of 30. This provides for 10% spares with 27 antennas in the observing array.
- All costs are in CY 2000 dollars. Benefits are taken as 29% of wages.

- The contingency of 15% is calculated on the total cost of the project less tasks already completed. The contingency rate is an average for all WBS Level 1 tasks of the project.
- The AUI management fee of 2% is only applied to the new funds requested from the NSF.
- The wages and work-years are based on summing individual staff members joining and leaving the project as needed. Wages are assigned in three categories corresponding to median wages for 1) technician, 2) technical specialist and 3) engineer or programmer.
- The correlator, the correlator control computers and basic software, the samplers and the FIR filters (WBS 9) could make use of much of the design done for the ALMA project. Only minimal funds for additional hardware or software design are budgeted here. If the Canadian design is chosen, it will be fully funded by the Canadian side.

Funding Assumptions

A basic assumption of the funding plan is that approximately 20 existing NRAO employees will be redirected from current VLA tasks to work on the VLA Expansion Project. This will only be possible if funding for the VLA operation is at a sufficient level for these people to be made available. If general NRAO funding were to be inadequate for continuing operation, this part of the funding plan for the VLA Expansion would be in jeopardy.

While the VLA Expansion Project is underway, much of the maintenance of the array will have to continue. Major ongoing maintenance activities include rail system repair, antenna painting and other infrastructure maintenance. If general mechanical and electrical systems and buildings are not maintained over the several years of the project, when the project is completed there will be an enormous expense of deferred maintenance that will need to be met before the array could be brought into full operation. Since the project plan calls for continuing to operate the VLA as a user instrument during the project duration, maintenance cannot be postponed. One of the fundamental assumptions of the plan is that funding for annual maintenance will continue at an adequate level.

Of the twenty employees that will be redirected to the VLA Expansion Project, a quarter of these are from the scientific staff whose current activity includes testing, evaluating, and characterizing the VLA as it is now, and planning and designing new systems. Work on the VLA Expansion Project is a natural continuation of this activity.

Another quarter of the redirected staff are programmers who are currently maintaining and upgrading the existing software system. Again, work on the VLA Expansion Project is a natural continuation of this activity. The same can be said for the third quarter who are in the Electronics Division, currently building new receivers and upgrading existing modules. Some of this effort will cease as the old system is declared obsolete. The receiver builders will just continue on with the new round of receiver systems. The final quarter are largely management staff whose primary focus will shift to building the new system.

In all of these groups, as attention shifts to the new instrumentation, there will be some loss of effort directed to the older system. Improvements to hardware and software of the old system will not be made. This is part of a temporary loss of performance expected in the VLA as the transition to the new instrument is made. A goal of the project is to minimize this loss of performance while maintaining the project on schedule and on budget.

Another funding assumption is that once begun, the project funding would continue at an adequate pace for the duration. If the project were to stop during the transition, the VLA might be left in a half finished state with even less capability than it had before the VLA Expansion Project began. Slowing down and then ramping up at a later date would certainly raise the project cost.

Project Assumptions

It is assumed that the Civil Construction (WBS 3) will be concentrated in the first two years. In particular, the fiber optic infrastructure would be installed by contract, preparing the way for later equipment installation. Similarly, the Monitor and Control hardware will need to be in place early so that as the first antennas become available with the new electronics systems, they will be able to be operated and rapidly join the working array. This in turn requires that the software development be initiated early in the project.

Table 8.2: **VLA Expansion Project: Costs**

Table 8.2 Budget VLA Expansion Project: Costs

CY2000 $k

		Stage 1				Stage 2				Stage 1 + Stage 2		
		Cost M&S	Subtotal M&S	Wages & Benefits	**Subtotal**	Cost M&S	Subtotal M&S	Wages & Benefits	**Subtotal**	Subtotal M&S	Wages & Benefits	**Subtotal**
WBS		($k)	($k)	($k)	($k)	($k)	($k)	($k)	($k)	($k)	($k)	($k)
1	**Project Management**											
	Management, planning	420				120						
	Office Equipment & Supplies	210				60						
	Advisory Comm support	210				60						
	Staff Travel & Relocation	980				240						
			1820	2260	4080		480	570	1050	2300	2830	5130
2	**System Integration & Testing**											
	Lab and Test Equipment	650										
	Other M&S	100										
			750	3840	4590		0	1100	1100	750	4940	5690
3	**Civil Construction**											
	FO cable installation	1440										
	Correlator room, chillers	200										
			1640	400	2040		0	0	0	1640	400	2040
4	**Antenna Mechanical**											
	Feed cones	1060										
	Other M&S					170						
			1060	1330	2390		170	120	290	1230	1450	2680
5	**Cassegrain Receivers**											
	Receivers and cryogenic compressors	3280				5100						
	Feeds	20				1300						
			3300	1290	4590		6400	3680	10080	9700	4970	14670
6	**Local Oscillator System**											
	Hydrogen maser	320										
	Synthesizers, 10 - 40 GHz	1590										
	Other synthesizer and PLO	940										
	Round-trip phase measurement system	470										
	Other M&S	800										
			4120	2320	6440		0	0	0	4120	2320	6440

Table 8.2: continued

		Stage 1				Stage 2				Stage 1 + Stage 2		
		Cost M&S	Subtotal M&S	Wages & Benefits	**Subtotal**	Cost M&S	Subtotal M&S	Wages & Benefits	**Subtotal**	Subtotal M&S	Wages & Benefits	**Subtotal**
7	**Fiber Optic System**											
	Wideband IF transmission system	1880										
	Narrowband IF, M/C, LO transmission sys	1080										
	FO ant cable, connectors and splice plates	180										
	Other M&S	320										
			3460	1340	4800		0	0	0	3460	1340	4800
8	**IF System**											
	Filter modules	1010										
	IF converters / band switches	1180										
	Other M&S	780										
			2970	2050	5020		0	0	0	2970	2050	5020
9	**Correlator / FIR Filter**											
	Samplers	430										
	Correlator	6000										
	FIR filter	850										
	Other M&S	260										
			7540	2540	10080		0	0	0	7540	2540	10080
10	**Computing / Monitor-Control**											
	Computing Hardware	750				0						
	Networking	600				700						
	Archiving	1100				0						
	Other M&S	390				50						
			2840	4030	6870		750	1130	1880	3590	5160	8750
11	**Education / Public Outreach**											
	Visitor Center M&S					500	500		500	500	0	500
	Subtotal		**$29,500**	**$21,400**	**$50,900**		**$8,300**	**$6,600**	**$14,900**	**$37,800**	**$28,000**	**$65,800**
	Contingency (15%)				$7,290				$2,130			$9,420
	AUI Management Fee (2%)				$710				$270			$980
	Total Project Cost				**$58,900**				**$17,300**			**$76,200**

Table 8.3: **VLA Expansion Project: Funding**

Table 8.3 Budget VLA Expansion Project: Funding
CY2000 $k

Source	Stage 1 Funds		Stage 1 Total	Stage 2 Total	Stage 1 + Stage 2 Total
Tasks Funded before 2001			$3,100		$3,100
43 GHz Receiver		2020			
MRI - NSF	440				
MRI - MPIfRA	280				
UNAM - Mexico	1010				
NRAO Operations	290				
23 GHz Receiver		1080			
NRAO Operations	310				
NRAO RE	770				
NSF, Redirected NRAO Operations			$7,800	$3,400	$11,200
Canada			$10,000		$10,000
Mexico			$2,000		$2,000
New NSF Project Funding			**$36,000**	**$13,900**	**$49,900**
Total Project Funding			**$58,900**	**$17,300**	**$76,200**

Table 8.4: **Personnel Requirements for the Ultrasensitive Array CY 2001 through 2009**

WBS	Category	Redirected NRAO Work-Years	New Hires Work-Years	Total Work-Years
1	**Project Management**			
	Project Manager & Project Scientist	9	9	18
	Documentation/Drafting	9		9
	Administrative Asst.		9	9
	Purchasing, buyer		8	8
2	**System Integration & Testing**			
	System engineer	9		9
	System technician		7	7
	Scientific Services	45		45
3	**Civil Construction**			
	Correlator room and chiller			
	Engineer		1	1
	Technician		4	4
	Fiber optic installation, contract supervision			
	Engineer		1	1
	Technician		2	2
4	**Antenna Mechanical**			
	Feed cone			
	Mechanical engineer/supervisor	1		1
	Antenna mechanics, HVAC, etc.	6	23	29
	Cryogenic plumbing		3	3
	Antenna vertex room, antenna rack rebuild			
	Engineer	1		1
	Mechanic	1		1
5	**Cassegrain Receivers**			
	Receiver engineer/supervisor	7		7
	Feed engineer	4		4
	Technical Specialists, testing, quality assurance	6	9	15
	Technicians, assembly/lab tech	6	9	15
	Technicians, low noise amplifier		15	15
	Shop technicians, machine shop		17	17
	Antenna mechanics, receiver installation, outfitting and alignment		13	13
6	**Local Oscillator System**			
	LO engineer/supervisor		7	7
	Technical Specialist, module production testing		7	7
	Technicians, module assembly / lab tech		17	17
	Tech Specs/Eng subsystem assemble & test		11	11
7	**Fiber Optic System**			
	FO engineer/supervisor		7	7
	Technical Specialist, prototype, FO splice, test		7	7
	Technicians, module assembly / lab tech		9	9
8	**IF System**			
	IF engineer/supervisor		7	7
	Technical Specialist, module production testing	7		7
	Technicians, module assembly / lab tech		10	10
	Tech Specs/Eng subsystem assemble & test		11	11

Table Continued on Next Page

Table 8.4 (continued)

WBS	Category	Redirected NRAO (Work-Years)	New Hires (Work-Years)	Total (Work-Years)
9	**Correlator / FIR Filter**			
	Correlator engineer / supervisor		7	7
	Engineer / technicians, samplers		8	8
	Engineer / technicians, correlator construction		20	20
	Engineer / technicians, FIR construction		9	9
	Programmer, control computer programming	2		2
10	**Computing / Monitor&Control**			
	Programmers, software development	35	23	58
	Total	148	290	438

Table 8.5: **VLA Expansion Project: Costs and Funding by Year**

Table 8.5 Budget VLA Expansion Project: Costs and Funding by Year

(Cy2000 $k)

Stage 1											
CY	**< 2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Total**
Project Cost											
M&S	2200	3400	4900	4500	4500	4700	2600	2700	0	0	**$29,500**
Personnel	900	2200	2800	3300	3200	3000	3000	3000	0	0	**$21,400**
Contingency & AUI Fee	0	900	1300	1300	1300	1300	900	1000	0	0	**$8,000**
Total	**$3,100**	**$6,500**	**$9,000**	**$9,100**	**$9,000**	**$9,000**	**$6,500**	**$6,700**	**$0**	**$0**	**$58,900**
Project Funding											
Previously funded tasks	3100	0	0	0	0	0	0	0	0	0	**$3,100**
Redirected NRAO	0	1200	1100	1100	1100	1100	1100	1100	0	0	**$7,800**
Canada	0	100	2200	2300	2300	2300	400	400	0	0	**$10,000**
Mexico	0	0	500	500	500	500	0	0	0	0	**$2,000**
New NSF funds	**$0**	**$5,200**	**$5,200**	**$5,200**	**$5,100**	**$5,100**	**$5,000**	**$5,200**	**$0**	**$0**	**$36,000**
Total	**$3,100**	**$6,500**	**$9,000**	**$9,100**	**$9,000**	**$9,000**	**$6,500**	**$6,700**	**$0**	**$0**	**$58,900**

Stage 2											
CY	**< 2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Total**
Project Cost											
M&S	0	0	0	0	500	1400	1300	1300	2000	1800	**$8,300**
Personnel	0	0	0	0	600	700	600	600	2100	2000	**$6,600**
Contingency & AUI Fee	0	0	0	0	200	300	300	300	700	600	**$2,400**
Total	**$0**	**$0**	**$0**	**$0**	**$1,300**	**$2,400**	**$2,200**	**$2,200**	**$4,800**	**$4,400**	**$17,300**
Project Funding											
Previously funded tasks	0	0	0	0	0	0	0	0	0	0	**$0**
Redirected NRAO	0	0	0	0	300	200	200	200	1300	1200	**$3,400**
Canada	0	0	0	0	0	0	0	0	0	0	**$0**
Mexico	0	0	0	0	0	0	0	0	0	0	**$0**
New NSF funds	**$0**	**$0**	**$0**	**$0**	**$1,000**	**$2,200**	**$2,000**	**$2,000**	**$3,500**	**$3,200**	**$13,900**
Total	**$0**	**$0**	**$0**	**$0**	**$1,300**	**$2,400**	**$2,200**	**$2,200**	**$4,800**	**$4,400**	**$17,300**

Table 8.5 (continued)

(Cy2000 $k)

Stage 1 + Stage 2 CY	< 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
Project Cost											
M&S	2200	3400	4900	4500	5000	6100	3900	4000	2000	1800	**$37,800**
Personnel	900	2200	2800	3300	3800	3700	3600	3600	2100	2000	**$28,000**
Contingency & AUI Fee	0	900	1300	1300	1500	1600	1200	1300	700	600	**$10,400**
Total	**$3,100**	**$6,500**	**$9,000**	**$9,100**	**$10,300**	**$11,400**	**$8,700**	**$8,900**	**$4,800**	**$4,400**	**$76,200**
Project Funding											
Previously funded tasks	3100	0	0	0	0	0	0	0	0	0	**$3,100**
Redirected NRAO	0	1200	1100	1100	1400	1300	1300	1300	1300	1200	**$11,200**
Canada	0	100	2200	2300	2300	2300	400	400	0	0	**$10,000**
Mexico	0	0	500	500	500	500	0	0	0	0	**$2,000**
New NSF funds	**$0**	**$5,200**	**$5,200**	**$5,200**	**$6,100**	**$7,300**	**$7,000**	**$7,200**	**$3,500**	**$3,200**	**$49,900**
Total	**$3,100**	**$6,500**	**$9,000**	**$9,100**	**$10,300**	**$11,400**	**$8,700**	**$8,900**	**$4,800**	**$4,400**	**$76,200**

Appendix A

Science with the Ultrasensitive Array

The VLA's astronomical contributions have run the gamut from mapping the magnetic fields of Jupiter, to imaging high-redshift galaxies; indeed, the breadth of the instrument has always been its strongest feature, allowing the VLA to make important discoveries in fields which did not even exist at the time it was built (*e.g.*, gamma-ray burst afterglows). The Ultrasensitive Array may confidently be expected to be similarly productive, becoming the instrument of choice for radio observations of almost any type. Chapter 4 highlighted a few of the observations which might be done with the new instrument; this Appendix gives a broader view of the possibilities. The list is by no means exhaustive, but concentrates on those areas where radio data provide important information which is complementary to that available at other wavelengths. As in Chapter 4, these unique radio contributions are gathered into four major groupings:

- *The Magnetic Universe*
  Magnetic fields are thought to be important in virtually all astrophysical contexts, but they are very difficult to observe. Radio observations offer some of the few direct probes of the strength, structure, and topology of magnetic fields, including synchrotron emission, Zeeman splitting, and Faraday rotation. The sensitivity, frequency agility, and spectral capacity of the Ultrasensitive Array will allow astronomers to map out the three-dimensional structure of magnetic fields on the Sun, image the polarized emission in thousands of spiral galaxies, and (through the use of faint background sources as Faraday rotation probes) trace the magnetic fields in the halos of individual galaxy clusters.

- *The Obscured Universe*
  Many interesting phenomena, including star formation and accretion onto massive black holes, generally occur behind dense screens of gas and dust which make optical and even infrared observations difficult or impossible. Radio waves by contrast are not easily obscured, and hence can be used to look directly through these dust screens. Examples of projects made possible by the Ultrasensitive Array include probing the depths of the atmospheres of the giant planets, measuring ambipolar diffusion and the proper motions of thermal jets in young stellar objects, imaging the densest regions of nearby starburst galaxies, and conducting unbiased searches for quasar absorption lines.

- *The Transient Universe*
  Astronomical transients tend to be compact objects which emit high-energy photons and accelerate high-energy particles; the latter are observable primarily through synchrotron

emission, which in turn is most easily seen at radio wavelengths. Radio observations are therefore quite important to studies of variable sources, particularly because of a number of practical advantages, including high angular resolution, the lack of confusing sources, and the ability to observe both day and night under most weather conditions. The Ultrasensitive Array will be the ideal instrument for these studies, providing accurate mass estimates and three-dimensional images of galactic novae, imaging every relativistic jet in the Milky Way, and measuring the sizes of up to a hundred gamma-ray burst sources every year.

- *The Evolving Universe*
  The formation of stars and galaxies, and the evolution of the gas content of the universe, are among the most important topics in modern astronomy. Radio data are useful both in measuring the evolution of H I and (especially redshifted) molecular gas, and in providing extinction-free measurements of three of the most important emission processes in both young stars and high-redshift galaxies (synchrotron, thermal free-free, and dust emission). Among other observations, the Ultrasensitive Array will allow astronomers to distinguish dust from free-free emission, and image disks and jets, in local star forming regions; and to measure the star formation rate, irrespective of dust extinction, in high-redshift galaxies.

The remaining sections of this chapter summarize the Ultrasensitive Array's contributions in each of these four areas, with special emphasis on the new capabilities provided by the instrument, and the new and unique science which will result. Unless explictly stated, all of the observations described here depend only on Phase I of the VLA Expansion Project. In a few cases key aspects of Phase II (mostly the longer baselines and the low-frequency coverage) are particularly relevant, and those are so noted in the text.

A.1 The Magnetic Universe

Magnetic fields are known or suspected to be important in every astrophysical context, from solar flares to the dynamics of galaxy clusters. But they are also very difficult to measure, with very few direct, observational probes. Almost all of these are associated with emission at centimeter wavelengths. Radio observations thus provide the most direct measurements available of the magnetic field distribution, orientation, and strength, based on synchrotron emission and polarization, Faraday rotation, Zeeman splitting, gyrosynchrotron emission, cyclotron masers, maser polarization, and more esoteric processes like synchrotron self-Compton emission, the Razin-Tsytovich effect, and anisotropic scattering. The VLA has been at the forefront of this work, particularly synchrotron observations, for many years, but even for the VLA these measurements are very demanding. For instance, synchrotron measurements require high sensitivity to detect low polarization fractions (a few tenths to tens of per cent) with high enough signal-to-noise ratios to determine accurate polarization angles; they also require wide bandwidths (to measure the spectral index, and to probe small Faraday rotations) and high spectral and spatial resolutions (to avoid depolarization within a frequency channel or a beam, and to ensure sensitivity to high Faraday rotations). Such *desiderata* stretch the abilities of the current instrument to its limits.

The Expanded Very Large Array, and particularly the Ultrasensitive Array, offers several important advances:

- *Improved sensitivity*
  With at least a factor of ten increase in speed over the current VLA, the Ultrasensitive Array will measure magnetic fields in larger samples of weaker sources, extending current observations of 'the best and the brightest' to more typical objects. The improved surface brightness sensitivity will also allow observations at much higher spatial resolution (factor of three to ten), yielding more detailed information on the distribution of the magnetic field, and avoiding beam depolarization. Finally, by significantly increasing the number of background sources suitable for rotation measure studies, the Ultrasensitive Array will probe the magnetic field even where there is no emission, allowing 'blind' searches that are simply not possible today.

- *Higher spectral resolution, over wider bandwidths*
  With 31 MHz or higher resolution over 8 GHz with full polarization information, the new correlator will revolutionize continuum studies, retaining full sensitivity while providing accurate spectral information and unambiguous rotation measures in a single frequency setting, and simultaneously avoiding Faraday depolarization. In place of the careful tradeoffs of sensitivity, frequency coverage, and spectral resolution required currently, *every* observation will provide more accurate and more complete polarization information than has yet been obtained for any source. Similarly, wide bandwidths will for the first time be available with high enough spectral resolution for maser and Zeeman splitting measurements, yielding a huge increase in efficiency when multiple sources are present in the beam, and permitting high-sensitivity searches to be performed at the same time as delicate Zeeman measurements. The amazing flexibility of the new system will also give excellent continuum measurements during spectral line observations. Since the latter do not benefit (except at the high frequency bands) from the improved bandwidth, one will still have to integrate for many hours to obtain (for instance) good H I sensitivity; with the new correlator one can at the same time obtain more sensitive rotation measure maps than any now existing.

- *Continuous frequency coverage from 1–50 GHz*
  Many broad-band probes of magnetic fields are strongly frequency dependent; for instance, both Faraday rotation and the strength of interstellar scattering vary as ν^{-2}, while the

Razin-Tsytovich effect leads to a sharp cutoff at the frequency where the phase velocity exceeds the speed of light. It is therefore advantageous to observe these processes over a broad range of frequencies, and to be able to tune an observation to match the physical conditions of a particular source. More generally, few sources emit via only one physical process, and covering a wide range of frequencies allows these processes to be distinguished by their spectral shapes. For instance, the intensity of synchrotron emission gives a direct constraint on the magnetic field strength, but one needs some information on the particle energy distribution, and some idea of what fraction of the measured (total) intensity is indeed synchrotron emission. The Ultrasensitive Array combines the flexibility to select the appropriate frequency for an observation, with the wide frequency coverage essential for an accurate decomposition of the observed spectrum.

The Ultrasensitive Array will thus have a major impact on the study of magnetic fields in astronomy. The remainder of this section details a few specific observations illustrating the possibilities; the intention is to give some feeling for the expected advances, rather than to provide an exhaustive survey. The improvements provided by this first phase of the VLA Expansion Project are so dramatic that one may confidently predict that the selection below represents the small tip of a very large iceberg.

A.1.1 Coronal Magnetography in Solar Active Regions

Solar active regions are localized areas on the Sun where magnetic flux has erupted through the photosphere into the chromosphere and corona. As their name implies, solar active regions are the sites of various kinds of solar activity: solar flares, radio bursts, enhanced coronal heating, and mass ejections. A key goal in solar physics is to understand their birth, evolution, and decay, the role of electric currents, and the origin of transient, energetic activity. Addressing this goal requires detailed measurements of the coronal magnetic field. The Ultrasensitive Array offers the unique capability of obtaining such detailed measurements, through rapid imaging observations over a wide range of frequencies.

When the magnetic field is sufficiently large ($\gtrsim$ 100 G) gyroresonance opacity is the dominant source of opacity in solar active regions. Radio waves with frequencies which are low integer multiples of the the electron gyrofrequency ν_B (*i.e.*, $\nu = s\nu_B; s = 1, 2, 3...$) may be resonantly absorbed and emitted by electrons gyrating in the local magnetic field. For example, the electron gyrofrequency in a 600 G magnetic field is $\nu_B = 1.7$ GHz, the third harmonic of which lies in the 5 GHz band. Given sufficient spectral and spatial resolution, one can exploit gyroresonance absorption to place unique constraints on the magnetic field at the base of the corona; that is, to perform *coronal magnetography*. There are no other techniques available to measure strong fields in the Sun's corona.

This works as follows: consider a given frequency ν which is optically thick to gyroresonance absorption in the solar corona at $s = 3$. It therefore yields a brightness temperature which is similar to the effective temperature of the corona ($\mathrm{T_B}(\nu) \approx 3 \times 10^6$ K). Now let ν increase – as ν increases, the resonance condition is matched at higher magnetic field strengths, which occur at lower heights in the corona. At some critical frequency ν_c, the resonance condition is matched at the base of the corona. For $\nu > \nu_c$, $T_B(\nu)$ drops precipitously as the resonance layer traverses the transition region and chromosphere where the effective temperature is much lower. A high resolution map of ν_c may therefore be converted into a map of $|B|$ at the base of the corona. With care, the field vector may also be constrained. Coronal magnetography provides the most direct means available of estimating the magnetic field at these heights. It would provide an invaluable tool for assessing departures of the field from potential configurations in active regions, and for assessing the role of electric currents.

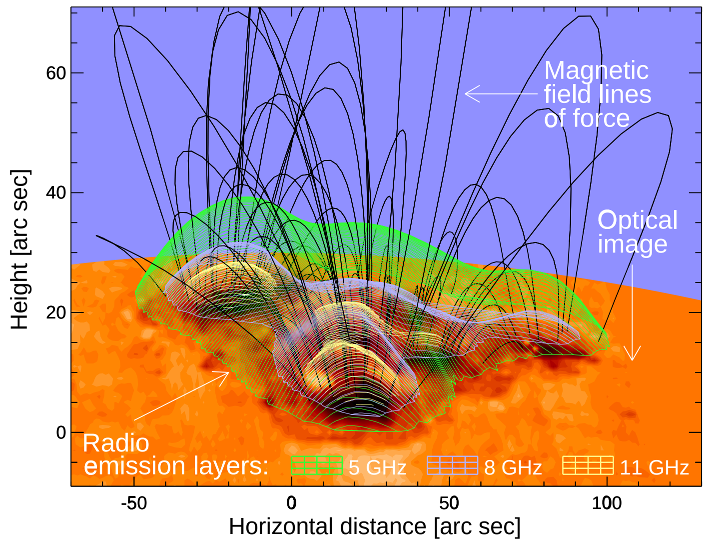


Figure A.1: A perspective view of a complex sunspot group (7 May 1991) in optical continuum, with field lines extrapolated into the corona using a nonlinear force-free extrapolation by Z. Mikić. The three surfaces are the calculated gyroresonant surfaces in the corona that will dominate the radio opacity at each of three radio frequencies: 5 GHz (B = 600 G), 8 GHz (B = 950 G) and 11 GHz (B = 1300 G). (Produced by Jeongwoo Lee/NJIT.)

A more ambitious goal is to infer the *three-dimensional* distribution of magnetic fields (and currents). At a given frequency, the gyroresonance emission originates from an isogauss surface. Tuning across a broad range of frequencies "peels the magnetic onion", and provides a three-dimensional map of the brightness temperature as a function of magnetic field strength (Figure A.1). Such measurements, when coupled with vector magnetic field measurements at photospheric and chromospheric heights, will impose powerful new constraints on field extrapolations.

High resolution imaging observations at many frequencies over a broad bandwidth are needed to exploit the techniques outlined above. While the VLA currently provides sufficient angular resolution, the continuous frequency coverage and the large bandwidth ratios of the Ultrasensitive Array are essential to mapping out the detailed magnetic field structure of the corona.

A.1.2 Imaging the Dynamic Heliosphere

The solar wind inflates a cavity around the Sun, extending to perhaps $\sim$ 100 AU, called the heliosphere; this is filled with a tenuous, magnetized plasma, known as the interplanetary medium (IPM). Radio interferometers like the VLA are ideally suited for measuring the angular broadening and intensity scintillations of background sources viewed through the IPM; these data can be used to deduce the solar wind speed and acceleration profile, to measure properties of the turbulence, and to map large-scale structures in the solar wind (Figure A.2). These studies exploit observations of sidereal background sources which, in the absence of the IPM, are either unresolved by the array or have known source structure. Phenomena such as angular broadening, scintillation, Faraday fluctuations, etc., are due solely to the intervening turbulent medium. Currently such studies are limited by sensitivity to occasional determinations of solar wind properties using a handful of strong sources at various elongations and position angles.

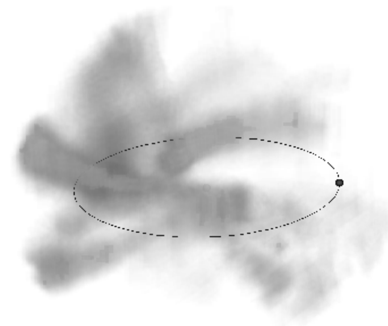


Figure A.2: An example of a tomographic reconstruction of the inner heliosphere, to a distance of 1.5 AU, which was derived from a combination of IPS intensity level data and velocity data obtained over one solar rotation period (23 June 1994 to 20 July 1994, Carrington Rotation 1884). Earth's orbit is as indicated. The technique is described in detail by Jackson *et al.* (1998).

The greatly improved continuum sensitivity provided by the Ultrasensitive Array is critical for this sort of work. Access to large numbers of background sources will enable determinations of the properties of the solar wind turbulence along many lines of sight over the course of a single observing run; such simultaneous measurements are essential for such a time-variable phenomenon, and will characterize the IPM in the inner heliosphere in a more global fashion. More exciting still is the prospect of mapping the large-scale transient disturbances in the IPM (*e.g.*, coronal mass ejections). Here one would like quite short integrations, to sample many instances of the scattering screen while mapping as large an area as possible; with the Ultrasensitive Array 10 minute snapshots would give on average 5−20 100σ sources per primary beam at 1.5−3.0 GHz, while greater numbers still will be available at lower frequencies.

A.1.3 Galactic Center Magnetic Fields

A strong and highly ordered magnetic field pervades the central region of the Galaxy. This field is oriented vertical to the Galactic plane and is two to three orders of magnitude stronger than the field in the Galactic disk. The primary evidence for the vertical magnetic field comes from VLA observations which reveal a system of long (tens of parsecs) and narrow (<0.5 pc) non-thermal filaments and thread-like structures oriented perpendicular to the Galactic plane (Figures A.3, A.4; Yusef-Zadeh, Morris, & Chance 1984; Morris & Yusef-Zadeh 1985; Anantharamaiah *et al.* 1991; Liszt & Spiker 1995; Gray *et al.* 1995; Yusef-Zadeh, Wardle, & Parastaran 1997; Lang *et al.* 1999). These synchrotron-emitting filaments are strongly linearly polarized with their intrinsic magnetic fields remarkably well aligned along their length. However, their generation remains an enigma.

The Ultrasensitive Array will make a number of major contributions to our understanding of the role of magnetic fields in the Galactic center region, and hence near the nuclei of other spiral galaxies as well. Spectral indices and linear polarizations will be obtained easily for even the faintest known filaments; rotation measure studies will reveal the magnetic field configuration within individual filaments, and in the entire central region, several degrees across. Zeeman measurements will be extended to many more masers and absorption lines, and even to the radio recombination lines which trace the ionized gas as a whole. The result will be a far clearer and more complete picture, on both large and small scales, of the strength and topology of the magnetic fields in the Galactic center region.

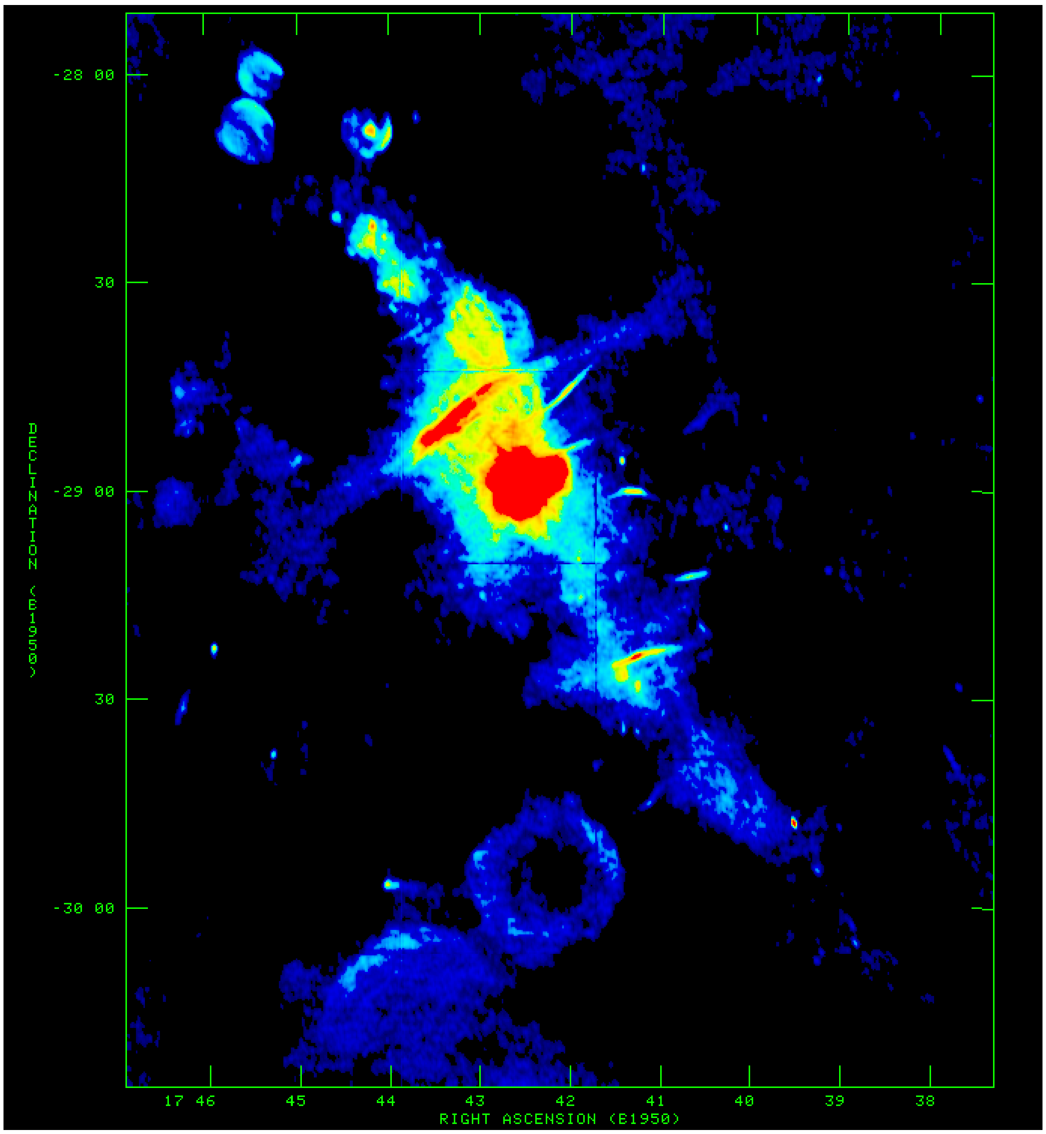


Figure A.3: 330 MHz VLA image of the central 4° × 4° of the Galaxy, at 48 arcsecond resolution. Courtesy Kassim, LaRosa, Lazio, & Hyman (1999).

Continuum Imaging

Current high-resolution VLA images (*e.g.*, Figure A.4) suggest that the entire $1-2°$ region surrounding Sgr A is permeated by these magnetic filamentary structures, many of which are barely detectable. All the known filaments appear to have unresolved sub-structure along their lengths. The Ultrasensitive Array will allow a factor of ≥ 4 more sensitive imaging with complete polarization and spectral information over the entire region. This will provide a far superior characterization of the distribution, structure, spectral index, and polarization properties of the filaments on sub-arcsecond scales, and may confirm the ubiquity of these features, as well as revealing the overall field configuration in the central regions of the Galaxy. Spectral indices in particular have never been measured accurately over a large field-of-view. Such measurements are essential to study the details of the interactions between magnetic filaments and associated ionized gas, which are currently thought to provide a mechanism for acceleration of particles and the subsequent synchrotron radiation (Serabyn & Morris 1994).

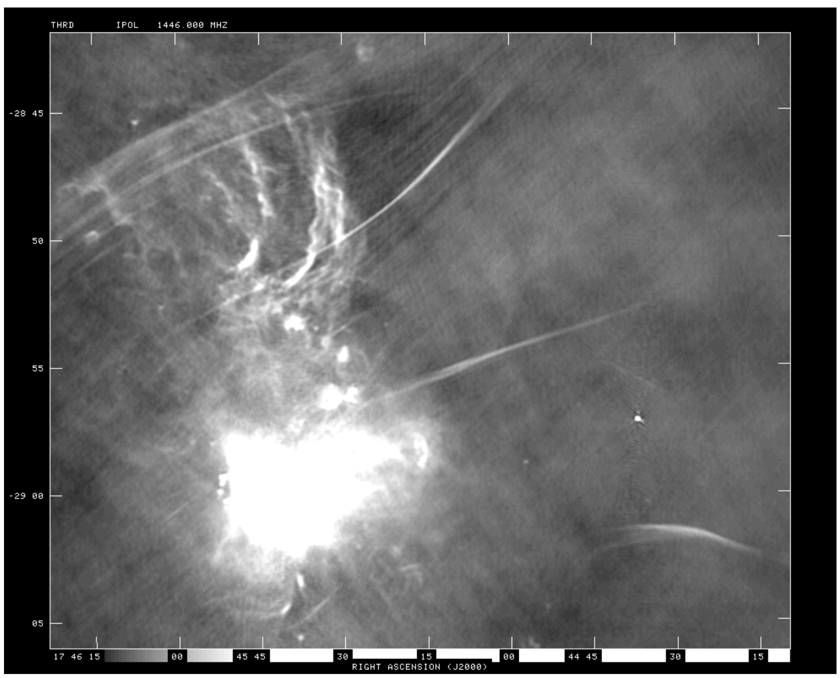


Figure A.4: Unique radio structures within 30 arcminutes (75 pc) of the Galactic center, as seen with the VLA at 1400 MHz (Lang *et al.* 1999). Similar filaments are observed up to 1.5° from the Galactic center.

Differential Faraday Rotation

The magneto-ionic medium in the Galactic center region causes large ($> 10^3$ rad m^{-2}) differential Faraday rotation of the plane of polarization. Multi-frequency, narrow-bandwidth observations are necessary to correct for this Faraday rotation and thus to determine the intrinsic orientation of the magnetic field in Galactic center sources. The rotation measures (RMs), which are determined in the process, give valuable information on the combination of the strength of the parallel component of the magnetic field and the electron density along the line-of-sight ($\int n_e \, B_{||} \, dl$). Given the high observed RMs, the spectral resolution of the current VLA correlator limits the total frequency coverage for polarization observations toward the Galactic center to < 25 MHz for frequencies below 5 GHz. This makes 5 GHz the most sensitive frequency for such observations with the current VLA; since this limits the field-of-view to $\lesssim 9$ arcminutes, and since the non-thermal filaments are weaker at higher frequencies, only a few selected regions have been studied. The simultaneous broad bandwidth and high spectral resolution of the new correlator will allow unambiguous determination of rotation measures and polarization over a $0.5°$ field-of-view in a single pointing at ν=1.5 GHz. One could thus determine for the first time the rotation measures and the magnetic field configuration over a large region of interest (several degrees) around the Galactic center. The improved sensitivity of the Ultrasensitive Array will also allow efficient polarization imaging at higher (sub-arcsecond) resolutions of the stronger filaments; observations of a few selected regions have already shown rotation measure changes from 100s to 1000s of radians/m^2 on scales of several arcseconds (Yusef-Zadeh, Wardle, & Parastaran 1997).

Zeeman Splitting

VLA observations of the Zeeman splitting in spectral lines of H I and OH in absorption (Killeen, Lo, & Crutcher 1992; Plante, Lo, & Crutcher 1995) and more recently in the 1720 MHz OH maser line (Yusef-Zadeh *et al.* 1999) have given direct measurements of very strong magnetic fields ($B_{\|} \sim 1-5$ mG) in the Galactic center region. Fields this strong may dominate the dynamics, and thus control the fueling of the central engine; the conversion of the substantial magnetic field energy may also dominate cloud heating near the Galactic center. Further, OH Zeeman splitting provides a much-needed probe of the magnetic field *inside* clouds, which seems to differ quite a bit from the field outside (cf. Serabyn & Morris 1996); this may provide a clue to the magnetohydrodynamic interactions in this region.

Currently the absorption measurements are at the limit of the VLA's sensitivity, while only a few 1720 MHz masers are known in this region. The Ultrasensitive Array will improve the current measurements and increase the number of detections substantially, both by allowing higher spectral resolution, and by lowering the system temperature by reducing the ground pickup (the Galactic center is a low elevation source for the VLA). The much-increased bandwidth will also allow simultaneous searches for, and measurement of Zeeman splitting in, a large number of masers. Finally, the Ultrasensitive Array will for the first time allow the detection of the Zeeman effect in radio recombination lines. This is a difficult observation, requiring multiple transitions to be averaged together to increase the sensitivity, while retaining high spectral resolution; high spatial resolution is also critical, to avoid kinematic broadening of the lines. The best observations so far give a 3σ limit of 8 mG toward the northern arm (Roberts & Goss 1993); the Ultrasensitive Array will give a factor of $5-10$ improvement, by allowing observations at 15 GHz, stacking four radio recombination lines together, and giving a factor of at least five higher velocity resolution ($\lesssim 2$ vs. 10 km/sec) over a 2000 km/sec bandwidth, allowing much-improved continuum subtraction. The potential rewards are enormous. Zeeman splitting measures the *local* field, and there is always the worry that the conditions in the absorbing or masing gas may not be representative of the region as a whole. Radio recombination lines by contrast arise from ionized gas which is spread throughout the Galactic center region, including pockets which are known to be present close to the central black hole. Since the magnetic fields observed at larger distances are of order a few milliGauss, the ability to measure 1 mG fields from RRLs should make it possible to measure (or set very interesting limits on) the field strength within a few tenths of a parsec of the black hole itself.

Anisotropic Scattering

Point-like radio sources (generally, OH masers) observed through the turbulent medium near the Galactic center are scatter-broadened, with measured sizes of more than an arcsecond at 1.6. GHz; the scattering region covers at least 25 arcminutes (Frail *et al.* 1994). The scattering disks themselves are elongated due to anisotropies in the ionized scattering medium, which in turn presumably reflect the orientation of an ordered magnetic field. Frail *et al.* observed five masers per day, each requiring a separate tuning of the array. The new correlator of the Ultrasensitive Array will allow the entire inner 30 arcminutes to be searched simultaneously for OH masers, with sub-km/sec channels, over a huge velocity range ($\pm 3000\,\mathrm{km/sec}$). This would map the sizes and orientations of the scattering disks across the entire region in one go, yielding direct information both on the magnetic field structure, and on the scattering material itself.

A.1.4 Large-Scale Magnetic Field Structures in Normal Galaxies

Synchrotron Emission: Polarization

The past decade has seen something of a revolution in our understanding of the strength, orientation, and orderliness of magnetic fields in spiral galaxies (*e.g.*, Beck *et al.* 1996), thanks in large part to high-resolution polarization observations of synchrotron emission by the VLA (Figure A.5). However, only the nearest and the (radio) brightest galaxies have been imaged, and then only with rather poor spatial resolution (a few hundred to a few thousand parsecs). This leaves many major questions unanswered:

- How are magnetic fields created? Does the standard dynamo model for generating magnetic fields work?
- What is the relationship between magnetic fields and turbulence and shocks? Are interstellar fields deformed by star-formation processes, and how do they in turn influence star formation?
- Do all galaxies show regular magnetic fields? How do these vary with Hubble type? How are magnetic fields related to spiral arms? Why is the inter-arm magnetic field often stronger and more ordered than that along the arms?
- How do gravitational interactions affect the magnetic field?
- What is the diffusivity of interstellar fields? Under what conditions is the field frozen into a gas flow?
- Which component of the ISM gas (molecular, Warm/Cold Neutral Medium, ...) is mainly responsible for anchoring the field lines?

Answering these questions requires polarization imaging of many galaxies at high ($\lesssim 100\,\mathrm{pc}$) resolutions. Large samples are necessary to understand how magnetic fields relate to the Hubble type and the galaxy environment; high resolution is essential in studying the relationship between magnetic fields and spiral structure, star formation, and the other components of the ISM. Current observations are limited by several effects. Synchrotron emission is strongest at low frequencies ($S_\nu \propto \nu^\alpha$, with $\alpha \sim -0.6$ to -1.0), but Faraday rotation ($\propto \nu^{-2}$) depolarizes the signal unless one observes at high spectral and spatial resolution. Currently the VLA correlator forces one to choose between spectral resolution and bandwidth/sensitivity, and this pushes observations up to fairly high frequencies (usually 8.3 GHz) where the emission is relatively weak. This then prevents observations at high resolution, since the surface brightness sensitivity of the array goes as θ^2. The

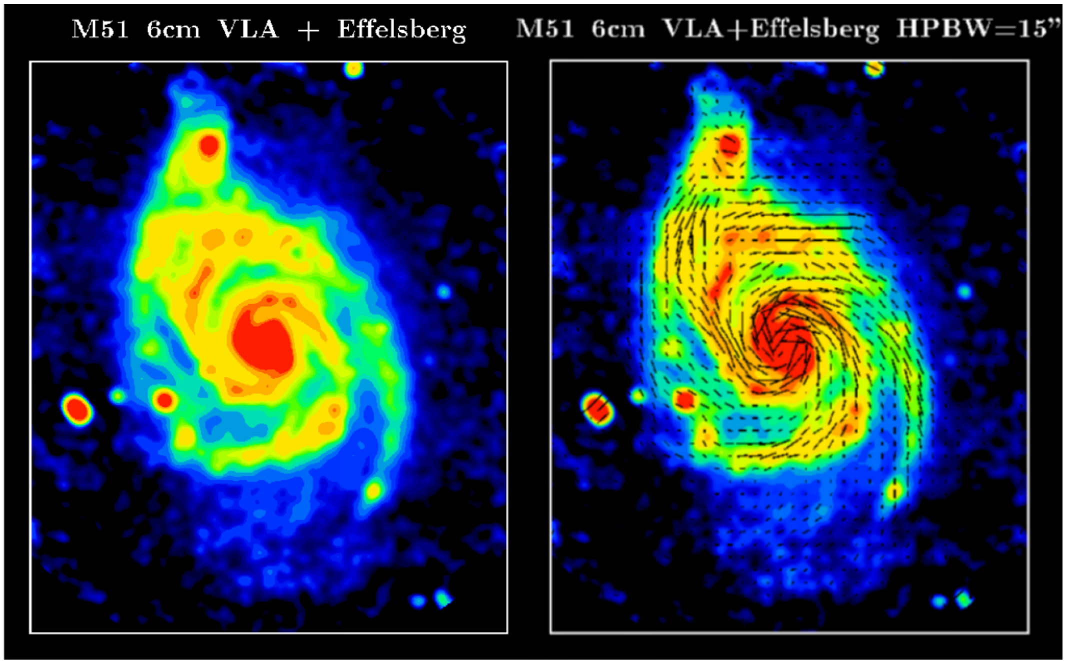


Figure A.5: Combined VLA+Effelsberg image of M51 radio continuum total (*left*) and polarized (*right*) intensity at 5 GHz, at a resolution of 15 arcseconds. The vectors show the magnetic field orientation, and their lengths are proportional to the polarized intensity. Courtesy R. Beck (1999).

result is that only about a dozen galaxies have so far been observed, requiring long (8–12 hour) observations, and achieving relatively poor (15–60 arcsecond) angular resolution.

The Ultrasensitive Array will dramatically improve the situation, due to a number of interlocking advances. The new correlator will provide high spectral resolution over huge bandwidths, allowing the measurement of Faraday rotation at even the lowest frequencies, while avoiding the effects of spectral depolarization. The improved sensitivity will allow observations with a factor of nine smaller beam, avoiding spatial depolarization and allowing a much more detailed comparison between magnetic fields and other features. Finally, the continuous frequency coverage will allow the choice of an observing frequency suited to each particular galaxy. For instance, there are indications that some spiral galaxies are optically thick to polarized emission at $\sim 1\,\mathrm{GHz}$ (see below), and those would be observed with the new 3 GHz system to maximize both sensitivity and resolution.

To make this more concrete, consider a typical spiral galaxy, which has a mean disk brightness temperature of $\sim 0.75\,\mathrm{K}$ at 1.4 GHz (Hummel 1981). This corresponds to $T_B \sim 0.4\,\mathrm{K}$ at 3 GHz (assuming $\alpha \sim -0.8$). The Ultrasensitive Array could detect $\sim 10\%$ polarizations in such a galaxy, at higher resolution than any previous study (7 arcseconds), in under 2 hours. This resolution corresponds to physical sizes below 100 pc for all galaxies in the Local Group. The UGC lists over 13,000 galaxies with diameters over an arcminute – the polarization could be mapped in *any* of these systems. The Ultrasensitive Array would allow us for the first time to study magnetic fields in detail in unbiased samples of ordinary spiral galaxies.

Mapping the Three-Dimensional Structure of the Magnetic Fields

Horrelou *et al.* (1992; see also Buczilowski & Beck 1991) showed that M51 becomes more and more depolarized with decreasing frequency, the effect turning on at about 1–2 GHz. They interpreted this in terms of a Faraday 'optical depth': the polarized emission from further into the disk is rotated more by Faraday effects than that in the front, and at low frequencies the difference is large enough that a line-of-sight through the disk begins to 'wash out' the polarization entirely[1]. That group is now working on turning these multi-frequency data into a three-dimensional map of the magnetic field distribution. Unfortunately, with only two spectral points at ~ 1 GHz available with the current VLA, and no information at all from 1.7 to 4.5 GHz, it is impossible either to check this mapping, or to obtain more than a very crude model. The new correlator and continuous frequency coverage provided by the Ultrasensitive Array would provide some *thousands* of spectral points, spread over the full interesting range from 1 to 3 GHz, with only a modest increase in observing time.

Faraday Rotation Towards Background Sources

One of the classic probes of magnetic fields (and ionized particles) in the Milky Way is Faraday rotation toward polarized background radio sources, giving the electron-density-weighted integral of the line-of-sight magnetic field. The Ultrasensitive Array will be able to perform similar observations toward nearby galaxies, opening a new window on their magnetic fields. Assuming an average 2% polarization for random background sources and following Condon's (1984) source counts, more than ten background sources could be seen through each of more than 40 UGC galaxies (Figure A.6). M31 is of course the best case; here one should obtain more than 1100 independent rotation measures scattered throughout the disk and halo.

A.1.5 Galaxy Clusters

Clusters of galaxies are filled with turbulent hot gas, relativistic particles, and magnetic fields. While X-ray observations offer the best probe of the hot gas in this intra-cluster medium (ICM), the magnetic and relativistic components are most readily observed at radio frequencies. The magnetic fields in particular are of great interest, as they may play an important role in galaxy and cluster evolution, and even in cluster dynamics; in addition, even relatively weak fields can have profound effects on energy transport within galaxies/clusters.

Radio observations provide the only means of directly measuring cluster magnetic fields. The detection of smooth, large-scale radio 'halos' shows that both particles and fields are present in several clusters (Feretti & Giovannini 1996). These data are consistent with the interpretation of recent hard X-ray measurements (Fusco-Femiano *et al.* 1999) as inverse Compton emission from lower-energy photons scattered off of relativistic particles; together, the radio and X-ray observations give much more accurate estimates of the division in energy between particles and fields. In addition, Faraday rotation measurements (*e.g.*, Clarke 1999, Feretti *et al.* 1999, Taylor & Perley 1993) provide independent evidence that the ICM is magnetized, possibly at dynamically significant levels.

Current instruments can only hint at the true potential of these observations. We know that some clusters have significant magnetic fields, and (from rotation measure studies) have some idea of their distribution and topology in a few key sources. But the details are far from clear. Do all clusters have large-scale magnetic fields, at some level, or is this confined to the known (bright) halo clusters? At what redshift do such fields 'turn on', and how do they evolve? Rotation measure studies currently are based almost entirely on sources embedded within the clusters; are

[1] This effect is sometimes referred to as *internal depolarization*.

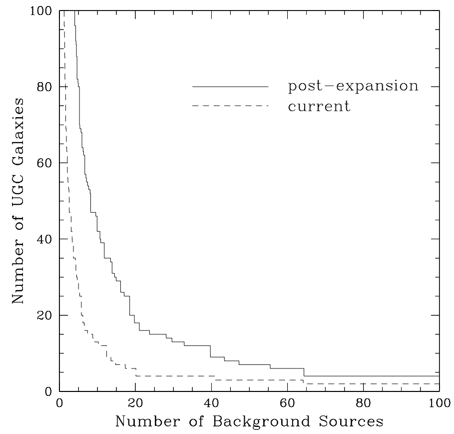


Figure A.6: The number of UGC galaxies with a given number of background sources suitable for rotation measure studies ($S_\nu > 150\sigma$) with the current VLA (dashed line) and with the Ultrasensitive Array (solid line). For instance, $\sim$ 50 UGC galaxies should have more than ten such background sources. A few galaxies (*e.g.*, M31, M33) are expected to have many more than 100 suitable background sources. Calculations assume 12-hour integrations at 1.5 GHz for the current VLA, and at either 1.5 or 3.0 GHz for the Ultrasensitive Array (the two frequencies give virtually identical source counts). Based on Condon's (1984) source counts. Note that the Ultrasensitive Array will be sensitive to a far greater range of RM as well, due to the vastly-improved frequency coverage and spectral resolution.

the magnetic fields thus observed created or heavily influenced by the sources themselves? What is the magnetic field topology *away* from such powerful radio sources, and are there strong fields without relativistic particles to 'light them up' via synchrotron radiation?

The Ultrasensitive Array will be ideally suited to answering these questions. It will allow accurate, high-resolution imaging of radio halos in dozens of clusters, showing whether cluster-wide magnetic fields are present in every cluster, and giving detailed information on cosmic ray acceleration in the cluster environment. The improved sensitivity will also vastly increase the number of rotation measure probes, giving unique information on the magnetic field strength and topology, independent of any relativistic particle population. And by providing sensitive rotation measure images of high-redshift radio galaxies, the Ultrasensitive Array may provide a very effective way to find high-redshift X-ray clusters, with important implications for cluster formation and evolution.

Diffuse Synchrotron Emission

Current studies of radio halos are restricted to low-resolution maps of a handful of the brightest sources, although theories of cluster formation predict diffuse relativistic particles and magnetic fields should exist in many or all clusters. Even the brightest halos can now just be detected above the noise level (Figure A.7; Giovannini *et al.* 1993); except for their general shape little detail is available, and spectral information is particularly sparse. Studies of sources like the M87 halo (Figure A.8; Owen, Eilek, & Kassim, *in prep.*) suggest that the picture will turn out to be much more complex, and that we may be looking at unfilled structures. The Ultrasensitive Array will allow many hundreds of fainter halos to be detected, studied as a function of frequency and redshift, and imaged with high fidelity and at high (few arcsecond) resolution. The larger sample will show directly whether cluster-wide fields are the rule or the exception, thus testing current models of cluster formation and early evolution; the more detailed studies will also measure the spectral and spatial distribution of the relativistic particles, thus constraining cosmic ray acceleration (primary or *in situ*) in the cluster environment.

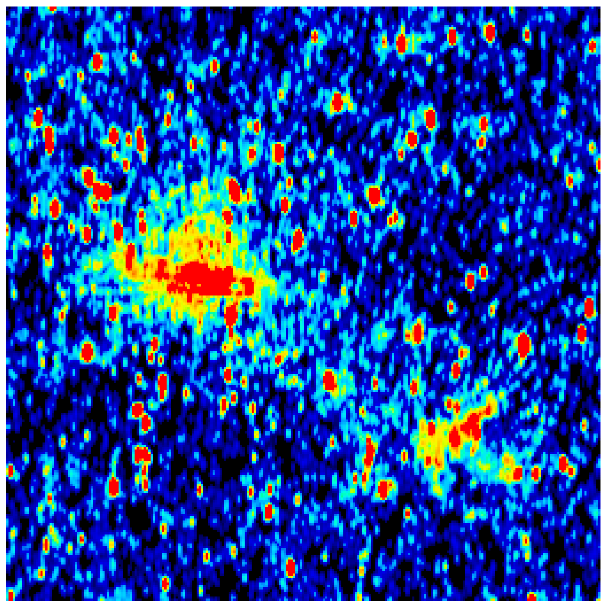


Figure A.7: WSRT image of Coma at 327 MHz (Giovannini *et al.* 1993), showing diffuse synchrotron emission on a Mpc scale. This is the prototype of the radio halos expected to be common in galaxy clusters; note also the 'relic' source to the southwest. Both provide direct evidence for a cluster-wide distribution of relativistic particles and magnetic fields. There are six undisputed radio halos known (Feretti *et al.* 1999); the Ultrasensitive Array will expand this to several hundred.

Faraday Rotation Studies

Faraday rotation gives an independent measure of the magnetic field and ionized medium along the line-of-sight, and also has the advantage of depending on the strength of the background source rather than the intrinsic radio emission. Two such probes are available in clusters: true background and cluster member sources. The number of useful sources is limited by the sensitivity (to give reasonable detections of the *polarized* emission, at high enough resolutions to avoid beam depolarization) and the spectral resolution (to avoid polarization angle wraps within a channel, while maintaining broad enough bandwidths to detect even low RMs). With major advances in both areas, the Ultrasensitive Array will bring about a revolution in these studies.

At the moment, RMs can be measured toward one or two background sources in a given cluster. Combining these for many galaxy clusters shows clearly that a magnetic field is present (Figure A.9), but cannot yet determine whether the fields detected are caused by strong radio galaxies in the cluster, or are intrinsic to all clusters. By contrast, the Ultrasensitive Array will

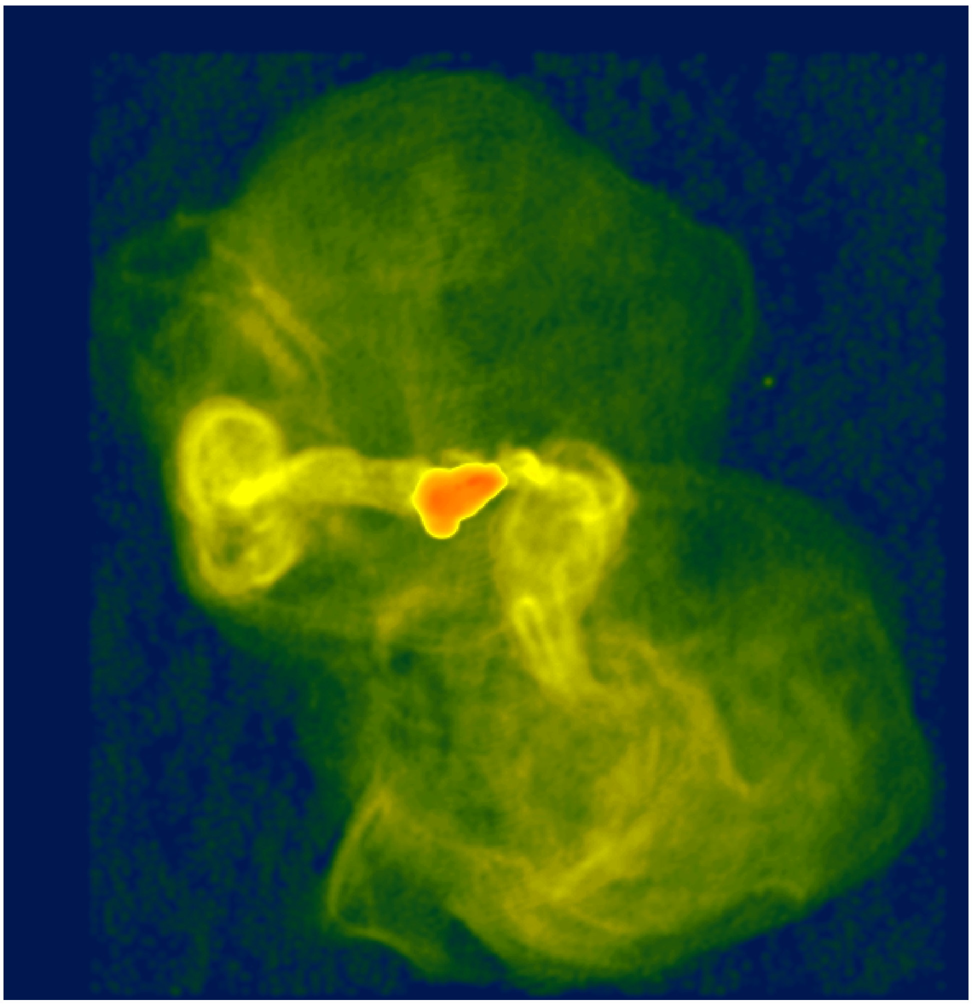


Figure A.8: 327 MHz VLA image of M87, the central radio source in the Virgo Cluster (D $\sim$ 17 Mpc; Owen, Eilek, & Kassim, *in prep.*). This 80-kpc radio source coexists with the X-ray cluster gas, and is dumping at least as much energy into that gas as is being lost to X-ray emission. The radio source is thus playing an important role in the central dynamics of the cluster gas.

give rotation measures toward more than 20 background sources within 0.2 Abell radii of *each* of more than 80 Abell clusters.

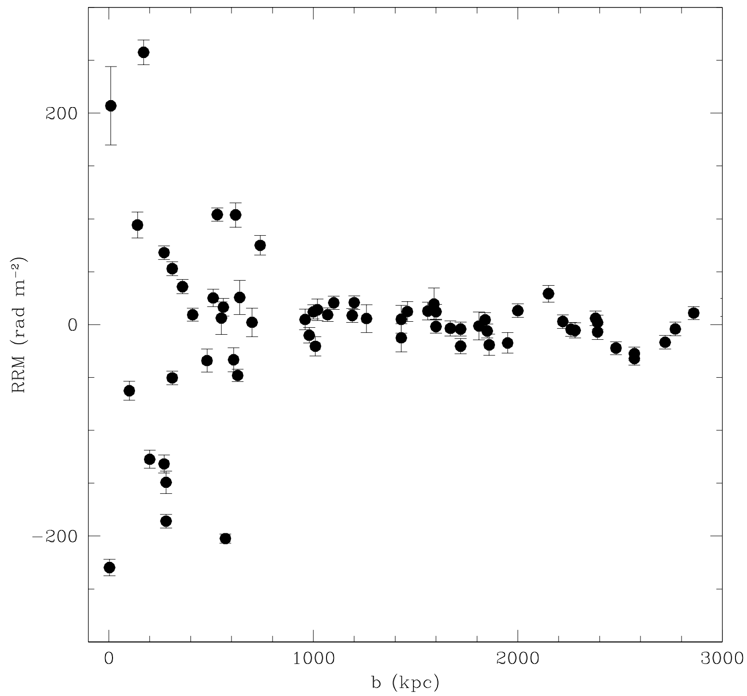


Figure A.9: The rotation measure (RRM) vs. impact parameter (b) for radio sources near, within, and behind Abell clusters (Clarke 1999). Note the clear increase in the width of the RM distribution at small radii. This plot can only be made currently by combining data from *all* clusters (22, in this particular plot); the Ultrasensitive Array will provide higher-quality measurements, toward more sources, in *individual* galaxy clusters.

The Ultrasensitive Array will similarly advance RM imaging of embedded sources, which provides the only observational measurement of the detailed magnetic field topology (strength and structure) within individual clusters. Virtually every source that can now be imaged in total intensity will give extended RM maps with the Ultrasensitive Array (cf. Figure A.10). By combining significant background studies with improved imaging of the cluster sources themselves, the Ultrasensitive Array will finally answer the question of whether magnetic fields exist in all clusters, and if so at what level, and with what spatial topology.

Extreme Rotation Measure Radio Galaxies

Over the past decade, extreme Faraday rotation has been seen toward a number of extended extragalactic radio sources (Dreher, Carilli, & Perley 1987; Taylor, Barton, & Ge 1994; Carilli *et al.* 1997). Rotation measures as high as 20,000 rad m^{-2} have been detected, as well as gradients in RM $\geq$1000 rad m^{-2} arcsec^{-1}. Observations of the closer radio galaxies have shown a clear correlation between extreme rotation measures and cluster environment: all sources located at the centers of dense, X-ray emitting cluster atmospheres show large amounts of Faraday rotation

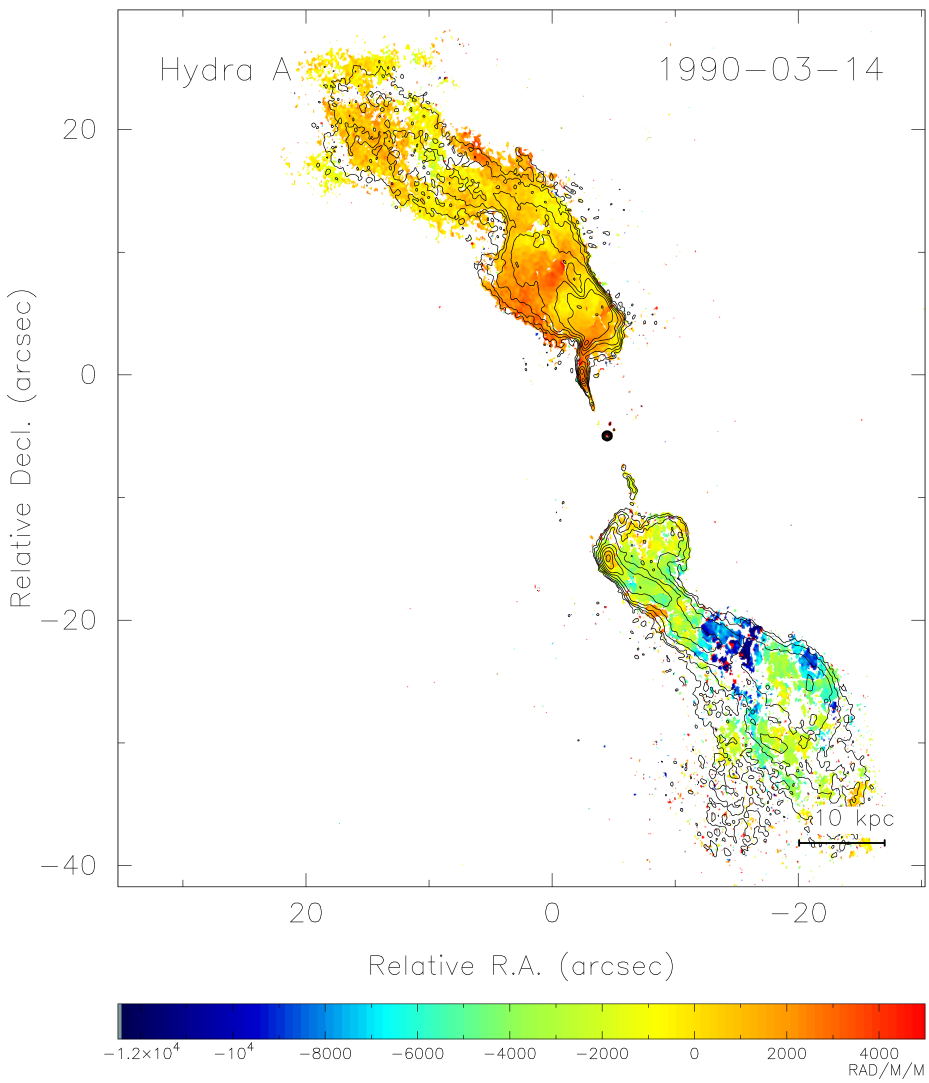


Figure A.10: The rotation measure structure of Hydra A at 0.3 arcsecond resolution (Taylor & Perley 1993). The colors indicate RM from −12,000 to 4000 radians/m^2; the contours represent the 8.4 GHz radio continuum. The Ultrasensitive Array will allow similar RM mapping of sources which are an order-of-magnitude fainter — basically every radio galaxy which can currently be imaged.

(Taylor, Barton, & Ge 1994). Since this correlation holds regardless of radio source luminosity and morphological class, the high rotation measures are probably associated with the clusters themselves, rather than with the individual radio sources.

High rotation measures are not confined to nearby galaxies; radio observations have already found 11 galaxies with source-frame RM$>$ 1000 rad m^{-2}, at redshifts between 2 and 3.8 (*e.g.*, Figure A.11; also Carilli *et al.* 1996; Athreya *et al.* 1998; Carilli, Owen, & Harris 1994). Such high RMs imply that we are looking through some sort of external magnetic field/density distribution; the analogy with low-redshift sources suggests that these are galaxy clusters, but they could also be smaller, higher-density cocoons associated with the radio sources themselves. The problem with the cluster hypothesis is that it requires gathering together both the total mass and the hot gas seen in local clusters, at a much earlier epoch. The 'individual source' model on the other hand implies that young galaxies (quite unlike the ones we see nearby) are surrounded by impressive magnetic fields and quite dense gaseous halos. Both possible explanations are very interesting, but one needs more detailed studies of a much larger sample both to determine which (if either) is correct, and to understand the differences between high and low rotation measure systems at these redshifts.

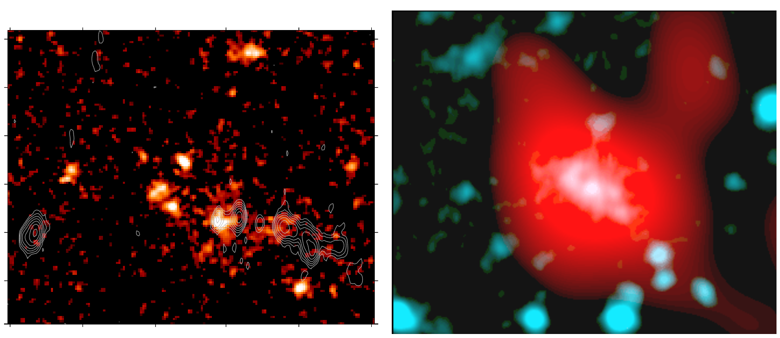


Figure A.11: Two views of the z=2.156 extreme rotation measure radio galaxy 1138$-$262. *Left:* VLA 5 GHz contours overlaid on an HST image (greyscale) (Carilli *et al* 1997; Pentericci *et al.* 1997, 1998). The field size in RA is 13 arcseconds. The optical and radio morphologies, together with optical velocities and velocity dispersions, all point to a dense local environment. *Right:* ROSAT HRI (X-ray) image in red, overlaid on an optical image in blue (Carilli *et al.* 1998). The field size is 40 arcseconds. The X-ray emission can be explained either as thermal emission from an enormous amount of hot gas ($> 10^{13}\,M_\odot$), or as nonthermal radiation from a hidden active galactic nucleus.

The increased sensitivity of the Ultrasensitive Array, combined with the availability of the 2$-$4 GHz band, will dramatically improve our ability to search for, and study, such extreme RM high-redshift radio galaxies. Resolved images of these systems (typically less than a few arcseconds across) are required, to properly determine the RM distributions across the radio lobes. Current searches have been limited to the largest sources, and to frequencies of $\gtrsim$ 5 GHz. Since the radio flux density drops sharply with frequency, especially for these high-redshift objects, such searches delineate, for the most part, the high surface brightness radio hot spots and core. Furthermore, the high radio frequency in the rest frame of the sources implies that only extremely large RMs can be detected ($\geq$1000 rad m^{-2}). The improved sensitivity of the Ultrasensitive Array will allow imaging the RM distribution across the radio lobes at sub-arcsecond resolutions 1$-$4 GHz, discovering many new extreme RM radio galaxies, and providing much more reliable rotation measure estimates, especially for relatively low RMs ($\leq$ a few hundred rad m^{-2}). These sources can then be studied using modern X-ray and optical telescopes, to determine whether they are in fact the signposts of massive clusters at high redshift.

A.2 The Obscured Universe

Much intriguing astrophysics goes on behind curtains of dust and gas which hide some of the most important processes from our direct view; two notable examples are the formation of stars in dense molecular clouds, and the shielding of massive black holes by the material they themselves accrete. Apart from preventing direct observation at optical, infrared, and in many cases even longer wavelengths, such opacity effects introduce subtle systematic biases; for instance, selecting against dusty sources or obscured lines-of-sight in optical samples. Radio observations by contrast are unaffected by dust extinction, and cover such a wide range in frequency (three orders of magnitude, at the VLA) that no single opacity source is likely to remain dominant. Straddling the transition between synchrotron (cosmic ray), free-free, and dust emission, radio data probe three physical processes common to almost every source in the universe. Superb spatial and spectral resolution complete the picture, making radio synthesis telescopes ideal for high-resolution imaging and dynamical studies of obscured regions.

The Ultrasensitive Array will make this ideal a reality. Continuous frequency coverage will allow imaging of the depths of the giant planets, and help disentangle the complex superposition of dust emission, H II regions, and thermal jets in star-formation regions. The improved continuum sensitivity will result in rapid and reliable astrometry and proper motions, probing the dynamics and measuring the gas accretion rate in the Galactic center, and determining the speed of young stellar outflows as near as possible to their acceleration regions. With the new correlator and a more flexible LO system astronomers will be able to directly observe ambipolar diffusion, and to determine the redshift evolution of the neutral baryon density without biases due to dust obscuration. The remainder of this section describes these and other observations, which are either completely out of the question or (for the very strongest sources) just barely possible with the current instrument. The intent is to illustrate the potential of the telescope, not to exhaust the possibilities: the true domain of the Ultrasensitive Array includes virtually every region where opacity is important, from the densest Galactic clouds to the most distant parts of the universe.

A.2.1 Bistatic Planetary Radar

Bistatic radar observations offer a unique probe of material beneath the solid surfaces of planets, moons, and asteroids. The Ultrasensitive Array offers two major advances for these studies: the ability to observe at 13 cm (2.3 GHz), allowing the VLA to take advantage of powerful 13 cm transmitters at Arecibo and Goldstone; and high enough frequency resolution to make Doppler images of even the smallest bodies in the solar system.

Radar observations of planetary surfaces yield important and unique information on their surface and near-surface structure and composition. Currently the VLA, in combination with the Goldstone 70m antenna, is one of the two most powerful 3.6 cm (8.4 GHz) radar instruments in the world (the other being Arecibo). With this combined instrument, it is possible to unambiguously image the surfaces of Venus, Mercury, and Mars with resolutions as good as 100 km, and to probe the surfaces of the Galilean satellites and Titan. Such observations have led to some of the most exciting results in planetary science in recent years, including the discovery of ice deposits in the polar regions of Mercury (Butler, Muhleman, & Slade 1993); the discovery that significant differences between the ice caps of Mars extend to large depths (Muhleman, Grossman, & Butler 1995); the discovery of a huge region near the equator of Mars which reflects no detectable energy (dubbed "Stealth") (Muhleman , Grossman, & Butler 1995); and the discovery that Titan has no deep global ethane/methane ocean, contrary to theoretical predictions (Muhleman *et al.* 1990). Figure A.12 shows maps of the surface reflectivity of Mars and Mercury as made with this combined radar setup. This setup has also been used to image several near-earth asteroids (see *e.g.*, de Pater *et al.* 1994), and an observation of a comet is planned for the future. The Ultrasensitive

Array will extend these impressive results to the other major radar frequency (2.3 GHz) and allow Doppler imaging of sources as small as the asteroids.

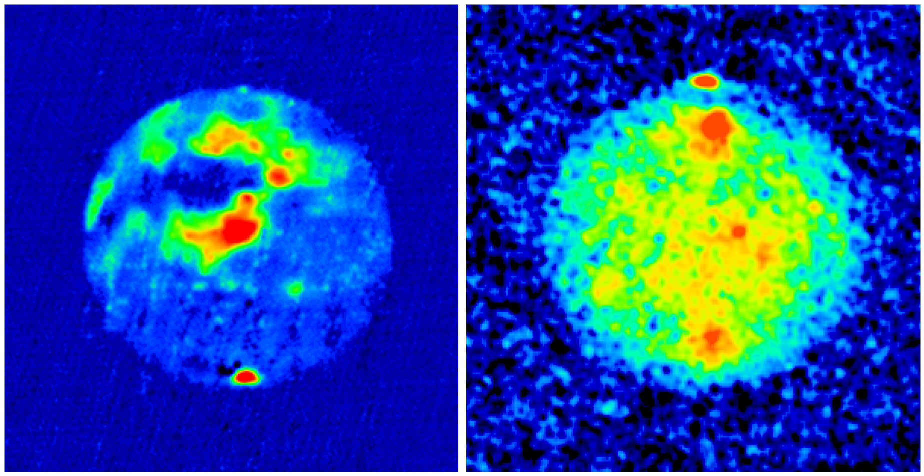


Figure A.12: Radar reflectivity images of Mars (*left*) and Mercury (*right*) made with the combined Goldstone/VLA radar. Courtesy B.J. Butler, D.O. Muhleman, & M.A. Slade (1999).

13 cm (2.3 GHz) Radar: Surface Textures

When an electromagnetic wave is transmitted toward a surface, the amount of energy scattered toward the transmitter is most heavily dependent upon the "roughness" (or "texture") of the surface on size scales of the order of the wavelength of the electromagnetic wave. Measurement of the reflected power yields information about the radar reflectivity – and therefore the composition – of the surface. Comparison of the scattering seen in the sense of circular polarization opposite to that transmitted (due to flat-facet reflections from a dielectric) to that seen in the same sense (caused by multiple reflections or by certain types of ices) yields additional information about surface roughness on scales comparable to the wavelength. So, at 3.6 cm (8.4 GHz), surface structures from slightly sub-cm to some tens of cm are most important, and dictate the amount of received flux. Going to longer wavelengths (such as 13 cm) provides information on surface roughness at larger scales, approaching 1 m. This is very important additional information regarding the state of the surface.

Both the Goldstone 70m and the Arecibo antennas are equipped with very powerful 13 cm (2.3 GHz) transmitters, and could be used in combination with the VLA. While the upgraded Arecibo system will have more power (on the order of 1 MW through a 300m dish), the Goldstone transmitter ($\sim$ 420 kW) is still very important due to its full-sky coverage, which is particularly important for comets and asteroids. The lack of a 13 cm (2.3 GHz) system at the VLA is the only bottleneck preventing very fruitful collaborations with both Arecibo and Goldstone in this area.

From 13 cm radar observations, in combination with 3.6 cm measurements already made, constraints on the depth of the very peculiar "Stealth" region of Mars and on the thickness of polar ices on Mars and Mercury could be obtained. Such observations would also provide the first good polarization measurements of Venus, greatly enhancing the usefulness of radar data from the Magellan mission (which provided only single-polarization radar); 3.6 cm observations are severely compromised by attenuation by the Venusian atmosphere.

High-resolution Doppler Imaging

Because different portions of a rotating planetary surface are approaching the radar line-of-sight at different velocities, the received radar power is spread in frequency by some amount. At 8.4 GHz, $\Delta\nu$ varies from about 27 kHz for Mars to about 50 Hz for Venus. Typical bandwidths for asteroids are on the order of 100 Hz. The frequency spreads scale linearly with frequency, so 2.3 GHz widths are about a factor of four smaller. With the current VLA correlator, the smallest channel width available is 380 Hz for a single IF: only the largest of the asteroids are resolved, and only if data from only one polarization is recorded. For a typical Goldstone-VLA radar observation, unless one is willing to give up the polarization information, the minimum channel width is 760 Hz. Unfortunately, this is wider than all of the returned signals except for Mars and barely comparable to those from the icy satellites. Because of inadequate resolution, Doppler information is lost; in addition, a penalty is paid in signal-to-noise ratio, since in those frequencies where there is no radar echo power, there is still noise power. In fact, in order to maximize the signal-to-noise on a particular surface feature, a channel width equal to the equivalent frequency spread of that feature is desirable. Again, this is currently obtainable for Mars, but not for any other body.

The new correlator provided by the Ultrasensitive Array will remove these restrictions, giving frequency resolutions of a few Hz over bandwidths of many kHz. In the case of Titan, such data could be used to calculate the position of the rotational pole, about which almost nothing is known. Determination of the rotational parameters of asteroids could also be done throughout the main belt, in association with the upgraded Arecibo at 13 cm (2.3 GHz).

Higher Angular Resolution

Ideally one would like spatial resolution at 13 cm which matches the 3.6 cm results, requiring baselines which are about a factor of 4 longer than the longest available in **A** configuration. With these long baselines one could also do interesting work at 3.6 cm, resolving for instance the polar caps of Mars. There is still plenty of flux to be imaged; the problem is simply one of missing antennas. While the New Mexico Array would be ideal for this work, the Pie Town-VLA link (already well under way) will certainly help, effectively doubling the resolution of the current VLA; note that the VLBA antenna at Pie Town already has a 13 cm system in place.

A.2.2 The Giant Planets

Ammonia (NH_3) is the major opacity source at centimeter wavelengths on all giant planets (Figure A.13): thermal radiation from depths with pressures greater than 1 or 2 bars can only be observed at frequencies below the broad NH_3 absorption band near 24 GHz. In effect, the gaseous planets have an "ammonia lid" on them which is nearly impenetrable in the frequency range from about 5 to 300 GHz. The VLA's gap in frequency coverage between 1.4 and 5 GHz greatly limits our ability to map the deep atmospheres of the giant planets, *e.g.*, at the levels of the expected water clouds. A striking example of this limitation is the interpretation of observations of the Comet Shoemaker-Levy 9 impact with Jupiter: quantitative analysis of the event depends on the existence or non-existence of the presently-unseen deep water clouds. VLA observations at 1.4 GHz may be sensing emission at the level of the water clouds but the maximum spatial resolution (about 1.2 arcseconds) limits the quality of the maps, severely for Saturn, Uranus, and Neptune (which has a maximum diameter of 2.5 arcseconds). The water vapor below the putative water clouds is another major opacity source that cannot be penetrated at centimeter wavelengths.

By providing new 2–4 GHz receivers, the Ultrasensitive Array will significantly improve our ability to study the deep atmospheres of Saturn and Uranus, in particular. Jupiter is a very important special case since radio maps of that planet at 1.4 GHz and lower frequencies are

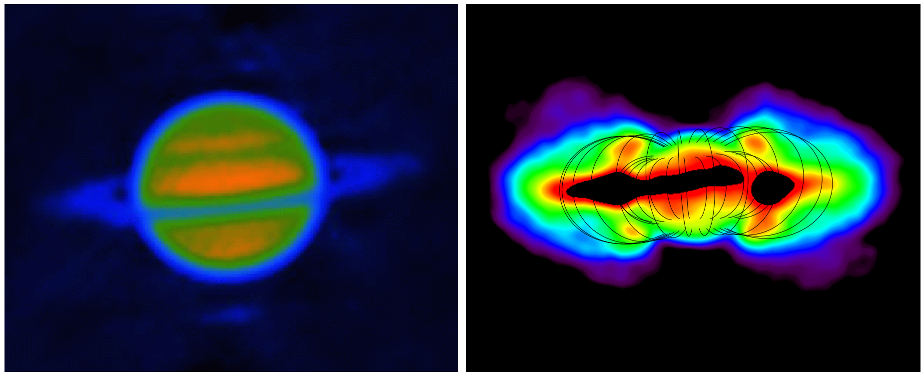


Figure A.13: VLA images of Saturn at 15 GHz (*left*) and Jupiter at 1.4 GHz (*right*). Lines on Jupiter image are theoretical magnetic field lines. Courtesy I. de Pater & F. van der Tak (1999).

completely dominated by non-thermal emission from the radiation belts. The $\sim 3\,\mathrm{GHz}$ window is ideal for escaping the effects of the ammonia clouds, without being completely dominated by the non-thermal emission. Uranus and Neptune will also benefit from the new frequency band, but here the addition of at least one VLBA antenna into the **A** configuration is vital for real progress; fortunately the Pie Town link is now beginning scientific operations, and should be fully integrated into the array shortly.

A.2.3 Young and Proto-stellar Objects

Continuum Observations: Disks, Cores, & Jets

One of the major results of star formation studies has been the clear association between accretion disks and jets (outflows). This makes the spectral energy distributions (SEDs) of young stellar objects (YSOs) a confusing superposition of several components, any or all of which may be present in an individual case: thermal emission from dust in the accretion disk, free-free emission from the Strömgren sphere and/or a thermal outflow, and even synchrotron emission from shocks and/or non-thermal jets (cf. Wilner, Reid, & Menten 1999). The situation is further complicated by optical depth effects: the dust may be optically thick even down to tens of GHz, while on the low-frequency side the free-free emission may just become optically thin at around the same frequencies. Disentangling these complexities requires accurate, high-resolution data over a wide range of frequencies, from a few to a few hundred GHz (cf. Figure A.14). ALMA will be the premiere instrument for dust and molecular studies; the Ultrasensitive Array will provide complementary information on the ionized gas, the relativistic particles, and the densest dust condensations. In particular, VLA observations are needed to address a number of key questions:

- Are jets always accompanied by accretion disks, and vice versa? Present models argue for a symbiotic relationship: the rotational energy of a disk powers and accelerates the jet, while the jet removes angular momentum that would otherwise prevent further accretion.
- Are jets and disks as coupled in high-mass systems as they are in low-mass young stars?
- How are jets accelerated and collimated?
- How do binaries differ from isolated stars? In particular, how frequent are binary disk/jet systems like L1551? Are compact ($r \lesssim 10\,\mathrm{AU}$) proto-planetary disks restricted to binary

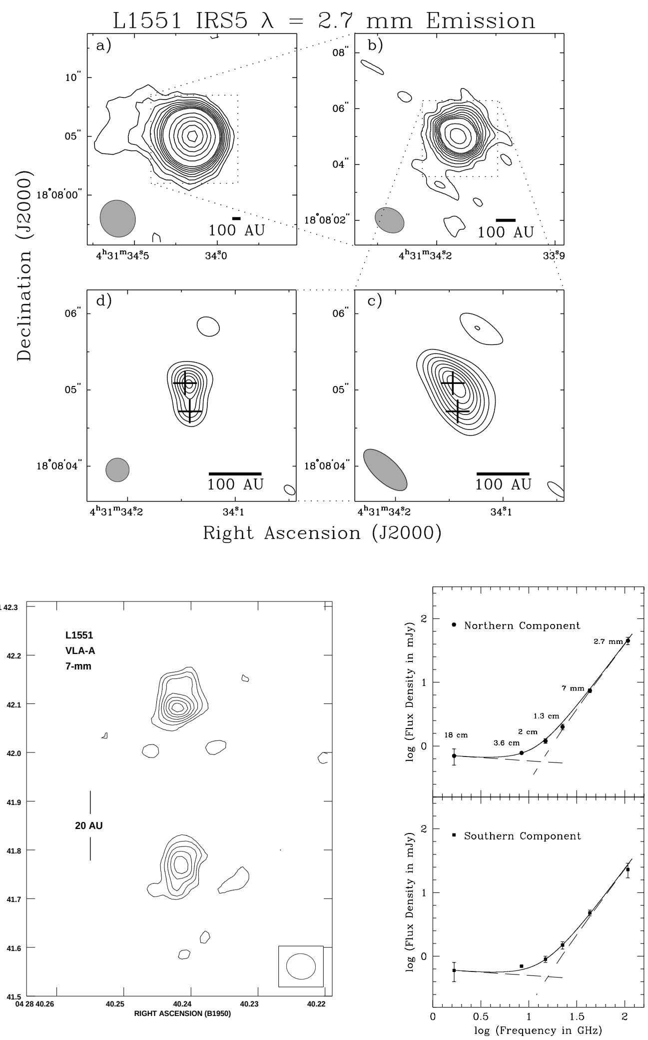


Figure A.14: Dust emission from L1551 IRS5. (*upper*) BIMA images at 110 GHz with increasing angular resolution (Looney *et al.* 1997), showing that L1551 is composed of two circumstellar disks located within a flattened circumbinary structure embedded in an approximately spherical large-scale envelope. (*lower*) VLA images at 45 GHz with 50 milliarcsecond (7 AU) resolution (Rodríguez *et al.* 1998) clearly resolve the individual dust disks surrounding the members of the proto-binary system. The spectral decomposition shows that the dust dominates the emission – and is optically thick – down to $\sim 22\,$GHz, below which optically-thin free-free emission takes over.

stars (again like L1551, Figure A.14), where tidal truncation provides a natural explanation?

- How do planets form? Would compact proto-planetary disks support gravitational instabilities, which could form planets in a few hundred years (*e.g.*, Boss 1997), or must they rely on the conventional million-year core accretion paradigm?

The fundamental data needed to address these questions are (i) SEDs for a large number of YSOs, covering the frequency range from several to hundreds of GHz, and measured independently for the disk, the jet, and the YSO itself; (ii) high-resolution imaging of both jet and disk emission; and (iii) AU-scale imaging of proto-planetary disks, at frequencies where the dust is optically thin enough to permit seeing deep into the accretion disk. The Ultrasensitive Array will supply crucial information for these studies:

- *1–50 GHz SEDs:* Currently the VLA can laboriously detect some tens of sources, and image a handful of those. The Ultrasensitive Array will permit the detection of up to 10,000 YSO disks/jet systems with masses larger than $0.01\,M_\odot$ within 1 kpc of the Sun, with continuous frequency coverage from a few to several tens of GHz, at resolutions sufficient to resolve proto-planetary disks for nearby systems (50 mas $\sim$ 7 AU at 150 pc, somewhat smaller than Saturn's orbit).

- *Deep imaging of known jets:* Radio images typically show a thermal jet extending perhaps an arcsecond from the star, only reappearing in the near-IR several arcseconds out (Figure A.15). Since the jet brightness drops roughly as the inverse square of the distance along the jet, the $\sim$ 30-fold increase in high-frequency sensitivity given by the Ultrasensitive Array should extend the inner radio jets by a factor of five. This will link the radio to the near-IR/optical jet, and allow us to follow the jet all the way from its origin to the working surface (the Herbig-Haro object – also a radio source). With information on the weaker parts of the radio jet we can address questions such as:

  - What is the recent history of the outflow? A few arcseconds from the star corresponds to the last few decades of the outflow, while the near-IR, optical, and molecular data record the time-averaged history of the last hundreds to thousands of years.
  - Is the radio outflow already clumpy (as the near-IR is) a few arcseconds from the source?
  - How important are time variations in the flow compared to interactions with the surrounding medium, in determining the structure of an outflow?

- *Temporal variations in outflows:* Measuring changes in time – variations in flow rate and possibly direction – requires the Ultrasensitive Array, even for relatively bright jets. Moving knots have been detected a few hundred AU from the exciting star in the HH 80-81 jet (Martí, Rodríguez, & Reipurth 1998); this required multi-epoch observations, separated by several years, of one of the brightest outflows in the sky. Are these enhancements in the flow periodic? Are these variations the rule or the exception? The Ultrasensitive Array could provide the answers, detecting proper motions of 300 km/sec at kiloparsec distances with only a month between the observations.

Ambipolar Diffusion: NH_3 vs. N_2H^+ Kinematics

Although the details of pre-stellar and proto-stellar infall and collapse are still poorly understood, it is clear that the fundamental physics involves gravitational and magnetic interactions. In particular, ambipolar diffusion is often invoked to separate the ions from the neutrals, allowing gravitational collapse in the presence of significant magnetic fields. Typical ion/neutral velocity

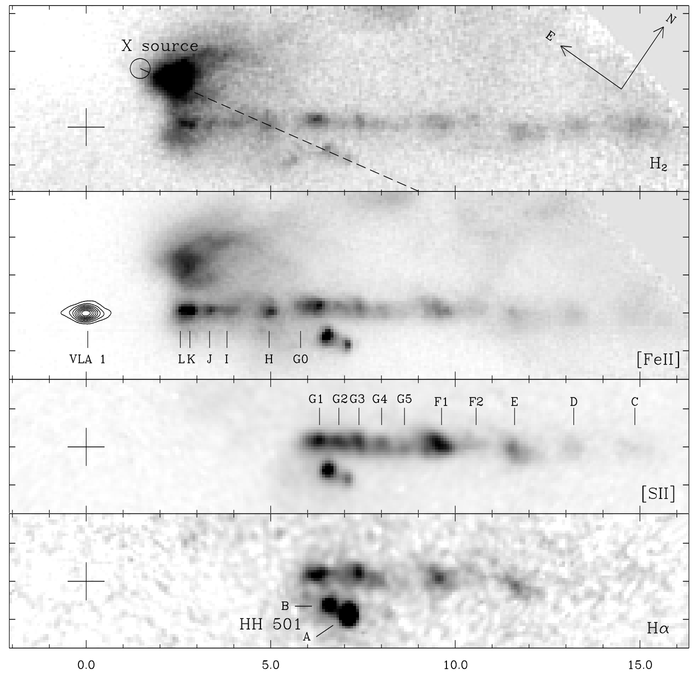


Figure A.15: The thermal jet in HH 1–2, combining VLA 8.4 GHz (*contours*) with HST optical and near-IR (*greyscale*) data. The [Fe II] panel in particular shows the radio emission from the thermal jet (VLA 1) extending about an arcsecond, while the [Fe II] picks up several arcseconds out and extends to ~ 10 arcseconds. The Ultrasensitive Array would give higher resolution and fill in the missing emission, allowing us to follow the jet continuously from the origin to the working surface (the Herbig-Haro objects). Courtesy L. Rodríguez, S. Heathcote, & B. Reipurth (1999).

differences are $\sim 0.1\,\mathrm{km/sec}$, so ideally one would like observations with spectral resolutions of $\sim 0.02\,\mathrm{km/s}$ on scales from ~ 0.1 to $\sim 10^4\,\mathrm{AU}$, of spectral lines which preferentially trace the cold, thermally-dominated gas in a dense core. Most molecular lines seen by ALMA will not be suitable for this sort of work, because (i) their linewidths are dominated by much higher-velocity bulk motions in the gas; (ii) they are optically thick; (iii) they are often high-J transitions, which trace warmer gas; (iv) many molecules freeze out onto grains in pre-stellar cores and only appear again once the proto-star begins to heat the interior. Transitions at centimeter wavelengths – especially NH_3 ($\sim 24\,\mathrm{GHz}$) – are ideal (*e.g.*, Myers & Benson 1983; Wiseman & Ho 1998). The hyperfine structure of ammonia allows the easy derivation of temperatures which, together with the kinematics, gives a clear physical picture of the dense core. NH_3 observations with the Ultrasensitive Array will be particularly efficient because the hyperfine components can be observed simultaneously within a single frequency band. Currently these observations are limited both by sensitivity and narrow bandwidths to a handful of star forming regions. The Ultrasensitive Array will provide unprecedented observations that can track the neutral gas at $\lesssim 0.1\,\mathrm{km/sec}$ velocity resolution, in hundreds of nearby and more distant star forming regions.

Of course, the real question is the interaction between the gravitational potential and the magnetic pressure at the critical radius where the proto-star first forms; one needs a direct comparison between the neutral and the ionized gas. N_2H^+ (at $\sim 80\,\mathrm{GHz}$) shares many of the attractive characteristics of NH_3 (including hyperfine structure). The major difference is that it is ionized, and hence responds directly to the magnetic field. Comparisons of the kinematics of NH_3 as seen by the VLA with ALMA observations of N_2H^+, both at $\sim 0.1\,\mathrm{km/sec}$ resolution, would thus give direct observational constraints on the magnitude and effectiveness of ambipolar diffusion (Benson, Caselli, & Myers 1998).

Measuring Densities with H_2CO

The extended frequency coverage of the Ultrasensitive Array will allow observations of two important transitions of formaldehyde, the 4(1,3)-4(1,4) line at 48.3 GHz (available now only at reduced sensitivity) and the 3(1,2)-3(1,3) line at 29 GHz. These are observed in a number of dense molecular cloud cores believed to harbor extremely young stars; and they act as useful densitometers. These K-doublet transitions have a 'spatial density filter' built into their excitation: for densities below $10^5\,\mathrm{cm}^{-3}$ the formaldehyde lines are in absorption for $J \leq 4$, while for higher densities all are in emission (Mangum 1990). At $J \geq 5$, lines will always be in emission for reasonable temperatures. Thus an observation of the $J = 4$ line, for instance, gives an immediate indication of the local density, with no complicated modeling required (*e.g.*, Mangum & Wootten 1993). Furthermore, the K-doublet lines have intrinsically lower optical depths than the millimeter and submillimeter lines, and hence allow the astronomer to explore deeper into the core of a star-forming molecular cloud. As a final benefit, formaldehyde is less susceptible than many other molecules (notably ammonia) to abundance peculiarities which can render interpretation difficult. Formaldehyde observations at a few tens of GHz will provide astronomers with an excellent densitometer, free from the complex cloud-envelope effects that plague the interpretation of formaldehyde lines at lower frequencies.

The Formation of Massive Stars

Although significant advances have been made in establishing the paradigm of low-mass star formation, the formation of more massive stars remains poorly understood. In particular, for stars above $20\,\mathrm{M}_\odot$, the radiation pressure on dust grains may be strong enough to prevent further accretion. Several models have been proposed to circumvent this, *e.g.*, coalescence of existing proto-stars and accretion through very massive disks (Stahler, Palla, & Ho 2000). The Ultrasensitive Array will make a fundamental contribution to these studies, by allowing simultaneous multi-transition ammonia studies of the hot, dense cores which are the suspected sites of massive star formation. The ammonia molecule is an ideal tracer of temperature gradients from 20 to several hundred Kelvins. Since the hyperfine transitions involved all occur at about the same frequency, they can be observed simultaneously and with almost identical angular resolutions, avoiding major sources of systematic error. In combination with ALMA and SIRTF studies of the heated dust at various physical scales, observations by the Ultrasensitive Array will provide a detailed picture of the distribution, density, and temperature of the gas and dust and of the location and luminosity of the embedded heating sources. The goal is to learn the amount and kinematics of the material, measuring the velocity dispersion among the clumps, and showing whether there are indeed very massive disks around these stars.

Phase-referenced Imaging at High Frequencies

Most, if not all, young stellar objects (YSOs), both high- and low-mass, go through a phase where conditions are conducive to the formation of water masers. These masers have very high brightness temperatures, and thus are excellent probes of the kinematics and dynamics of the gas near the central objects. The rest frequency of the maser line is 22.235 GHz. At this frequency the troposphere of the Earth (also due to this water line) has variable opacity, and introduces rapid interferometric phase variations which are difficult to calibrate out. At nearby frequencies (23–24 GHz) there are also several transitions of the ammonia molecule (see above), which are often too weak to detect in the presence of these phase variations; similarly the broad-band continuum is often smeared out by residual phase errors. With the large bandwidths and excellent spectral resolution allowed by the Ultrasensitive Array's correlator, the water masers and several ammonia transitions can be imaged simultaneously. The masers, a collection of point sources, can be used to track tropospheric variations, and provide nearly perfect phase calibration for both the ammonia lines and the continuum emission. Apart from excellent images of all three components, the ammonia and continuum positions would be automatically referenced to the masers, giving milliarcsecond or better relative astrometry. Measuring several transitions of the ammonia molecule provides an excellent thermometer for the emitting ($\sim 10^5\,\mathrm{cm}^{-3}$) gas, as well as giving kinematic information which can be directly compared to the water masers from much denser ($\sim 10^9\,\mathrm{cm}^{-3}$) gas.

In a similar vein, the Ultrasensitive Array will permit the simultaneous measurement of the sizes, relative positions, and temperatures of the radio photospheres of asymptotic giant branch (AGB) stars. Many of these stars have thick circumstellar envelopes with molecular masers (OH [1.7 GHz], H_2O [22 GHz], and SiO [43 GHz]). Using the strong masers as phase reference sources, continuum observations at nearby frequencies can be made with essentially perfect phase calibration. Absolute positions of the radio photospheres can then be determined since the absolute positions of the masers are readily measured. In addition the excitation and kinematics of the masers can be refined based on the relative position of the star.

A.2.4 The Galactic Center

Sgr A* is the closest example of a super-massive black hole, and offers unique opportunities to study the interaction between such a massive compact object and its environment. The Ultrasensitive Array will lead to substantial progress in two areas of particular interest, the dynamics (through observations of the three-dimensional motions of ionized gas and masers) and the gas accretion rate (by measuring stellar outflows and ionized gas masses and motions).

Three-Dimensional Gas Dynamics

Recent infrared studies of stellar proper motions within the central 0.25 pc (Eckart & Genzel 1997; Ghez *et al.* 1998) have shown that the stars are moving with large velocities, up to 1400 km/s, implying a mass for the central object of $2.6 \times 10^6\,\mathrm{M}_\odot$. Proper motions have recently been reported for the ionized gas as well (Roberts, Yusef-Zadeh, & Goss 1996; Yusef-Zadeh, Wardle, & Parastaran 1997; Zhao & Goss 1998), using VLA observations of free-free emission to measure motions of up to 30 milliarcseconds/year (1200 km/s) (Figure A.16). While the bulk motion of the gas is consistent with the gravitational influence of the black hole, the motions of individual features imply in addition hydrodynamic accelerations, presumably from stellar winds, outflows, or explosive events. These data further suggest that the orbiting ionized gas clouds lose angular momentum and accrete onto the central black hole, with some evidence even of tidal disruption.

Although these initial studies are intriguing, they are limited (by sensitivity) to measuring relatively large proper motions of only the higher flux density regions. The area within a few tenths of a parsec of Sgr A* is full of long, narrow (< 0.1 arcsecond) filaments as well as H II regions; the Ultrasensitive Array's enormous increase in sensitivity will allow proper motion studies of all of these sources. The best measurements so far give proper motions for about a dozen sources with error bars between 35 and 180 km/s over an eight year baseline, depending on signal-to-noise ratio. With a factor of 30 increase in sensitivity, and working at 45 rather than 22 GHz, one can do a factor of eight better in a single year, raising the possibility of measuring accelerations (on 10-year timescales) as well as simple velocities. The number of targets will go up by a similar factor.

In addition to the motions in the plane of the sky, radio observations can probe the line-of-sight velocities through radio recombination lines. Here the wide bandwidths and high spectral resolution of the Ultrasensitive Array help in a different way, by allowing the observer to 'stack' multiple lines in a single observation (up to 17 in the 1.5 GHz band), while retaining sufficient velocity resolution to measure interesting Doppler shifts.

The same characteristics will make the Ultrasensitive Array the perfect instrument for stellar OH, H_2O, and SiO maser searches and proper motion/velocity studies. While the gas dynamics probes hydrodynamical and gravitational effects in local regions like the central parsec, the stellar dynamics are set by the Galactic mass distribution on scales out to hundreds of parsecs. Currently one has to use wide-band single dish telescopes to find roughly where a maser is, then 'zoom in' on the appropriate velocity with the VLA for a good position/proper motion measurement. Apart from being tedious and expensive in observing time, single dishes are not nearly as sensitive as the VLA (both intrinsically, and due to confusion of emission with ubiquitous absorption lines), and are undoubtedly missing many useful dynamical probes. Since the primary beams of the single dishes are much smaller than that of the VLA, those searches also tend to be biased toward 'expected' position/velocity pairings, which may lead to systematic errors in their interpretation.

In sum, with proper motions and radial velocities for 'unattached' ionized gas, H II regions, and masers associated with stars, the Ultrasensitive Array will provide a fully three-dimensional movie of gaseous and stellar motions around the nearest super-massive black hole.

Feeding the Monster

So far we have concentrated on the ionized gas as a probe of the gravitational potential, and of hydrodynamical effects; but the gas is also interesting in its own right. Mass loss from young massive stars in the central 0.1 pc has been suggested as one of the major sources of fuel for the central black hole. Radio observations can determine the stellar mass loss rates directly, as well as tracking the gas as it falls toward the black hole. These winds are also expected to arise from the large number of OB supergiants and WR-type stars which reside in the three dense stellar clusters located within the central 30 pc: (i) the Central cluster (within 0.1 pc of Sgr A*), (ii) the Quintuplet cluster, and (iii) the Arches cluster, itself known to have more than 100 OB supergiants. Radio continuum emission from at least two stellar wind sources (IRS 7 and IRS 13) with mass loss rates of $\sim 10^{-4}\,M_\odot$/yr, together with a proper motion of 30 milliarcseconds/yr for one of them (IRS13), have already been detected using the VLA (Yusef-Zadeh, Roberts, & Biretta 1998). With 30 times the sensitivity, the Ultrasensitive Array will detect mass loss rates as low as $\sim 10^{-6}\,M_\odot$/yr, giving a much more complete picture of mass loss in the very central regions of the Galaxy. The same observations will allow similar advances in the study of very compact H II regions and continuum emission from OH/IR stars. The result will be the most complete picture yet of the star formation environment in the central Galaxy.

A.2.5 Nearby Starburst Galaxies

The dense, central regions of starburst galaxies are almost by definition heavily enshrouded in dust, with $A_V \gtrsim 20$ not unusual. In such cases optical and even infrared imaging may give more insight into the topology of the dust than into the star formation process itself (*e.g.*, Sams *et al.* 1994). In these circumstances radio observations offer a unique dust-free window into the center of the star formation region. Radio continuum images of the nearest starburst galaxies reveal substantial numbers of compact radio sources, a mixture of supernova remnants (SNRs) and H II regions (*e.g.*, Ulvestad & Antonucci 1997), giving two independent determinations of the

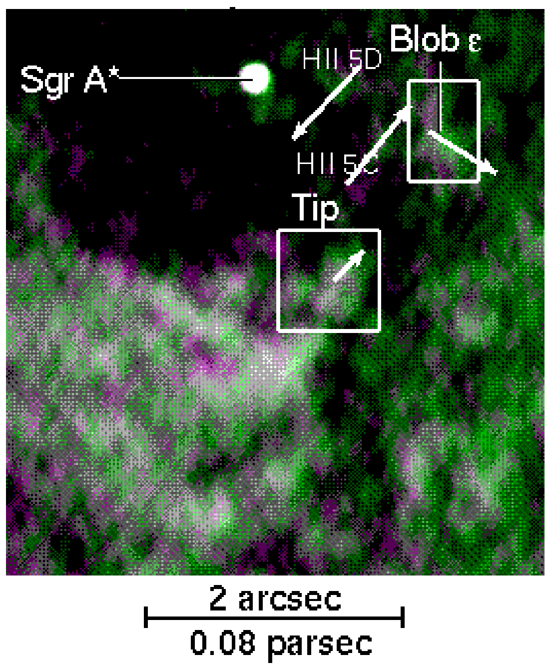


Figure A.16: 22 GHz VLA proper motion measurements for the ionized gas near Sgr A* (courtesy J.H. Zhao 1999), as determined from cross-correlation of data taken between 1991 and 1998. The proper motion vectors are on a relative scale with the value for HII 5c= 1160 km/sec (31 milliarcseconds/year).

star-formation rate, as well as some indications as to the physical conditions in these unusually active regions. Radio recombination lines are also detected from a number of starburst galaxies (*e.g.*, Zhao *et al.* 1997), giving direct constraints on the number, size, and electron densities of the H II regions, as well as providing an unextincted dynamical probe of the central region. Finally, observations of more distant ultraluminous infrared galaxies (*e.g.*, Condon *et al.* 1991) have shown that many of these systems are optically thick even up to 8.4 GHz, requiring enormous emission measures, and suggesting that the central parts of these galaxies may best be thought of as hot, dense H II regions hundreds of parsecs across. Both continuum and line observations are now just at the limit of what is possible; the Ultrasensitive Array will realize the promise of these early detections, by providing (i) the sheer sensitivity needed to extend current samples; (ii) the frequency coverage and spatial resolution necessary to differentiate SNRs from H II regions, and to see into the optically-thick ULIRGs; and (iii) the bandwidths essential to covering the entirety of the $\sim$ 1000 km/sec-broad radio recombination lines.

Continuum Observations

The interpretation of radio continuum observations of starburst galaxies rests primarily on spectral imaging, which alone allows one to differentiate between synchrotron emission from relativistic cosmic ray electrons, and optically-thick and optically-thin thermal emission from ionized gas. Knowing which is which, one can count SNRs and watch them decay, estimate the temperatures and emission measures ($\int n_e^2 \, dl$) of H II regions, and generally gain a better understanding of the star-formation rate, the initial mass function, and the basic conditions of the interstellar medium out of which those stars are formed. Current VLA observations are hobbled by an inability to image the sources at multiple frequencies with sufficient sensitivity and resolution to undertake this decomposition cleanly.

For example, in NGC 253, one of the most nearby starbursts (~ 3 Mpc), a very detailed study at 3 pc resolution gave accurate spectral indices (errors less than 0.2) for only 15 of the 50 or more known sources (Ulvestad & Antonucci 1997). The Ultrasensitive Array will allow parsec-scale imaging of all the known sources (and presumably many more besides) from 15 to 50 GHz, cleanly separating the SNRs from the H II regions, mapping the spectral index (and possibly determining polarization fractions and rotation measures) across the individual SNRs, and determining directly both the brightness temperature and the turnover frequency (and hence the emission measure) of the compact H II regions. Such observations would incidentally either detect or give much stricter limits to the decay of the SNRs (the known remnants have flux densities $\gtrsim 400\,\mu$Jy, 400σ in 12 hours with the Ultrasensitive Array), giving a fairly direct handle on the supernova formation rate. The strongest of these sources could of course be imaged with the VLBA, but there the sensitivity is down by a factor of 30 or more.

Galaxy mergers are another fruitful area for study. The Antennae (NGC 4038/4039) at $\sim$ 21 Mpc is among the nearest and most famous, and both of the galaxies involved are clearly undergoing massive bursts of star formation. Ultraviolet, optical, and infrared observations show a wealth of structures at resolutions of about 0.1 arcseconds (10 pc). Once again however radio observations are the key to finding the most massive star clusters, which are probably buried in dust; a number of compact radio sources have already been detected (Neff *et al.*, *in prep.*), but imaging more than a handful would require microJy sensitivities at high frequencies. The Ultrasensitive Array, possibly in conjunction with the Pie Town VLBA antenna, would be ideal for this work, imaging at least 50 star clusters with $\lesssim 10$ pc resolution.

Radio Recombination Lines

Radio recombination lines (RRLs) have been detected in at least 14 starburst galaxies (Phookun, Anantharamaiah, & Goss 1998; Zhao *et al.* 1997), providing unique constraints on the physical conditions of the gas and the gas dynamics on sub-arcsecond scales, at the very heart (few hundred parsecs) of the star formation region (*e.g.*, Figure A.17). Comparisons between these data and high-resolution observations of dense molecular gas, particularly HCN and HCO^+, will provide an unequalled view of the details of the star formation process in starburst systems. The Ultrasensitive Array is absolutely essential to this work. Currently the radio observations are difficult at best. Detection of a single line at 1 arcsecond resolution in the most sensitive VLA band (8.4 GHz) takes 8 hours or more, and yields a spectrum covering only ~ 900 km/sec at ~ 60 km/sec resolution. Many galaxies (*e.g.*, Arp 220) are already known to have much broader lines, and this velocity resolution is also inadequate for any detailed dynamical studies. Further, while the detection of a single line does (in conjunction with the continuum measurement) place significant constraints on physical conditions, two or more lines would be vastly better, removing much of the confusion as to filling-factors and source sizes which currently dominate the literature.

The Ultrasensitive Array will provide several important advances. With continuous frequency coverage and similar sensitivity from a few to 50 GHz, many more RRLs can be observed, implying much stricter constraints on the emitting material. This is particularly interesting at the high frequencies, since the lines grow stronger with frequency (to a certain point; beyond ~ 50 GHz the lines may begin to mase, complicating the interpretation). A more flexible correlator, and the ability to tune all four IF pairs independently, will allow measuring several lines at once, with more than enough line-free channels and excellent (better than 10 km/sec) velocity resolution. Perhaps even more importantly, since even the broadest bandwidths will give a few hundred km/sec velocity

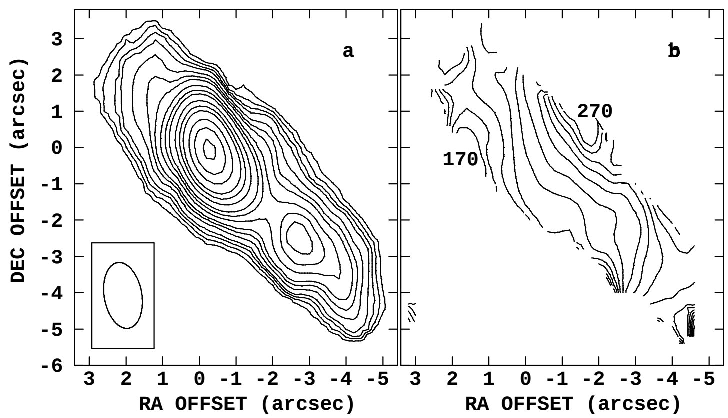


Figure A.17: The radio recombination line H92α (8.4 GHz) in the central $\sim$ 150 pc nearby starburst galaxy NGC 253 (Anantharamaiah & Goss 1996). The *left* panel shows the integrated line emission; the *right* panel shows the velocity field from 170 to 270 in steps of 10 km/sec. The gas in the inner regions is rotating in a plane perpendicular to the main galactic disk. The Ultrasensitive Array will allow similar measurements at several times higher spatial and spectral resolution.

resolution, the new correlator will allow searches for RRLs in *every* deep continuum observation; and simultaneously provide multiple lines to check any putative detection. Since most RRLs are now just at the limit of detectability, the Ultrasensitive Array is likely to lead to a vast increase in the number of known lines, and an equally impressive qualitative improvement in the science which can be done with them.

A.2.6 High Column Density Quasar Absorption Line Systems

With the high spectral resolution over wide bandwidths provided by the Ultrasensitive Array, the VLA will for the first time be able to conduct unbiased spectral line surveys over a large range of redshifts. In this section we describe two possible surveys which together would determine the redshift evolution of the cosmic neutral baryon density from $z = 0$ to 3, without the uncertainties due to dust obscuration inherent in optical studies.

Dust obscuration prevents optical studies of quasar absorption line systems from seeing the highest column density systems: $N(\mathrm{H} + \mathrm{H_2}) \geq 10^{22}$ cm^{-2} corresponds to a visual extinction of more than 6 magnitudes, assuming a Galactic dust-to-gas ratio. These high column density systems are thought to contain most of the neutral baryonic matter in the universe, and are the best tracers of the dense, (pre-) star-forming interstellar medium (ISM) in nascent galaxies. Radio telescopes are well suited to observing such systems, both in the H I 21cm line and in many molecular line transitions, thereby providing very detailed physical probes of the absorbing material. The major difficulty in studying these high column density absorption line systems is finding them, since optical selection is no longer applicable. To date, only four redshifted molecular absorption line systems are known, all seen toward 'red quasars', meaning flat spectrum radio sources with faint, or absent, optical counter-parts (for references, see Carilli *et al.* 1999). The Ultrasensitive Array will be ideal both for finding and for studying these systems, due to the combination of excellent sensitivity, very wide field-of-view (45 arcminutes at 1 GHz), high spectral resolution, and broad bandwidth.

Detecting H I 21cm and molecular absorption in and toward high-redshift galaxies opens up many new windows on the detailed physics of the dense ISM in high-redshift galaxies, including:

- Determining the redshift distribution of high column density absorption line systems (*i.e.*, 'damped Lyα systems'), and hence the evolution of the cosmic density of neutral baryonic material, without uncertainties due to dust obscuration.
- High resolution imaging of the cloud structure and dynamics on scales ranging from parsecs to kpc, including (i) imaging the circumnuclear gas in active galactic nuclei, (ii) imaging the gas in star forming disks in ultra-luminous infrared galaxies, and (iii) imaging the ISM and large-scale dynamics of gas in 'normal' galaxies at high z.
- Determining the evolution of the cosmic microwave background temperature by measuring the excitation temperature of the molecular gas (Wiklind & Combes 1996).
- Studying astrochemistry at high redshift, including: (i) determining the water and molecular oxygen abundances (these molecules cannot be studied in our own Galaxy with ground-based observations due to atmospheric absorption lines), and (ii) studying the evolution of the deuterium abundance in the molecular ISM.
- Determining the evolution of basic physical constants, such as the fine structure constant and the nucleon mass (Drinkwater *et al.* 1998).
- In the case of absorption by gravitational lenses, determining the dynamical mass of the lensing galaxy, hence providing a fundamental check on gravitational lens theory (Chengalur & de Bruyn 1999).

The Ultrasensitive Array will play a dominant role in such studies, due to its high sensitivity, high resolution, and wide field of view, and the natural interference rejection afforded by an interferometer.

Redshifted Molecular Absorption

Searches for molecular absorption line systems are impossible with the current VLA due to the correlator and the limited bandwidth: the VLA at the moment is limited to a 50 MHz bandwidth (dual polarization) at 43 GHz with eight spectral channels, implying a total velocity range covered of only 300 km/sec (Figure A.18). The new VLA correlator will allow searches for molecular absorption line systems over a large range in redshift toward faint, flat spectrum radio sources. As an example, the Ultrasensitive Array could survey the frequency range 26 to 50 GHz with a velocity resolution of 50 km/sec to a noise level of 0.05 mJy/channel in under 24 hours. This corresponds to the 5σ detection of 10% absorption toward 2.5 mJy sources, of which there are ~ 7 per square degree. Possible lines include the first-order transition of CO at redshifts between 1.3 and 3.4, and HCN and HCO^+ at redshifts between 0.7 and 2.3.

Redshifted H I 21cm Absorption

Another, complementary project would be a search for H I 21cm absorption line systems toward high-redshift radio-loud quasars and radio galaxies; with the new Cassegrain system one could observe from $z = 0$ to 0.4. This could be done toward known high-redshift radio sources. However, the new VLA correlator allows the interesting possibility of blind surveys over a large area and redshift range. In 200 hours, the Ultrasensitive Array could survey the redshift range 0 to 0.4 to a 4% optical depth limit (1σ) toward 1.5 mJy background continuum sources at 30 km/sec velocity resolution, corresponding to an $N(\text{H I})$ limit of $2{\times}10^{20}$ cm^{-2} assuming a spin temperature

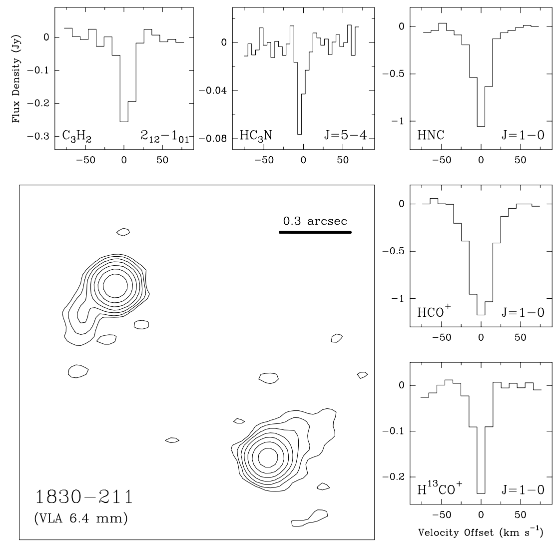


Figure A.18: The contour plot shows a VLA image of the 'Einstein ring' radio source PKS 1830−211 at 43 GHz with a resolution of 0.1″. The source redshift is 2.507. The spectra show molecular absorption by gas in the lensing galaxy, as observed with the Very Large Array toward the southwest radio component. Zero velocity corresponds to a heliocentric redshift of 0.88582 (Carilli, Menten, & Moore 1999).

of 100 K. Source counts imply about 55 background radio sources with flux densities of 1.5 mJy or more at 1 GHz in a VLA primary beam (45 arcminutes FWHM), most of which will be at $z \geq 0.5$. Ultraviolet studies with the HST indicate about one high column density absorption system ($N \geq 10^{21}$ cm^{-2}) per unit redshift in this range. Hence we expect at least 22 systems to be detected at $\geq 5\sigma$ in such a survey. Note that this is a *lower limit* to the number of expected systems, due to the dust bias inherent in optical studies. Moreover, given that all the sources surveyed are within 45 arcminutes of each other, these data could also be used to study large-scale structure in the universe by studying the correlation between absorption systems as a function of redshift and source angular separation. Phase II of the VLA Expansion Project would in addition (i) double the redshift range, allowing observations from $z = 0$ to 0.8 in one go (using the prime focus system); and (ii) provide sub-arcsecond imaging of any detected gas toward the (typically) extended background continuum radio source.

A.3 The Transient Universe

Radio telescopes are in many ways ideal for observations of transient (highly-variable) sources. Observations at centimeter wavelengths are naturally sensitive to non-thermal processes and relativistic particles, and hence to jets, shocks, and particle acceleration associated with transient phenomena and compact sources. Since they can observe over many decades in frequency, radio instruments can characterize both absorption and emission processes in exquisite detail, both at a given epoch and as a function of time. A radio telescope can also observe the entire sky visible from its location, day or night, 365 days a year, providing accurate and consistent flux densities and astrometry; this allows uniform observations of variability and proper motions, on timescales from milliseconds (*e.g.*, pulsars) to decades (*e.g.*, H II regions and supernova remnants). The VLA in particular has provided multi-frequency radio light curves of such diverse sources as solar flares, novae, and gamma-ray bursts, and monitored the expansion of supernova remnants and extragalactic jets; these data have been used to derive sizes, distances, velocities, and magnetic field strengths, as well as the mass and clumpiness of both ejecta and surrounding gas. Almost every important variable source found at other wavelengths has been observed with the VLA, from X-ray transients to optical novae to gamma-ray bursts.

The Ultrasensitive Array will provide even more impressive capabilities. The enhanced *instantaneous* sensitivity is particularly important, because long integrations are generally not an option for variable sources. With improved sensitivity, detailed observations can be made of more typical and more distant objects; these larger samples will yield a much better determination of the luminosity function, particularly important for transient sources as they often differ enormously from event to event. For individual sources, going fainter means observing both earlier (while the source is still optically thick) and longer (as the flux density fades): the former gives important information on particle acceleration and the absorbing material, while the latter connects the initial event to its environment (through deceleration, growing instabilities, or simply abrupt changes in flux signaling sudden changes in a shock front). The enhanced sensitivity also allows observations over a wider range of frequencies, important again for absorption, but also for resolution – the Ultrasensitive Array will be able to detect at 45 GHz any source strong enough to be seen now by the VLA at any frequency, giving spatial resolutions as high as 50 milliarcseconds. Multi-frequency synthesis will also allow better imaging in the limited time which can be allocated at the last minute, as well as opening the possibility of producing high-fidelity images using only a subarray of the full VLA (which may make scheduling much easier). Continuous frequency coverage from 1 to 50 GHz will allow one to 'zoom in' on the right frequency for any particular phenomenon (*e.g.*, refractive scintillation), while the availability of high spectral resolution over wide bands will allow line searches 'for free' toward any transient event, giving instant H I kinematic distances within the Galaxy, permitting extragalactic sources to be used as wide-band absorption line probes, and providing limits on radio recombination lines toward thermal sources like novae. Finally, an observational point which may be the most important of all, the shift to dynamic scheduling, coupled with the enormous increase in sensitivity (which makes even very short observations useful), will lead to much faster reaction times and much more detailed light curves. Currently, unless one is very lucky (the transient is found during business hours, both the local scheduler and the first observer contacted are available and willing, and act quickly and decisively), there is an inevitable delay of at least a day, and often a week, in getting onto the source. Since the initial rise is often critical to the interpretation (*e.g.*, was the source beamed?), and since some sources at least turn on and decay very rapidly (*e.g.*, the prompt radio emission from SN 1987A, and the optical outburst of GRB 990123), this delay means the loss of important and irreplaceable information.

The rest of this section enlarges on these themes, as applied to a few specific types of transient sources; but the key point is that the Ultrasensitive Array will mark a major advance in the study of *all* such sources, from local scattering events to the most energetic explosions in the universe.

A.3.1 Coronal Heating

One of the fundamental questions in solar physics is how the solar corona maintains its high temperature of several million Kelvin above a surface with a temperature of 6000 K. The power needed to maintain the corona above an active region against radiation and conduction losses is $> 10^{28}$ erg s^{-1}. The leading theories for coronal heating involve either some form of resonant wave heating or a superposition of many tiny flare-like events ("nanoflares").

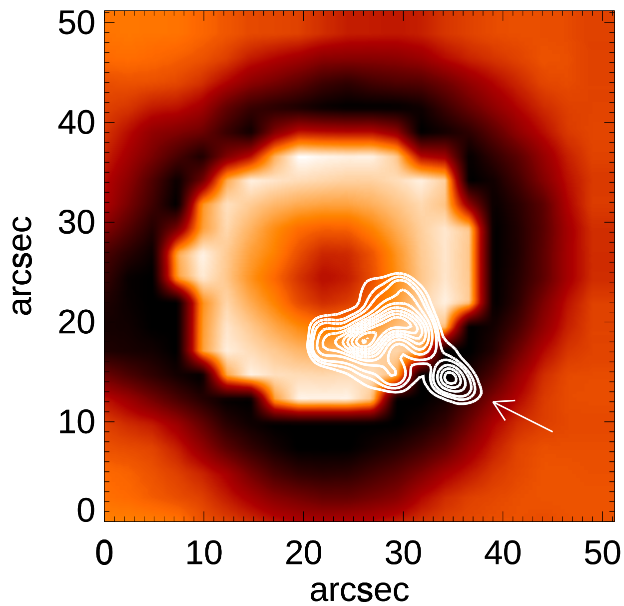


Figure A.19: Example of radio emission from a transient microwave brightening (Gopalswamy *et al.* 1994). The contours represent 15 GHz emission observed by the VLA. The greyscale shows the umbra of a sunspot seen in white light. The total energy liberated by the event was $\sim 10^{24}$ ergs.

Wave Heating

Wave heating models make specific predictions of where and on what timescales energy deposition occurs in coronal magnetic loops. The Ultrasensitive Array will provide a detailed history of the temperature, density, and magnetic field in coronal loops in active regions, from which the rate of energy deposition can be calculated as a function of position and time.

Nanoflares

The role of "nanoflares" – tiny, flare-like releases of energy from small magnetic reconnection events – depends critically on the rate at which they occur. Numerous studies have shown that X-ray events ranging over as much as five orders of magnitude in energy, from 10^{27} to 10^{32} erg, form a single power-law with slope 1.5−1.6. Smaller events cannot be energetically significant relative to the larger events unless the rate distribution at lower energies becomes significantly steeper.

Microwave observations are the *only* means available for probing these tiny energy release events. Even events near the limit of visibility for the Yohkoh Soft X-Ray Telescope (SXT) are

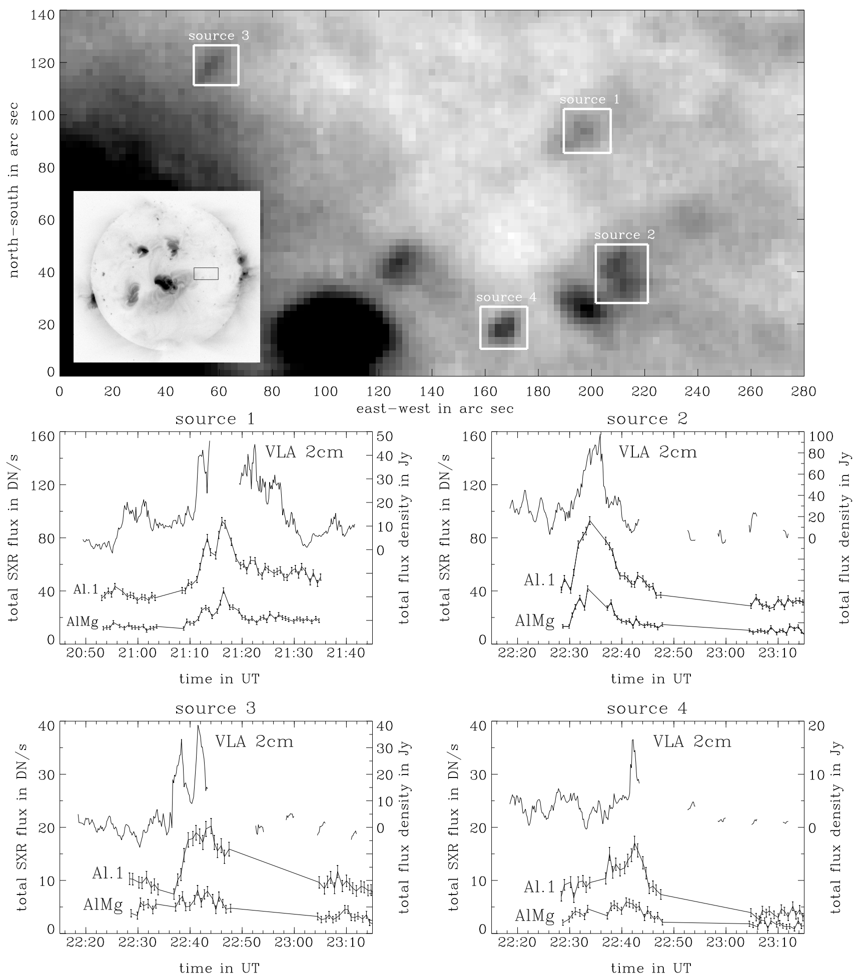


Figure A.20: Temporal evolution of network flares observed in soft X-ray (SXR) and radio emission on 20 Feb 1995 (Krucker *et al.* 1997). The image at the top shows the region observed in SXRs; the inset shows its location on the solar disk. Enhanced emission is dark. The locations of network flares are indicated by boxes. The plots below show the temporal variations of the SXR flux in the Al.1 and AlMg filters, and the 2 cm radio emission for the different network flares.

easily detectable in total power by small non-imaging radio telescopes. Interferometric observations are vastly more sensitive, as demonstrated by VLA detections of events over the penumbra of a large sunspot (Figure A.19) which are two orders of magnitude weaker in energy content than those detected in soft X-rays: the inferred energy release rates are as low as 3×10^{22} erg/sec, and total energies are not much above Parker's canonical nanoflare value of 10^{24} ergs. Recent observations using multi-band VLA and SOHO[2] EIT[3] and MDI[4] data have shown that even tiny transient events in the quiet chromospheric network are, in fact, flare-like (Figure A.20). Attempts to characterize the distribution function of these small events have so far given mixed results. The Ultrasensitive Array will significantly improve on the state-of-the-art by wide, continuous frequency coverage with vastly improved continuum sensitivity. The resulting observations will extend and quantify the flare/microflare/nanoflare distribution function at the smallest energies, and show definitively whether nanoflares heat the solar corona.

A.3.2 Radio Stars

Prior to the VLA's completion, only a few stars were confirmed radio sources, and those comprised an oddball collection of extreme objects. Thanks primarily to its great sensitivity, the VLA has completely revolutionized the field of stellar radio astronomy, with detections across almost the whole Hertzsprung-Russell diagram, and the opening of entire new fields of research (see Figure A.21). The Ultrasensitive Array will permit similarly impressive advances in this field, including the study of time variability in sources which can now barely be detected, and the characterization of the radio properties of stars over a much wider range of stellar activity. One major milestone will be the detection for the first time of solar-level activity on other stars.

Solar Analogs & Ordinary Stars

The stars detected as radio sources so far are all very luminous compared to the Sun; these are the same active stars which show strong variability at other wavelengths, notably in optical flaring and in X–rays. This gap between solar and stellar activity makes it difficult to fit the Sun into the general picture of stellar radio emission – we do not for instance know whether the Sun is a typical G star in its magnetic field strength and flaring activity, nor do we have any information on changes in the solar radio emission on timescales longer than the historical record. The Ultrasensitive Array will make a fundamental contribution, by detecting for the first time other stars with radio emission as weak as the Sun, and more generally by investigating the radio properties of *ordinary* stars, not just the very active minority we can currently study. For example, of the several thousand stars within 25 parsec of the Sun, only about 100 have been detected by the VLA – the Ultrasensitive Array should detect almost all of them.

Young Stars

The VLA has shown that stars $\sim 10^6$ years old tend to be very luminous radio sources, detecting them as far away as the Orion nebula at 500 pc; but by 10^7 years, they have faded enormously. Currently there are too few detections (tens of stars at $\sim 10^6$ years, none at $\sim 10^7$) to understand the cause of this abrupt decline: we need to correlate luminosity levels with other stellar parameters such as rotation rate and age in order to understand what generates the radio activity. Only the factor of 10$-$30 improvement in sensitivity provided by the Ultrasensitive Array will give the required sample of older stars.

[2]Solar and Heliospheric Observatory
[3]Extreme-Ultraviolet Imaging Telescope
[4]Michelson Doppler Imager

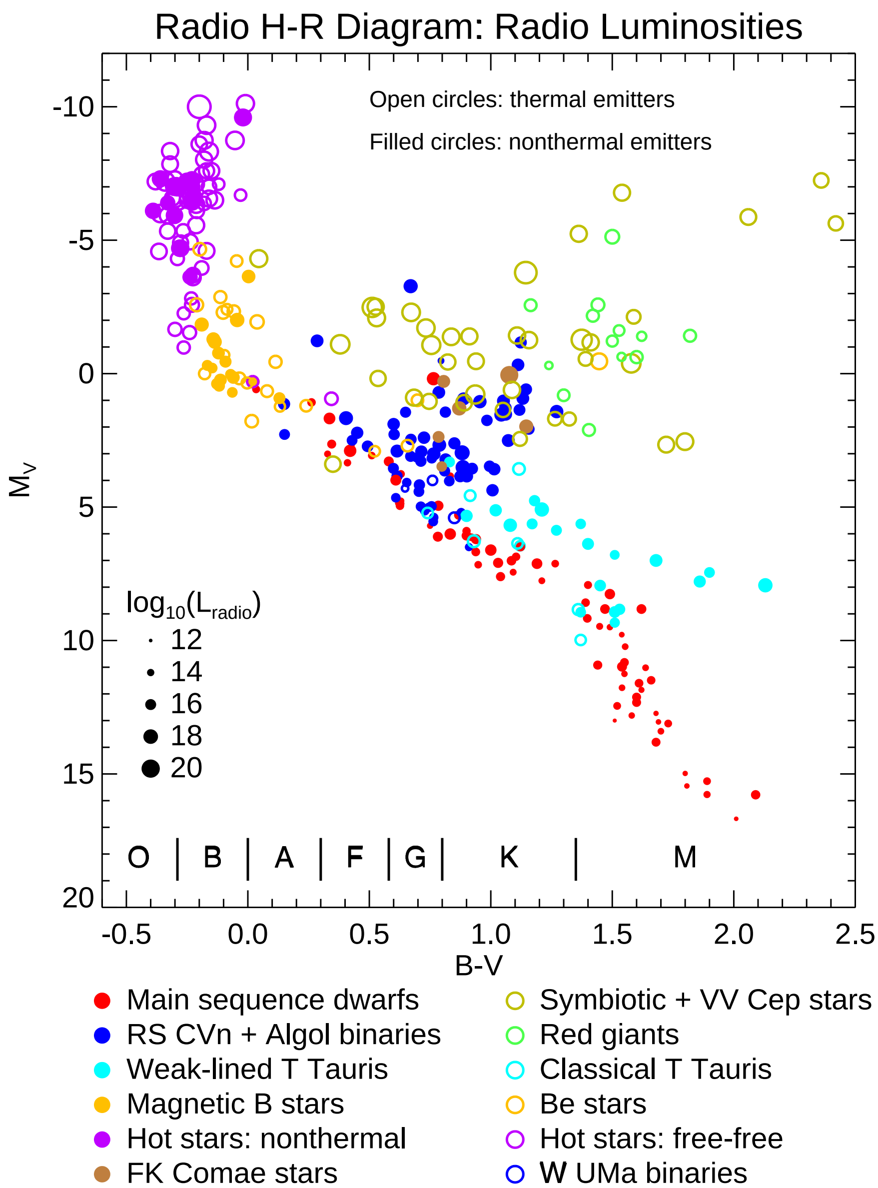


Figure A.21: An HR diagram for stars detected as radio emitters. For hot stars corrections for extinction have been applied where available. The size of the symbol reflects the radio luminosity of the star as labeled (in ergs s^{-1} Hz^{-1}). The Sun's radio luminosity is of order 10^{11} ergs s^{-1} Hz^{-1} at 8 GHz. The diagram is restricted to stars for which distances are available, and therefore is an incomplete but reasonably representative sample of all the stars detected by the VLA. Stars believed to be nonthermal emitters are represented by filled symbols, while thermal emitters are shown by open symbols.

Interday Variability in Cool Stars

The radio variability of cool stars on timescales of days is analogous to the Sun's slowly–varying emission, which results jointly from intrinsic changes in active regions on the surface, and from the rotation of those regions on and off the visible hemisphere. Nonthermal emission from electrons accelerated in the atmospheres of very active stars is detected, but the thermal emission from hot gas in strong magnetic fields, which is how the Sun's slowly–varying emission is produced, is just below detectability. Observations of this form of emission (its spectral and polarization behavior and time variability) can be used to infer the magnetic structure of the stellar atmospheres, which is crucial for our understanding of the solar–stellar connection. The Ultrasensitive Array will be able to detect this emission from hundreds of nearby stars.

Radio Flares in Pre-main-sequence Stars

The VLA has detected radio flares from 50−100 pre-main-sequence stars in the Taurus, Ophiuchus, Chameleon and Orion molecular clouds, but typically at flux levels of order 1 mJy, making polarization and variability studies very difficult. The Ultrasensitive Array will detect many more, perhaps thousands, of these stars, and permit detailed studies of their radio properties. This is particularly exciting because the role of magnetic fields in these very young stars is at best poorly understood; we do not know whether their activity arises from the same process as occurs in the Sun (a stellar dynamo at the base of the convection zone), or whether an entirely distinct physical mechanism is operating. Many of these stars are believed to be fully convective, in which case the generation of magnetic fields in the stellar interior may take on a completely different form.

Physical Processes in Stellar Atmospheres

The large instantaneous bandwidths and broadband spectral processing capabilities of the Ultrasensitive Array will allow the first detailed spectroscopic observations of coherent bursts in dMe and RS CVn stars. The basic properties are clear – highly circularly polarized coherent radiation, a rich variety of structure in both time and frequency, brightness temperatures which can exceed 10^{16} K – but the basic emission mechanisms have not yet been identified. Early radio observations of the Sun identified the role of particle beams and of shocks in the solar corona; more detailed observations of these coherent radio bursts on other stars may similarly open up completely new areas of astrophysical research. The extremely high brightness temperatures of certain coherent bursts may also drive phenomena which are impossible to study in other astrophysical objects, *e.g.*, stimulated Compton or Raman scattering.

A.3.3 Galactic Novae: Light Curves, Masses, and 3D Imaging

Galactic novae are the closest natural thermonuclear explosions to the Sun. Some tens of times each year a white dwarf in a binary star system in the Galaxy accumulates enough matter on its electron-degenerate surface to ignite a thermonuclear runaway explosion; the resulting blast produces substantial radio, infrared, optical, and ultraviolet radiation, which, unless obscured by dust, can be visible for weeks or months. The Ultrasensitive Array will provide excellent radio light curves and images of every nova found in the Galaxy, measuring shell masses, showing directly the varying physical conditions within the shell, and (through radio recombination lines) measuring the kinematics throughout the source as well.

Radio emissions are uniquely valuable in providing a direct look at the entirety of the ejected mass; optical lines by contrast pick out regions of specific densities or temperatures. The potential of radio observations is best illustrated by the two novae which have been imaged in some detail at radio wavelengths, Nova QU Vul 1984 (Taylor *et al.* 1988) and V1974 Cyg 1992 (Pavelin *et al.* 1993;

Hjellming 1996a,b). Both confirmed the tentative conclusion from radio light curve fitting: nova explosions eject five to ten times more mass ($4.8 \times 10^{-4}\,M_\odot$ for QU Vul, $3.1 \times 10^{-4}\,M_\odot$ for V1974 Cyg) than predicted by theoretical models of the explosion process. By contrast, optical mass estimates are typically a factor of ten lower but are derived mainly from spectral line observations that measure the mass only of the inner regions. The radio results imply either that white dwarfs are significantly more massive than usually supposed, or that the explosion models themselves are wrong. This is a severe problem, because most known biases (*e.g.*, unmodeled opacities) work in the opposite sense, and because the physics is believed to be simple enough that there is little room for more fundamental disagreements.

Apart from simple mass estimates, sequences of radio images can show directly the *three-dimensional* distribution of both temperature and density within the source: the decreasing optical depth effectively 'peels the onion,' allowing one to see deeper and deeper into the source. The imaging sequence of V1974 Cyg (Figure A.22), for instance, reveal high temperatures (10^5 K) in the nova shell even 80–100 days after the outburst. The images also show clear morphological changes as the emission becomes optically thin, revealing the distribution of the gas as a clumpy ellipsoid with a 90-degree change in orientation between the outer and inner shell. Rather surprisingly, a detailed fit to these images also reproduces the shapes of the optical lines quite well (Hjellming 1996a,b).

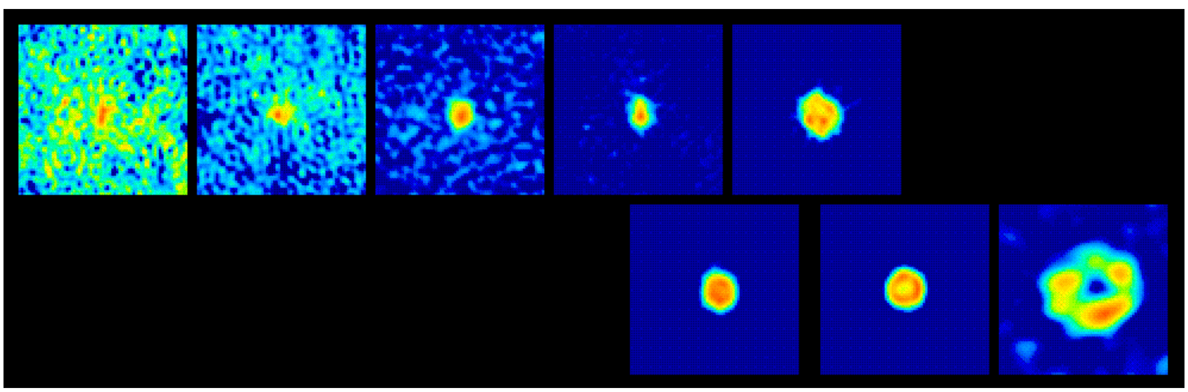


Figure A.22: Merlin (*upper*) and VLA (*lower*) images of Nova V1974 Cyg 1992 (Pavelin *et al.* 1993; Hjellming 1996a,b). The 5 GHz Merlin data were taken 81, 106, 155, 173, and 271 days after outburst; the 22.5 GHz VLA data were taken 255, 313, and 769 days after outburst. Note the evolution from a centered-filled source highly elongated north-south, to a shell slightly elongated east-west. This corresponds to the change from optically thick to optically thin emission, with the later images 'peeling away' the outer skin to reveal the three-dimensional structure.

The combination of detailed, multi-frequency radio light curves and radio imaging covering both the optically thick and optically thin stages thus provides an excellent observational probe of the *entire* gaseous content of ejected nova shells. The source elongation, shell thickness, and ejecta clumpiness derived from these images can then be combined with ultraviolet, infrared, and optical data to yield very detailed and accurate models. The Ultrasensitive Array will make these observations routine, as well as adding important new capabilities. For the first time, we will:

- *detect and follow the light curves of not just a few, but all novae that are found in our Galaxy.* The strongest novae are some tens of mJy at a few kpc; even the most distant and faintest will therefore peak at some tens of microJy, easily detectable in an hour with the post-expansion

VLA. Detailed radio light curves can be used to derive good estimates of the shell velocity and total shell mass, but these data exist so far for only nine sources. The Ultrasensitive Array will provide multi-frequency monitoring of even the faintest sources (potentially several every year) over their entire lifetimes, from the faint radio rise to the optically-thin decay.

- *resolve and image most nova shells to determine brightness temperatures, temperatures during optically thick phases, and the evolution of both radial and clumping mass distributions.* The inner and outer velocities of nova shells range from 500 to 5,000 km/sec, with 1000–3000 km/sec being most common. The angular size is therefore

$$\theta = 210\,\mathrm{mas} \cdot \frac{v}{1000\ \mathrm{km/sec}} \cdot \frac{t_{\mathrm{year}}}{d_{\mathrm{kpc}}} \tag{A.1}$$

  By providing superb sensitivity at 33 and 45 GHz, the Ultrasensitive Array will produce excellent images at $\sim$ 50 milliarcsecond resolution, resolving novae from a few months to many years after the outburst.
  After Phase II of the VLA Expansion Project, the New Mexico Array will give a factor of ten higher resolution at these frequencies, resolving the sources within a few *days* of the explosion; the longer baselines will also allow high-resolution observations over a significant range of frequencies, giving direct spectral index maps.

- *measure the velocity profiles of radio recombination lines in some cases, allowing fits to the 3-D spatial and clumping distribution of the gas.* This cannot be done with the current VLA, because the lines are both very weak (a few μJy) and very broad (1000s of km/sec); only the broad bandwidths and excellent high-frequency sensitivity of the Ultrasensitive Array will make these observations possible. Because the line-to-continuum ratio rises as $\nu^{1.1}$, while the linewidths (in MHz) increase as ν, 33 and 45 GHz are the optimal observing frequencies. Assuming a 2000 km/sec line, one could achieve 5σ detections in 40 km/sec channels in 12 hours, even for 10 mJy sources. For novae with higher flux densities the Ultrasensitive Array will be able to image the clumps and structure directly in three dimensions, with no strong density or temperature selection of the regions being detected.

- *address the major mismatch between the observed shell masses and those predicted from current theoretical modeling.* With only a handful of novae imaged at the moment, and those the strongest, best-studied, and hence known to be the most unusual, it is not clear whether this disagreement is fundamental or idiosyncratic. The observation of more and more typical novae will pin this down, and possibly aid the interpretation by suggesting links between the severity of the shortfall and other physical parameters.

Recurrent Novae

The rarer class of recurrent novae occur in binary systems with longer orbital periods than those of classical novae. Indeed, in the best-studied members of this class, the mass-donating star is a red giant and outbursts probably occur via thermonuclear runaway on the surface of its mass-accreting white dwarf companion. Unlike classical novae, where the inter-outburst period is thought to be 10^4 to 10^5 years, recurrent nova outbursts occur on timescales of decades.

The best-studied outburst of any recurrent nova was that of RS Oph in 1985 (*e.g.*, Bode 1987). It turned out to be a strong and rapidly evolving object from the radio to the X-ray. Models of the outburst involve the interaction of the high-velocity ejecta with the slower wind of the red giant, built up since the last outburst. In many ways, what then follows is comparable to the evolution of a supernova remnant, but on timescales of months rather than millennia. Unfortunately, although the light curve coverage of RS Oph was very detailed, only two images were obtained in the radio, and then at the margins of detection. Real tests of these models await the next recurrent nova; the Ultrasensitive Array will ensure that even a weak one will be detected, and allow for excellent imaging (if it is anything like RS Oph) for many hundreds of days.

A.3.4 X-ray Transients: Relativistic Jets in the Milky Way

The advent of all-sky X-ray monitoring satellites like Ginga, CGRO BATSE, and RXTE ASM has given new impetus to the study of X-ray transients, primarily X-ray binaries powered by Roche lobe overflow or wind accretion onto a neutron star or black hole. Radio follow-up observations have led to some spectacular results, including the first clear correlations between X-ray and radio emission, tying accretion disk instabilities to relativistic particle ejection; the discovery of the first Galactic superluminal jet sources (GRS 1915+105 [Mirabel & Rodríguez 1994], GRO J1655-40 [Hjellming & Rupen 1995; Figure A.23], & 1748-288 [Hjellming *et al.*, *in prep.*]); and the rapid imaging of the radio emission from a large number of these sources, showing that relativistic jets are typical byproducts of accretion onto massive, compact objects. Radio monitoring is now used as a standard trigger on virtually all target-of-opportunity X-ray observations. Despite these impressive results, there are many outstanding questions:

- Do disk instabilities (as seen in X-rays) always trigger relativistic particle acceleration (as seen in the radio)?
- Does the speed of the jet reflect the mass or rotation rate of the compact object?
- Do relativistic jets really obey the extragalactic lore built up over the past decades? For example, does a one-sided jet always indicate strong Doppler boosting, and are jets always emitted perpendicular to the originating accretion disks?
- How do individual jet ejecta decay over time?
- Do all jets precess? What determines their precession periods? How is this related to warping and precession of the accretion disk?
- Do quiescent accretion disks also produce radio emission (as predicted by ADAF[5] and other models)? What are the implied accretion rates?

All of these questions are answerable, given sensitive and reliable monitoring and imaging of a substantial number of sources. The Ultrasensitive Array will make this possible.

Imaging

Although the rewards are great, imaging relativistic jets in the Galaxy is a challenging business, first because long-lasting, high-flux events are so rare (perhaps one a year), and second because the sources evolve so rapidly. A characteristic angular size is

$$\theta = 170\,\mathrm{mas}\,\beta_{app}\,t\,[\mathrm{days}]/d\,[\mathrm{kpc}]$$

where $0.1 \lesssim \beta_{app} \lesssim 2$, and $1 \lesssim d\,[\mathrm{kpc}] \lesssim 15$. Ten days therefore corresponds to 60 milliarcseconds (about the size of the VLA's 45 GHz beam in **A** configuration) for a $0.3c$ source at the Galactic Center. The actual timescale is set by the decay of the ejecta, which in exceptional cases might be weeks or months, but is more usually a few days to a week. Such sources rapidly expand beyond the size-scales sampled by the VLBA (see Figure A.23), but only the most long-lived can be imaged

[5] Advection Dominated Accretion Flow.

with the current VLA, observing in **A** configuration at the highest frequencies. Even then the sensitivity of the current 22 GHz system leaves much to be desired for such steep-spectrum sources (45 GHz is even worse), and the weak, extended features which are most interesting are seldom detectable. Spectral index maps are currently impossible.

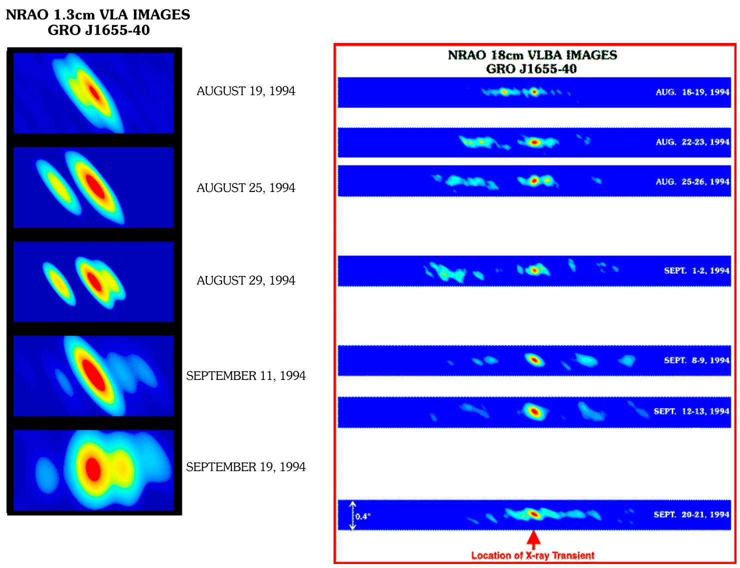


Figure A.23: VLA 22 GHz (*left*) and VLBA 1.6 GHz (*right*) images of GRO J1655−40, a Galactic superluminal jet source (Hjellming & Rupen 1995). Note the timescale. By the second epoch the source was so extended that the VLBA missed more than half the flux density, picking out only the smallest and narrowest features. Resolutions are 20–40 milliarcseconds for the VLBA, 200–400 milliarcseconds for the VLA.

The Ultrasensitive Array will vastly improve the situation, permitting many more sources to be observed, over a much longer time, at higher resolution, with much greater sensitivity. Many sources are too faint, fade too rapidly, or simply go off at the wrong time (not during **A** configuration) to be imaged. The Ultrasensitive Array will provide a factor of 30 improvement in sensitivity at high frequencies; since typical sources fade as $\sim t^{-1}$ to $t^{-1.5}$, this corresponds to tracking a source 10 to 30 times longer. Many sources currently fade beyond observability in a week. If those could be followed instead for 70 or more days, they would be half an arcsecond or more across, and could be imaged even in **C** configuration, using the new high-sensitivity 45 GHz system. The VLA could thus perform useful imaging in three (rather than one) of its four configurations, effectively tripling the number of targets. Those sources which happen to go off in **A** configuration could be imaged for several months, the strong or long-lasting ones for years, yielding invaluable information on the flux decay of individual ejecta. Accurate spectral indices would be obtained at the same time (given the wide bandwidths allowed by the new correlator), while the use of fainter calibrators would cut down on uncertainties due to self-calibration. After Phase II of the VLA Expansion Project, the New Mexico Array will bridge the gap in coverage between the **A** configuration and the VLBA, providing excellent imaging capability at all times, and allowing even the smallest features to be imaged without worrying about missing flux density or large-scale structure.

Monitoring

The Ultrasensitive Array is even more important for monitoring programs. Current monitoring projects are granted at most an hour every week or two, enough to monitor a few sources at the 0.5 mJy level. While this provides useful and unique information, most often the results are non-detections, or a poorly-sampled decaying light curve at one or two frequencies. It is not clear whether this is fundamental – the sources simply are not emitting radio waves most of the time – or the result of poor sensitivity, although long-term monitoring of a few very strong sources by the Green Bank Interferometer (SS433, Cygnus X-3, GRS 1915+105) suggests that some binaries at least remain radio-active at a low level most of the time, with occasional flares to very high levels.

For the same commitment of a few hours a month, the Ultrasensitive Array would provide continuous, sensitive, multi-frequency (five or more) radio light curves for months, for any transient as strong as those which have so far been detected. Such detailed light curves constrain theoretical models much more tightly than the current $3 - 5\sigma$ sprinkling of possible detections. Even without imaging one can learn the time offset between the radio ejection and the X-ray flare, whether there was a single or multiple outbursts, and whether the jets (assuming they are jets) are expanding freely. Several sources have slowed their decays significantly after an initial sharp decline; this opens the possibility of imaging long after the initial outburst, and learning something about both the 'old age' of the ejecta, and the medium into which they expand. Currently we only know about the strongest of these long-lived sources, the others having faded beyond detection before reaching this stage.

The detection of weak 'quiescent' emission is potentially even more exciting, because we may be seeing deep into the accretion disk. In GRS 1915+105 (Figure A.24) the radio tracks the X-ray flux density almost exactly, on timescales of minutes, implying that even moderate instability in the accretion disk can produce relativistic particles. The radio micro-flares appear to be tied to the 20−30 minute cycles which are now believed to be tied to the "disappearance" (into the black hole?) of the inner portions of the accretion disk. We have no idea whether this behavior is common to all sources (or just black hole systems), or whether the correlation holds on even finer timescales in GRS 1915+105. The Ultrasensitive Array could detect GRS 1915+105 in 1 millisecond ($5 - 7\sigma$), allowing an unprecedented comparison between the radio flux and the incredible small-scale structure seen at X-rays.

Even more fundamental is the general question of quiescent radio emission — do accretion disks create winds of relativistic particles? This is part of the standard model for high-energy X-rays, and some models at least (ADAFs) predict a core which might give off observable radio emission. One source, V404 Cyg, has already been detected at the 0.2–0.4 mJy level (Hjellming, Rupen, & Narayan, *in prep.*), but there is no prospect of determining any sort of detailed light curve. The Ultrasensitive Array could provide $> 10\sigma$ detections at five frequencies every 10 minutes, giving basic information on the nature of the emission (is this a series of flares, or a slowly-varying continuous level of emission? is there any connection to the X-rays? etc.), either within a single many-hour run, or over the course of many weeks. Such observations would also yield good polarization measurements or upper limits. Flaring and other rapidly-variable emission is very difficult to model, and theorists instead concentrate on relatively simple quasi-equilibrium models like ADAFs; high-sensitivity detections of steady low-level radio emission from X-ray binaries would help enormously in tying down those models.

A.3.5 Radio Supernovae

After several decades of study, the radio emission from supernovae remains something of a mystery. All agree that the emission is synchrotron, in most cases due to relativistic particles accelerated in the shock front between the supernova ejecta and the surrounding circumstellar material, presum-

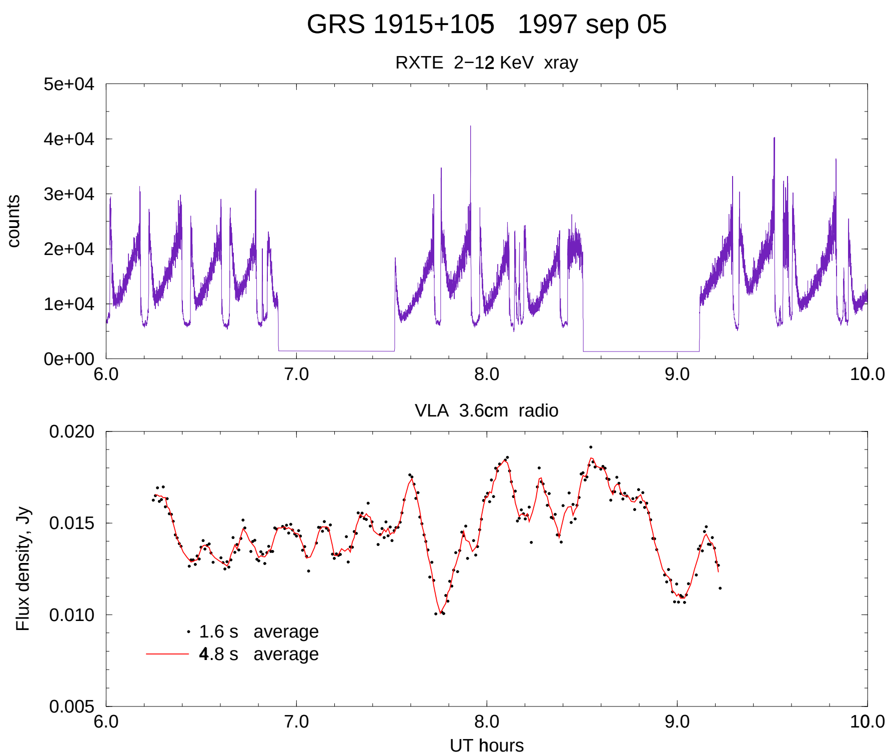


Figure A.24: X-ray (*top*) and radio (*bottom*) light curves of GRS 1915+105 (Mirabel *et al.* 1998), the first Galactic superluminal jet source to be discovered. The periodicities in the two bands are correlated, as are the length of the X-ray minimum and the strength of the radio oscillation. The current interpretation associates both the X-ray flares and the radio emission with the violent expulsion of material from the inner parts of the accretion disk; the radio peaks grow as the period lengthens, because more of the disk is being expelled, creating more violent flares. The offset between X-ray and radio peaks is caused by light-travel time effects for the optically-thick synchrotron emission. This same source shows quasi-periodic oscillations in X-rays down to timescales shorter than a second; the Ultrasensitive Array will allow searches for similarly rapid variability at radio frequencies.

ably ejected earlier by the progenitor star or its companion. Beyond this the controversies arise (see Figure A.25):

- Why are so few supernovae strong radio sources, even in cases where optical data suggest significant circumstellar material?
- Do type Ia supernovae produce radio emission, or is this really confined to the explosions of massive stars?
- What sets the peak radio flux density?
- What causes the opacity at early times (free-free, synchrotron self-absorption, Razin-Tsytovich effect), and what determines its decay?
- Why have we not seen evidence for a pulsar in any extragalactic supernova, even decades after the explosion?
- How are radio supernovae related to radio supernova remnants?

The Ultrasensitive Array will address all of these questions, by observing many more sources, over a wider range in frequency, for a much longer time. With some tens of radio supernovae detected each year (compared to the current one or two), we will at last be able to compare optical, infrared, and radio properties for a real sample, and learn for instance whether the narrow lines seen in some supernovae do indeed imply significant circumstellar material, with associated radio emission. Such a sample would also show conclusively whether radio supernovae can be used as distance indicators (Weiler *et al.* 1998), and more fundamentally, determine the real radio luminosity function of these explosions. We know already from SN 1987A that some supernovae are thousands of times weaker than the strong ones the VLA can see now; there is no hope of seeing such extragalactic sources at the moment (SN 1987A as seen in M81 would peak at $\sim 20\,\mu$Jy), but with the Ultrasensitive Array this would be the work of a few hours. Easy and quick spectral studies, extending to high frequencies, are equally important, giving a much clearer picture of the nature and evolution of the absorption: the high frequencies 'see through' the absorbing material, allowing a direct determination of the absorption at lower frequencies. This is of great interest because that absorption, if well understood, may give direct information on the source size (Chevalier 1998), the distribution of the surrounding material, the deceleration of the shock front (Chevalier 1982; Weiler *et al.* 1989), and the clumpiness of the circumstellar medium. The high frequencies are also critical for models of particle acceleration: one wants to watch the 'raw' flux density evolve from the earliest possible moment, just when absorption obscures most of the low-frequency flux and all of the intrinsic flux information.

The improved sensitivity will stretch radio light-curves out to much greater ages, decades to centuries in fact (since most radio supernovae follow power-law decays). As well as looking for upturns (as in SN 1987A), indicating renewed particle acceleration, and downturns (as in SN 1980K), indicating abrupt changes in the shock conditions, one can hope at last to tie supernovae (where we see the explosion) to supernova remnants (where we see the final stages of interaction with the general ISM). More speculatively, one could hope to do a deep survey for radio remnants surrounding known optical supernovae, from back to the 1880s; the resulting general and complete statistics would provide a unique probe into supernova particle acceleration and ISM interaction, with attached timescales, initial velocities, and ejecta masses (from the original optical spectra).

Finally, there is the question of 'missing' sources, such as young pulsars and type Ia supernovae. Even a single detection of either population would have enormous implications; a significantly larger number of non-detections would also be very important, placing limits both on pulsar nebulae, and on the mass-loss rates of type Ia progenitors. In the same vein, it is becoming embarrassing that

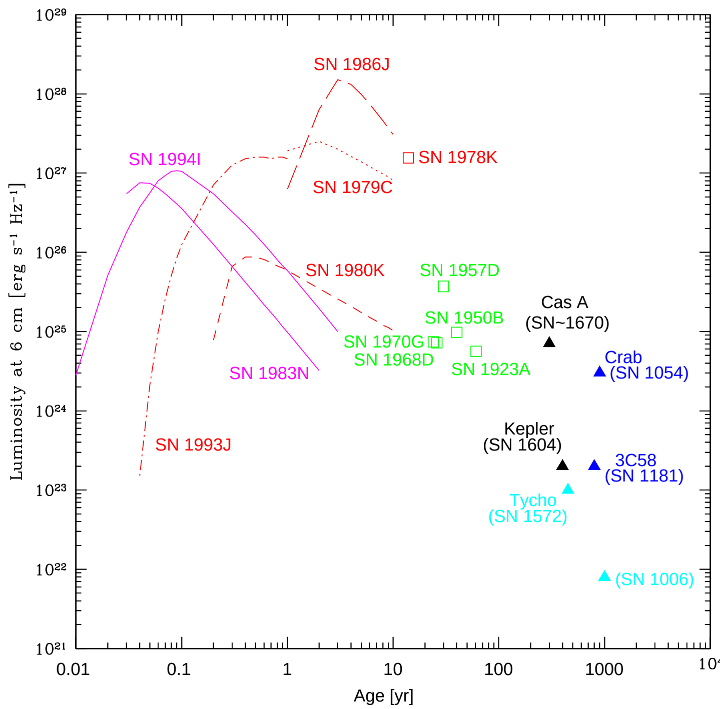


Figure A.25: The radio luminosity *vs.* age for a number of young radio supernovae (*curves*), older "historical" supernovae which have been detected (*squares*), and the youngest known galactic SNRs (*triangles*). The prompt burst of SN 1987A peaked at a luminosity about an order of magnitude below the bottom of this plot; the Ultrasensitive Array could detect such a source in a few hours out to > 5 Mpc. (Courtesy S. D. Van Dyk, K. W. Weiler, R. A. Sramek, M. J. Montes, & N. Panagia 1999).

searches in starburst galaxies have yet to turn up a single new supernova. Radio observations are the best way to look for these, since (i) heavy dust obscuration makes optical and near infrared searches impossible, (ii) poor resolution, copious dust emission, and the expected steep spectral index make far infrared searches unattractive, and (iii) if the radio flux does indeed grow with the local density, such enshrouded supernovae should be very impressive radio sources. The Ultrasensitive Array will both make these searches far easier (by detecting 'standard' radio supernovae in a minute or less), and extend them to more distant (and hence more active) star forming systems (to $z \sim 1$ for the most luminous known radio supernovae).

A.3.6 Gravitational Lenses and H_0

Gravitational lenses are excellent tools for studying cosmology; in particular, individual lens systems can be used to determine H_0, independent of the cosmic 'distance ladder' (*e.g.*, Blandford & Narayan 1992). This requires the accurate measurement of the time delays between lensed images, which in turn rests on continuous, well-sampled light-curves for the individual lens components (*e.g.*, Biggs *et al.* 1999). Radio observations are in principle ideal for these studies, since they may be made day or night, any time of the year, and since radio interferometers can easily provide sub-arcsecond images in almost any weather. However, there are currently several practical difficulties. First, the VLA spends half its time in the compact **C** and **D** configurations, which cannot provide sub-arcsecond images at frequencies below 45 GHz; the resulting gaps in the light-curves may miss the sharp changes in intensity which are needed to accurately measure the time delay (*e.g.*, Figure A.26). Second, the VLA is currently limited by sensitivity to observing such systems at low frequencies. This has several unfortunate side effects: poorer resolution, making it difficult to distinguish different lens components; confusion with more extended emission, which tends to be stronger at lower frequencies; and relatively weak intrinsic variability (typically 5−10%). Third, the VLA simply does not have the sensitivity to effectively monitor any but a handful of the highest flux density lenses. Finally, the uncertainties in current radio light curves are dominated by systematic errors in the flux scale; these are alleviated considerably by comparison with flux densities of background sources in the field, but these sources are generally weak and such comparisons are themselves limited by sensitivity.

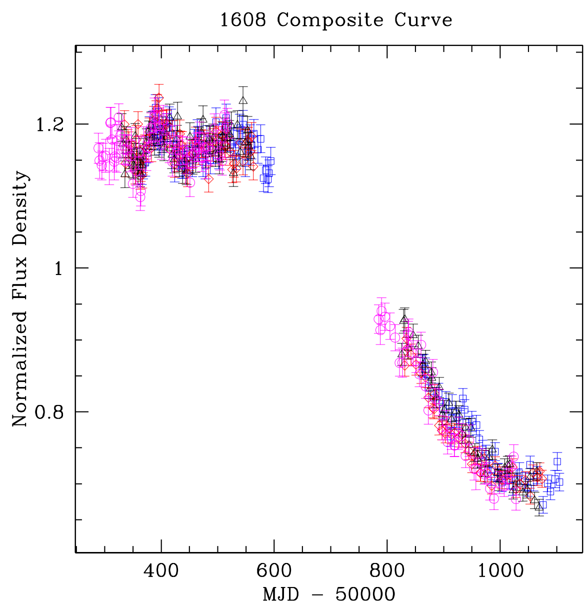


Figure A.26: Composite radio light curve for the CLASS B1608+656 lens system. The curve is constructed from the four individual light curves associated with the four lensed images in this system. These component light curves have been shifted by the best estimates for the system time delays, and scaled by their relative magnifications (Fassnacht *et al.*, *in prep.*). The change from a constant flux to a monotonic decay occurs in the gap in the light curve associated with the VLA being in its **C** and **D** configurations.

The Ultrasensitive Array will address all of these problems, by providing over a factor of 30 improvement in sensitivity at the high frequencies, allowing any currently-detectable lens to be monitored at 30−50 GHz, and providing a much larger sample of higher-signal-to-noise-ratio detections of background sources. The sensitivity will allow many more lenses to be monitored. This monitoring could be carried out at high frequencies. where the spatial resolution is highest, allowing effective imaging in all but **D** configuration. Smaller lenses could be monitored as well, since at 45 GHz the VLA's resolution is $\sim$ 50 milliarcseconds in **A** configuration. Even better, since most radio sources are more variable at higher frequencies, it will be much easier to align the light curves of the different components, even with a relatively short series of observations.

A.3.7 Gamma-ray Bursts

The study of gamma-ray bursts (GRBs) has undergone a renaissance since the launch of the Italian-Dutch satellite BeppoSAX and the subsequent discovery of long-lived "afterglows" at X-ray (Costa *et al.* 1997), optical (van Paradijs *et al.* 1997) and radio (Frail *et al.* 1997) wavelengths. We now know that GRBs are the most violent explosions (10^{52}-10^{54} erg) in the cosmos, driving relativistic shocks into their surroundings with bulk Lorentz factors $\Gamma_\circ \simeq 300$. The progenitor object(s) of GRBs remain unknown but there is mounting evidence that GRBs announce the births of black holes.

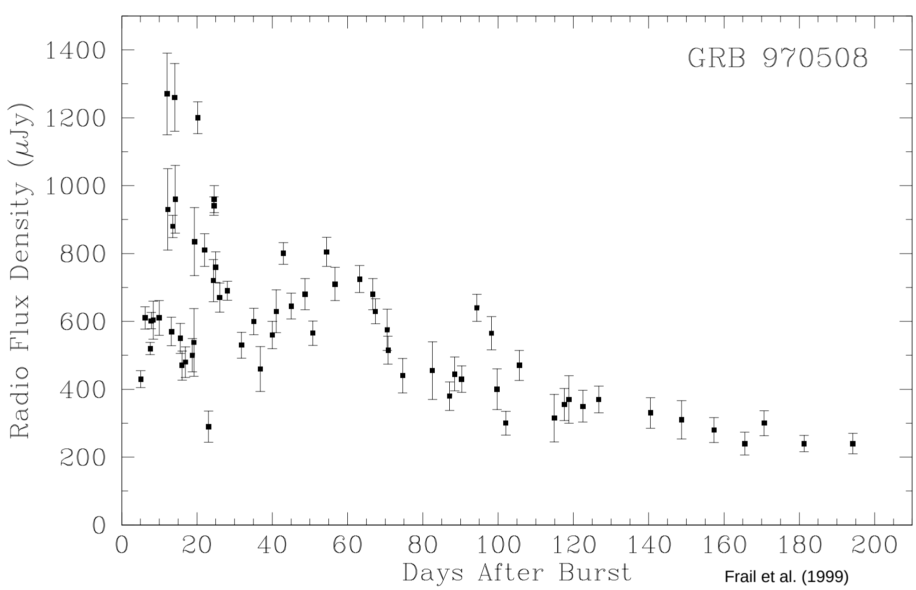


Figure A.27: 8.46 GHz light curve of the radio afterglow from GRB 970508 (Frail *et al.* 1999). The flux density fluctuations at early times are the result of refractive interstellar scintillation, an interference effect produced by the intervening ionized gas along the line of sight. This scintillation provides a direct measurement of the angular size of the expanding fireball (see text for details). At late times (>100 days) the radio light curve undergoes the same power-law decay seen at X-ray and optical wavelengths.

The VLA has been at the forefront of this emerging field, making the first discovery of a radio afterglow in 1997 (GRB 970508; Figure A.27) and making all subsequent radio afterglow discoveries in the northern hemisphere. Despite this impressive beginning, the potential of radio observations has barely been touched. The Ultrasensitive Array will find and follow the evolution of as many as a hundred GRBs a year (compared to the current one or two), in greater detail, over a wider range of frequencies, and for longer times than any current afterglows. Here the excellent sensitivity and responsiveness of the Ultrasensitive Array is the key, since even the strongest radio afterglows peak at around 1 mJy. These data will make fundamental contributions in several areas:

- *Complete spectral energy distributions:*
  Combining VLA data with those from optical (Keck, Gemini, HST), submillimeter (JCMT, ALMA), infrared (UKIRT, SIRTF), and X-ray (XMM, Chandra, Astro-E) observatories gives the instantaneous spectrum of the afterglow over ten orders of magnitude. This can be used to derive the total GRB energy and the ambient density of the surroundings, and to probe the physics of particle acceleration in relativistic shocks (*e.g.*, Sari, Piran, & Narayan 1998; Wijers & Galama 1999). Radio observations are particularly important in constraining theoretical models, because the radio emission is observable throughout all the major phases in the light curve. For instance, the most robust estimates of the total energy and the geometry come from radio observations at late times, when the blast wave has slowed to sub-relativistic speeds and the entire radiating surface is visible. In providing detailed and long-lasting light curves of many dozens of GRBs each year, the Ultrasensitive Array will make a major contribution to our physical understanding of these sources.

- *Sizes and expansion rates:*
  GRB afterglows are only a few microarcseconds in diameter; surprisingly, such diameters can actually be measured by radio telescopes, thanks to refractive interstellar scintillation (RISS). The propagation of radio waves through the turbulent ionized gas of our Galaxy introduces a modulation of the received signal; the strength and character of these modulations depends on the size and shape of the background source. Well-sampled data taken at the right frequency (which depends *e.g.*, on the Galactic latitude) can measure GRB sizes and expansion rates, and have already provided the only *direct* demonstration that GRBs and their afterglows originate from relativistic shocks (Figure A.27). Such measurements are currently limited to a few of the stronger radio afterglows; the Ultrasensitive Array will extend this to provide sizes and expansion velocities for dozens of GRBs every year.

- *Jets, rings, or spheres:*
  RISS can in principle determine not only the size but also the geometry of the radio afterglow, at least to the extent of settling one of the major outstanding questions: are GRBs jets or spherical outflows? This requires very well-sampled and low-noise radio light curves, and the Ultrasensitive Array is ideally suited to providing them. Additional constraints on the geometry come from the intrinsic linear polarization, which can in principle be followed for much longer times at radio wavelengths; the evolution of the polarization fraction and orientation should then reflect the shift from highly beamed to more isotropic radiation. Current instruments are simply not sensitive enough to measure radio polarizations. The Ultrasensitive Array by contrast could detect (5σ) 10% polarization in the $\sim 500\,\mu$Jy afterglows seen now, in under 10 minutes.

- *Dust-free samples:*
  There are now several afterglows which have only been detected at radio frequencies, and several others where there are clear signs of reddening (Taylor *et al.* 1998). This raises the possibility that optical studies may miss a substantial fraction of the afterglow population, and particularly those GRBs born in dense, star-forming regions. Radio afterglows can be detected regardless of dust extinction, and the Ultrasensitive Array will provide a large enough sample that such biases can be rigorously checked.

In addition to providing unique data on the bursts themselves, the Ultrasensitive Array will image radio emission from the host galaxies. Any model of GRBs must be consistent both with the positions of the GRB within their host galaxies, and with the properties of the host galaxies themselves; for instance, models based on the explosions of massive stars ("hypernovae") predict an association with the disks of actively star-forming galaxies. Currently this work is the domain of optical studies, and is limited by the small number of optical afterglows and the possibility of optical obscuration. The Ultrasensitive Array will be able to detect the radio emission from host galaxies out to $z = 1$ or beyond in a few hours, giving extinction-free estimates of the host galaxy's star formation rate, and providing sub-arcsecond measurements of the position of the GRB within the galaxy. After Phase II of the VLA Expansion Project, the New Mexico Array will improve this relative astrometry by another factor of ten, allowing even more stringent tests of progenitor models.

A.4 The Evolving Universe

What was the early solar system like? How are stars born? When and how were galaxies formed? What role does their environment play in their births, their lives, their deaths? These are among the most basic questions of modern astronomy. Like most basic questions, their answers are far from obvious, and likely to be both subtle and complex. Star formation obviously requires accretion, but exactly how this works in the presence of angular momentum and magnetic fields is still a mystery. Galaxies are basically defined as conglomerations of stars, which presumably were themselves made out of primordial gas; but when, how quickly, and how efficiently this occurred, is still hotly debated. The situation is made more difficult observationally by the penchant of stars to be born out of dusty, dense gas, and by the fact that galaxies were young a long time ago, a time now to be glimpsed only by looking back to the most distant parts of the universe. Much of what is most interesting occurs behind clouds of dust, or on size-scales requiring the utmost in angular resolution; at the same time the complex interaction of physical processes, and the redshifting of distant light into different bands, require observations over a huge range of the electromagnetic spectrum. For these reasons multi-wavelength studies are more important in this than in any other area of astronomy. One needs optical instruments like the HST and Keck to observe the stars, and (sub-)millimeter telescopes like IRAM, JCMT, SIRTF, and ALMA, to see the dust which re-radiates most of the luminosity, and to map the molecular gas out of which stars are formed. High-energy satellites like ROSAT, Chandra, and Constellation-X offer another, orthogonal view, probing the final stages of stars, the hot thermal gas in which galaxies live, and both massive stellar explosions and the neutron stars and black holes which they create.

Radio observatories too offer unique information, and unique possibilities. Stellar cores are surrounded by dust too dense to penetrate even at submillimeter wavelengths; here radio waves offer the only hope of seeing directly into these regions where planets may be formed. Luminous young stars also ionize their surroundings, and radio observations of free-free emission can be used to measure both the amount and the distribution of this material, on scales ranging from ultra-compact H II regions in Orion, to giant star-forming regions in galaxies tens of megaparsecs away. The resulting star-formation rates are independent of extinction and allow much higher resolution than current submillimeter telescopes. Finally, at lower frequencies synchrotron radiation dominates, providing a unique probe of cosmic ray generation and evolution. Cosmic rays are generated in high-velocity shocks, and so act as useful tracers of such activity near young stellar objects, black holes, and neutron stars, as well as in supernova remnants. This latter connection makes synchrotron emission another valuable, extinction-free indicator of massive star-formation, as dramatically evidenced by the far-infrared/radio correlation. Finally, cosmic rays are an important heat source in dense molecular clouds, closing the circle between dying stars and stellar nurseries. Of course, relativistic particles are also accelerated in active galactic nuclei (AGNs), somewhat confusing this simple picture; but this confusion also allows interesting tests of the relative importance of star formation and nuclear activity in shaping galaxy evolution, since the two can be distinguished both by imaging the radio source in question, and by sampling the spectral energy distribution at both radio and far infrared wavelengths. Assuming one understands the operative physical mechanisms, one can even use such broad-band millimeter and centimeter photometry to derive rough redshifts for sources which may be too faint (or too extincted) to see optically.

In addition to these continuum considerations, radio telescopes are sensitive to a number of very interesting spectral lines, including the lowest energy transition of neutral hydrogen, an enormous number of radio recombination lines, several very useful maser transitions, and important lines of such simple molecules as ammonia and formaldehyde. While ALMA will be the premier telescope for most molecular observations, the cold neutral gas is best studied at radio wavelengths. Radio telescopes also offer important data on low-order transitions of molecules like carbon monoxide, which rapidly redshift into the centimeter regime. Evolutionary studies demand observations across the entire electromagnetic spectrum, and the radio band makes its unique contributions as much as the submillimeter or optical.

Unfortunately, these studies are severely restricted currently by the limitations of the VLA. The sensitivity (especially at the high frequencies) allows observations of only the most luminous and nearest objects; the limited frequency coverage, together with uneven sensitivity, makes it difficult to measure the full spectral energy distributions (SEDs); the narrow bandwidths and poor spectral resolution prevent spectral line searches, restricting us to low-resolution follow-up spectroscopy of sources with known redshifts. The VLA Expansion Project will change all this. The Ultrasensitive Array will permit the observation of intrinsically-faint young stellar objects (YSOs) over the entire range from 1 to 50 GHz, imaging both synchrotron and thermal jets, and (especially in combination with ALMA data) allowing a reliable decomposition of their SEDs. Similar observations will be possible for star-forming galaxies over a wide range in redshift; continuum observations will provide unextincted estimates of the star-formation rate, rough 'photometric' redshifts, images of the star formation regions and the structure of the magnetic fields, and reveal as directly as possible the role of active galactic nuclei in galaxy evolution. For spectral lines, the new correlator will for the first time allow efficient surveys with the VLA, with a single frequency setting covering hundreds of thousands of km/sec in H I, checking for redshifted absorption irrespective of dust against hundreds of background sources, and looking for CO emission at redshifts of several to 10 or beyond. In our own Galaxy the VLA will finally be able to observe multiple transitions at once, take advantage of maser lines to calibrate weak continuum signals, and observe with fine enough velocity resolution to see signatures of infall and rotation at $\lesssim 0.1$ km/sec. The improved sensitivity will also provide numerous high-redshift targets for absorption and rotation measure studies, giving a unique probe both of the intervening gas, and of the magnetic fields both at large redshifts and in local star formation regions. Some of these observations have been discussed in the preceding sections; here we concentrate directly on a few projects of special relevance to understanding evolution, the birth, aging, and death of objects ranging from asteroids to galaxies.

A.4.1 Minor Bodies of the Solar System

The minor bodies (comets, asteroids, and satellites) provide very important information about the formation and evolution of the solar system. Radio observations in principle offer unique information, particularly about the surfaces and near-subsurfaces of these bodies, because they are cold enough that thermal emission is expected at relatively low frequencies, and because radio photons probe depths roughly equal to their wavelength, *i.e.*, a few to some tens of millimeters. In addition, OH provides a useful indicator of out-gassing. But radio studies have so far been quite limited, primarily because of limited sensitivity. The Ultrasensitive Array will make a huge difference, allowing the detection of many tens of sources from a few to 50 GHz, giving a unique look into and beneath the surfaces of a wide variety of the smaller denizens of the solar system.

Comets

- *OH imaging:*
  The outgassing of water drives most of the observable phenomena of comets; unfortunately interference by terrestrial H_2O has prevented its direct observation in all but one comet. The primary photo-dissociation product, OH, has both UV and radio transitions, but only the radio lines can be observed with velocity resolution finer than the outflow velocity. The VLA has successfully imaged the 1667 MHz transition in a few comets, providing the only cometary images which are resolved both spatially and in velocity (*e.g.*, Palmer, de Pater, & Snyder 1989). However, the VLA resolves out as much as 2/3 of the total flux, even in **D** configuration; nor is it possible currently to image multiple transitions with adequate

frequency resolution and sensitivity. The wide bandwidths, high spectral resolution, and improved RFI excision provided by the Ultrasensitive Array will allow simultaneous imaging of all four 18 cm lines of OH, in both senses of polarization; this should lead to a much better understanding of the state of this molecule in cometary comae.

Recovering the full flux would require simultaneous total power measurements, preferably combined with a more compact arrangement of the antennas (the **E** configuration) to maximize surface-brightness sensitivity. This would unambiguously resolve long-standing uncertainties about the degree of symmetry in outgassing of comets (Bockelée-Morvan & Gérard 1984; de Pater, Palmer, & Snyder 1986; Combi 1987). The **E** configuration will be studied during Phase I of the VLA Expansion Project, and possibly implemented during Phase II.

- *Thermal emission from cometary nuclei:* Only a single cometary nucleus has been detected thus far at radio wavelengths – that of comet Hale-Bopp (Fernandez *et al.* 1997). The Ultrasensitive Array will not only detect but also obtain full spectral information from 15 to 50 GHz on nearly all short period comets with diameters more than a few kilometers, and on all newly-discovered long-period comets which come within ~ 2 A.U. of the Earth. Apart from spacecraft encounters, these data offer the only means to place constraints on the actual physical structure of cometary nuclei surfaces and sub-surfaces.

Kuiper Belt Objects

Kuiper Belt Objects (KBOs) are relatively small icy bodies in the outer parts of the solar system which may hold a record of the very earliest stages of the formation of our solar system. As for cometary nuclei, observations of KBOs at radio wavelengths are important because they offer a unique probe into the sub-surfaces of these bodies, and hence constrain surface and subsurface temperatures and physical characteristics. For example, the distribution of temperature with depth in an icy body in the outer solar system might be used to help determine the nature and distribution of ices on the surface of that body, and hence give indirect information on the chemical composition of the upper part of its surface. Having this type of information on all of the small icy objects in the outer solar system will help in determining the cause for their variation in properties (*e.g.*, their spectral diversity). Unfortunately, no current radio telescope is sensitive enough to detect these objects at $\lambda \gtrsim 350\,\mu$m.

The Ultrasensitive Array will extend this down to almost 5 cm for the brightest objects. At the shorter wavelengths ($\lambda \lesssim 2$ cm), more than half of all currently known KBOs could be detected in 12 hours or less (Figure A.28). Sub-arcsecond astrometry would of course also be obtained for these detections. These data could then be used in conjunction with higher-frequency measurements by ALMA to give a full three-dimensional view of the temperature structure in the outer few to 10 cm of these bodies.

Asteroids

- *Main-belt asteroids:*
  Thermal emission has been detected from the four largest asteroids (Ceres, Pallas, Vesta, & Hygiea) at wavelengths from 1 mm to 20 cm (Webster and Johnston 1989, and references therein), and from a few smaller asteroids at 2 cm. Such measurements place constraints on the thermal and electrical properties of those objects' surface layers. The existing observations indicate that the asteroids studied so far are covered with fine-grained regoliths, which are thought to result from meteoroid bombardment ("sand blasting") of the surfaces over hundreds of millions of years. Differences in the microwave spectra of Ceres, Pallas, Vesta, and Hygiea suggest variations in the dielectric properties of those regoliths and/or variations

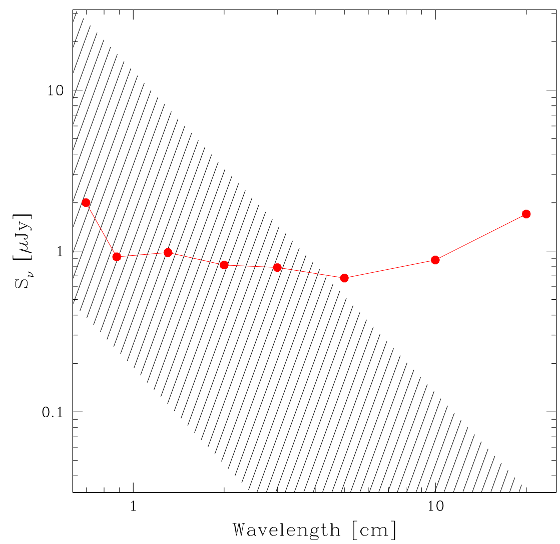


Figure A.28: The estimated sensitivity of the upgraded VLA in a 12 hour observation (connected dots) and the estimated range of thermal emission from all currently known KBOs as of July 1998 (hatched area).

in the regolith thickness. However, those few objects represent just a tiny fraction of the thousands of main-belt asteroids, most of which cannot be detected with the current VLA: a 100 km object at a distance of 1 AU has a flux density of only ~ 0.4 mJy at 15 GHz, and ~ 0.1 mJy at 8 GHz. In addition, there is an important gap in the wavelength coverage between 1 mm and 1 cm. Over this range, the spectra show a distinct drop in brightness temperature. The Ultrasensitive Array's improved sensitivity and wavelength coverage will lead to detections of large numbers of these objects at several wavelengths. Of particular importance is the 7mm (45 GHz) band, which fills the 0.1−1.0 cm wavelength gap.

- *Near Earth Asteroids:*
  NEAs are of especial interest, since one may eventually crash into the Earth. The Ultrasensitive Array will be able to detect all NEAs more than about 100 m across at the shorter wavelengths ($\lesssim 2$ cm) with 5σ confidence in a single track (6 hours on-source). Here the ability to observe during daytime and obtain accurate astrometry is particularly important.

A.4.2 Distinguishing Dust, Free-Free Emission, Disks, and Jets in Local Star Formation Regions

As discussed in §A.2.3, disks and jets around young stellar objects are part of the early evolution of solar-type stars. The current paradigm for the formation of single stars leads naturally into the formation of disks that may then evolve into a planetary system. Thus the study of such disks and accompanying jet/outflow systems are required to understand the origin of our own solar system.

The spectral energy distribution of an embedded young stellar object from optical to radio wavelengths shows that, at wavelengths shorter than about 7 mm, dust emission dominates the spectrum. Longward of about 7 mm, free-free emission from ionized gas, presumably from the jets/outflows begins to be important. Finally, in at least one source, non-thermal synchrotron emission, apparently from a double-sided jet has been discovered (W3(OH): Reid *et al.* 1995).

Thus, in order to understand both the gas and the dust and their interaction, imaging observations at several wavelengths from long-wavelength centimeter the sub-millimeter are required. Complementary, similar-resolution observations from the Ultrasensitive Array and ALMA will be necessary to disentangle the emission from these competing mechanisms.

Radio observations are also essential for the innermost regions of dense dust cores, which are probably opaque at millimeter wavelengths. Here the high sensitivity of the Ultrasensitive Array will allow the high-resolution observations at $\sim 1\,\mathrm{cm}$ which are required to see into the regions where solar systems might form.

A.4.3 Spectral Imaging of Nearby Galaxies

The Ultrasensitive Array will be the perfect instrument for spectral studies of radio emission from nearby galaxies, mapping the aging of cosmic ray electrons, showing directly the origin of the far infrared/radio correlation, detecting and imaging complete samples of individual supernova remnants in other galaxies, and giving dust-free measurements of the flux of ionizing photons – and hence the star formation rate – throughout nearby galactic disks. The key improvement is the availability of excellent sensitivity over several decades of frequency, from 300 to 50000 MHz.

The radio emission from normal galaxies is dominated by synchrotron emission from relativistic cosmic ray electrons (CRE) and thermal free-free emission from ionized gas at $\sim 10^4$ K. Both are intimately related to the star formation process: cosmic rays are produced by supernovae and supernova remnants, and provide an important heat and ionization source for molecular clouds and dust; while thermal emission from H II regions is a dust-free tracer of luminous young stars. The two processes are distinguishable primarily by their spectra, with synchrotron emission generally much stronger at low frequencies ($S_\nu \propto \nu^\alpha$, with $\alpha \sim -0.5$ to -3), while thermal emission either gently falls (optically thin, $\alpha = -0.1$) or sharply rises (optically thick) with frequency. Disentangling the two requires sensitive imaging at the same resolution over as wide a range of frequencies as possible. High spatial resolution is also important, to separate the different emission regions as cleanly as possible; at the same time, since the spectral decomposition is based on the change in the *total* flux density with frequency, it is essential to retain sensitivity to large-scale structures. This makes wide-field spectral imaging a particularly demanding problem in terms of sensitivity and *(u,v* coverage. The Ultrasensitive Array will be ideal for this work, combining high sensitivity and scaled-array capability across a huge frequency range with the ability to image a large range of spatial scales with excellent fidelity. A few of the scientific advances which will result are expounded below.

Low-Frequency Halos

Because the energy loss rate for synchrotron-emitting particles varies as E^2, regions with little on-going particle re-supply/acceleration have steeper spectra; the range from $\nu^{-0.5}$ to ν^{-3} has been observed in nearby galaxies. The sites and length scales of this spectral evolution, both in and out of the disk, therefore give direct information on where CRE are accelerated, and about the diffusion and convection processes which determine their subsequent movement. These effects are seen most clearly in the steep-spectrum radio 'halos' ($\sim \nu^{-2}$ to ν^{-3}) which have been observed kiloparsecs above the disks of a number of edge-on galaxies (*e.g.*, Allen, Baldwin, & Sancisi 1978; Carilli *et al.* 1992 [Figure A.29]). These halos are difficult to detect, let alone image, because they are easiest to see at low frequencies where the resolution is poorest and the confusion with disk emission most serious. The improved sensitivity of the Ultrasensitive Array will allow imaging both at higher frequencies and with a factor of 3–4 higher spatial resolution. With far more accurate spectral information as well (cf. Figure A.30) it will be much easier to see the detailed changes in spectra with height above the disk, and so to place direct constraints on models for cosmic ray diffusion/convection, as well as on theories about the origin of chimneys, bubbles, and other phenomena connecting disk to halo. The eventual goal is to match individual supernova remnants and H II regions to individual outflows above the disk, and track the aging of the electrons as they escape from the plane.

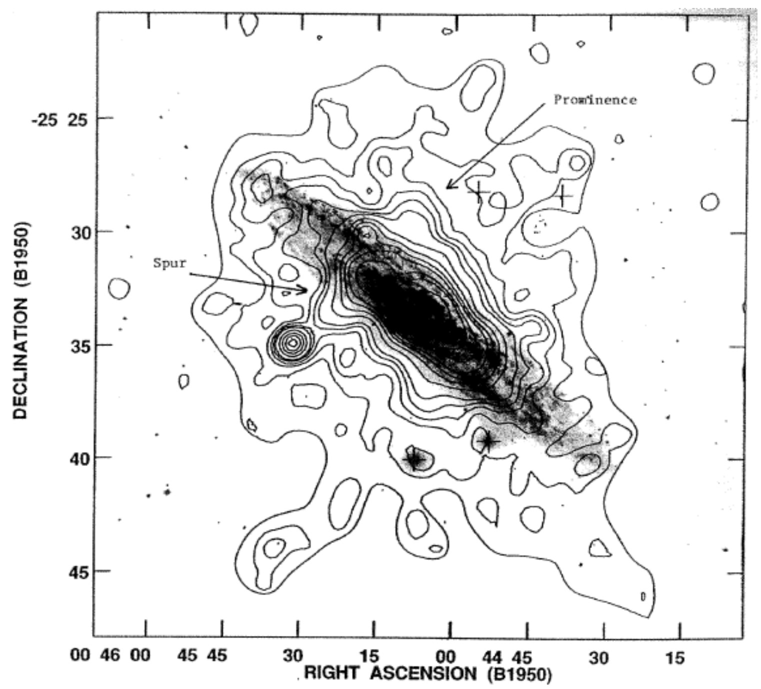


Figure A.29: The radio halo of NGC 253 (contours), as seen by the VLA at 330 MHz (Carilli *et al.* 1992), superimposed on an optical image (greyscale). The halo rises to a height of at least 9 kpc.

The Far-Infrared/Radio Correlation

The primary difficulty in disentangling synchrotron emission with varying spectral index from thermal emission is the limited spectral range now available. This is where the real strength of the Ultrasensitive Array is apparent, making available the full range of frequencies from 300 to 50000 MHz. With so many measurements of the radio spectrum available as a function of position in a galaxy (Figure A.30), one can finally hope to image the thermal and non-thermal emission *separately*, following the spectral aging of the synchrotron component with good spectral index sensitivity over a wide range of spatial scales. The combination of high- and low-resolution observations will allow both the identification of SNRs and H II regions, and their removal from the low-resolution images needed to trace more diffuse structures. This is essential to any detailed understanding of galaxies in general and the interstellar medium in particular. To take a single example: one of the great puzzles found by the Infrared Astronomical Satellite (IRAS) was the far infrared-radio correlation, which shows an amazingly tight relation between far infrared (FIR) and radio emission over many orders of magnitude. The origin of this relationship, and the heat sources for the dust which emits the FIR radiation, remain controversial. While the dust must be heated by stars, whether those stars are mostly the very bright ones in H II regions, or the more diffuse population of A and B stars, is still debated. On the radio end, the synchrotron emission can presumably be traced eventually to SNRs, but the details of this are not at all clear. The Infrared Space Observatory (ISO), new NASA missions like SOFIA and SIRTF, ground-based instruments like SCUBA on JCMT, and most especially ALMA, will provide high-resolution probes of the FIR emission. The Ultrasensitive Array will make similarly-detailed images available at radio wavelengths, and more importantly, show whether the FIR-radio correlation is tighter when done with pure thermal/non-thermal emission (either or both might be expected). Assuming we do understand this correlation, various astronomers (especially Helou) have used the details of the relative FIR/radio distribution to constrain cosmic ray diffusion lengths; these models can only be tested and refined through high-resolution, multi-wavelength studies.

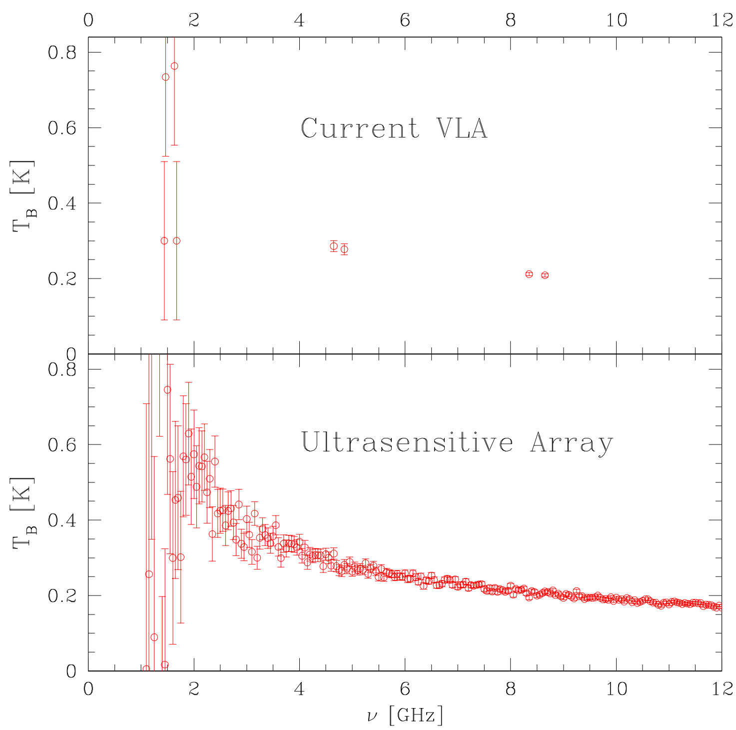


Figure A.30: Spectral index mapping of local galaxies now, and after the first phase of the VLA Expansion Project. The red points illustrate the data obtained for identical total integration times (12 hours at each of three bands for the current VLA; 9 hours for each of four bands for the Ultrasensitive Array; both assume 50 MHz channels, and 6 arcsecond resolution [100 pc at M81, or 22 pc at M33]). The underlying spectrum is that of a random location in a typical spiral galaxy, which emits ten times more synchrotron ($\propto \nu^{-0.7}$) than free-free ($\propto \nu^{-0.1}$) emission at 1 GHz (Condon 1992), and has a mean brightness temperature at that frequency of $\sim 0.75\,$K (Hummel 1981).

Supernova Remnants

Supernova remnants (SNRs) are the last signposts of the deaths of stars. They reflect both the star(s) that exploded, and the medium with which the ejecta or pulsar nebulae are interacting;

they are also thought to be a major source of high-energy cosmic rays in galaxies. SNRs are rather difficult to study in our own Galaxy, primarily due to a combination of distance uncertainties and extinction. Extragalactic studies can provide a large sample of SNRs at known (or at least common!) distances, with (generally) much lower opacities, and with unambiguous locations with respect to the various ISM and stellar components. Radio observations in particular provide very valuable information. Many SNRs (*e.g.*, the Crab Nebula) are much more prominent at radio than at optical wavelengths. Radio waves can penetrate extensive dust layers with ease, allowing one to see SNRs even in starburst systems where A_V may be 20 or more. And most importantly, the radio emission is the direct result of the energetic particles which the SNRs create, interacting with the magnetic fields which both accelerate and confine them.

Current observations of extragalactic SNRs are limited by sensitivity and resolution. The state-of-the art for normal (non-starburst) galaxies is illustrated by recent VLA observations of M33 (Gordon *et al.* 1999), in which flux densities and spectral indices were measured for some 53 SNRs — by far the largest extragalactic radio sample to date. Unfortunately the interpretation was hampered by relatively poor spatial resolution (7 arcseconds $\sim$ 30 pc at 840 kpc), which made it impossible to resolve the SNRs, and led to confusion with thermal emission from associated H II regions. More distant systems would be even more challenging.

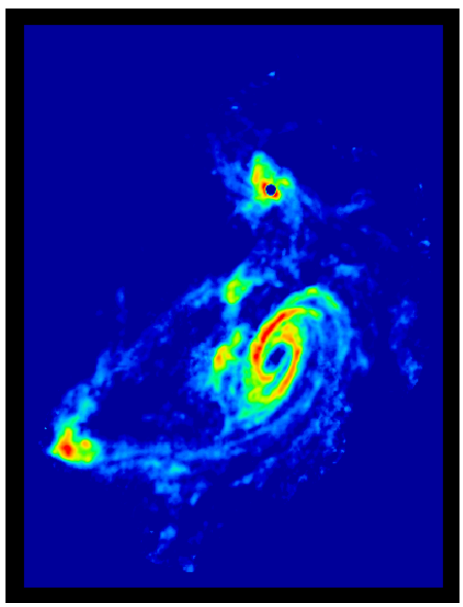


Figure A.31: VLA H I mosaic of the M81 group. M81 is the large spiral; M82 inhabits the concentration of gas to the north. The entire field is roughly 2° across, and the resolution is about 1 arcminute. Courtesy M. S. Yun (see Yun, Ho, & Lo 1994).

The improved sensitivity and frequency flexibility of the Ultrasensitive Array will truly revolutionize this field. A simple extrapolation of Gordon *et al.*'s source counts implies that a *one hour* observation at 1.5 or 3.0 GHz would yield 1100 SNRs ($\sim 5\sigma$) – five times the number known in our own Galaxy (Green 1998). Of course, if there aren't any such faint SNRs, we will instead have the only complete sample of radio SNRs in any galaxy, which might be even more interesting in understanding the origin and diffusion of cosmic rays. Spectral indices would come along 'for free,' given the 2:1 bandwidth ratio and excellent spectral resolution afforded by the new correlator and feeds. Observing in **A** configuration would give a 0.8 arcsecond (3.3 pc) beam, sufficient to resolve any of the famous SNRs in the Milky Way; the sensitivity for these relatively strong (0.7 mJy) sources would easily allow mapping polarizations like those seen in Galactic remnants, tracing the magnetic field orientation directly for the first time in extragalactic SNRs. For even higher resolution, a 12-hour observation at 33 GHz would provide 0.3 pc (0.08 arcsecond) imaging with sufficient sensitivity to provide more than 20 beams (in each dimension) across sources like Tycho or Kepler; the previous observations show there are about 40 such sources in M33.

One could also extend these studies to more distant systems, and a wider variety of galaxies. The M81 group for instance offers a nice example of strongly interacting galaxies (Figure A.31), including perhaps the most famous starburst galaxy (M82). A 6-hour observation with the Ultrasensitive Array would give similar sensitivity to the current M33 measurements, at twice the spatial resolution. Such observations would give unbiased samples of significant numbers of equidistant SNRs in a variety of galaxy environments, showing directly the influence of interactions, central starbursts, and galaxy morphology on the end products of star formation – and the generation and retention of cosmic rays.

H II Regions

Table A.4.3. H II Regions with the Ultrasensitive Array

H II Region	Diameter [pc]	10^7 E.M. [cm^{-6} pc]	5σ in 1hr	5σ in 6hrs	5σ in 12hrs	Resolved to [Mpc]
Ultracompact	0.1	1	0.8 Mpc	1.3 Mpc	1.5 Mpc	0.25 Mpc
Compact	0.5	1	4.0	6.3	7.8	1.3
NGC 253	1.0	20	30	47	56	2.6
Orion	5.0	0.16	16	26	30	13
Giant	100.	0.05	180	290	340	260
Supergiant	100.	0.01	82	130	150	150
ULIRG	100.	30	$z \sim 0.6$	$z \sim 0.9$	$z \sim 1$	340

The distance to which the Ultrasensitive Array could detect various types of H II regions. Most entries are taken as representative of typical Galactic values; starburst galaxies are observed to have much higher densities, both locally (as in the individual parsec-scale H II regions in NGC 253) and over large regions (as in the starburst cores observed by Condon *et al.* 1991). Detection limits assume 5σ at the optimal frequency, usually 6 GHz. The *Resolved to* column shows the distance at which the source would begin to be resolved at 33 or 45 GHz (depending on sensitivity).

These same observations would give, 'for free,' the most sensitive radio surveys yet obtained for free-free emission from H II regions. Extragalactic H II regions, direct tracers of luminous young stars, are traditionally studied in Hα, Hβ, and other optical lines characteristic of gas at 10^4 K. Radio observations, though difficult, offer the key advantage of seeing through the dust associated with star-forming clouds, allowing both a dust-free measure of the (luminous) star-formation rate, and (by comparison with optical measurements) a direct determination of the optical extinction. This is particularly important in observations of the most actively star-forming galaxies; the H II regions seen in radio surveys of local starbursts (*e.g.*, NGC 253, Ulvestad & Antonucci 1997) very seldom have UV, optical, or even infrared counterparts. Radio observations offer a uniquely reliable probe of the details of star formation in such systems.

The Ultrasensitive Array will at last allow observers to fully exploit these advantages. A 10 minute observation could detect the H II region created by a single 05 star, out to the distance of M81 (3.63 Mpc). For nearby galaxies this means picking up many more of the optically-detected H II regions, allowing the determination of extinctions, and the direct measurement of temperatures and densities (useful for example in abundance work). Such observations would give the ages and (high end) initial mass functions for star-forming regions across entire galactic disks, in unprecedented detail, with no worries about extinction. This simply cannot be done now. On larger scales, another 10 minute observation would reveal individual optically-thick regions like those in NGC 253 out to Virgo, allowing one to easily search for 'mini-starbursts' throughout the entire galaxy cluster. Giant and supergiant H II regions could be imaged in Coma in a few hours, and starburst galaxies as a whole detected to $z \sim 1$ or beyond.

A.4.4 Redshifted Molecular Lines

The Ultrasensitive Array will for the first time allow efficient spectral line searches with the VLA, through a combination of continuous frequency coverage, wide bandwidths, and excellent spectral resolution. Carbon monoxide (CO), with rest frequencies at 115, 230, 345, ... GHz, is among the most interesting molecules to look for. A major coolant of dense molecular gas in actively star-forming regions, the CO luminosity is a robust tracer of total molecular gas mass, and the gas temperature can be inferred directly from the peak line brightness. Despite the initial concern that CO may not be present in the early universe due to low metallicity, secure detections of luminous CO-emitting galaxies have now been made out to $z = 4.7$ (Figure A.32; see also Ohta *et al.* 1996 and Omont *et al.* 1996), including the first two dusty SCUBA galaxies which have been looked at in CO (Frayer *et al.* 1998, 1999). This is presumably due to local enrichment in actively star-forming systems (cf. Yun *et al.* 1997), and suggests that it is reasonable to expect luminous CO emission in gas-rich starburst galaxies and proto-ellipticals even in the early epochs when the mean cosmic metallicity was very low.

The study of redshifted CO rotational transitions in actively star-forming galaxies is one of the key science drivers for ALMA. Spectral energy distributions for the recent submillimeter-detected sources suggest dust (and presumably gas) temperatures of about 50−100 K, implying that the best CO transitions to study are $J = 6 \rightarrow 5$ ($E_J = 155$ K) and lower.

The Ultrasensitive Array will provide information in this area which is both unique and complementary to ALMA. The improved sensitivity, frequency coverage, bandwidth, and spectral resolution of the Ultrasensitive Array will be ideally suited for studies of the CO emission at $z \geq 10$, as the key CO transitions redshift into the VLA receiver bands. The contraction of the redshifted spectrum (*i.e.*, $\nu_{obs} = \nu_o/(1+z)$) also means that the VLA receiver bands cover a much broader redshift range for each CO transition, and several rotational transitions can be observed simultaneously (*e.g.*, $J = 2 \rightarrow 1$, $3 \rightarrow 2$, & $4 \rightarrow 3$ for $z = 10$). Observing multiple transitions both confirms the individual detections and gives a direct indication of the excitation conditions. This last is especially interesting since the cosmic microwave background temperature ($T_{\rm CMB} = 2.7\,[1+z]$) becomes high enough to affect the population of the lower J levels at redshifts of only a few. In this respect, the Ultrasensitive Array will complement ALMA very nicely by observing the lower J transitions (Figure A.33). The expected detection limits are shown in Figure A.34.

A.4.5 Studying Star Forming Galaxies at High Redshift

The presence of dust at high redshift leads to a bias in optical studies against the dense, dusty stages of star formation in high-z galaxies. Current optical estimates of the cosmic star formation rate may under-estimate the total at $z > 1$ by a factor of three or more due to this dust bias,

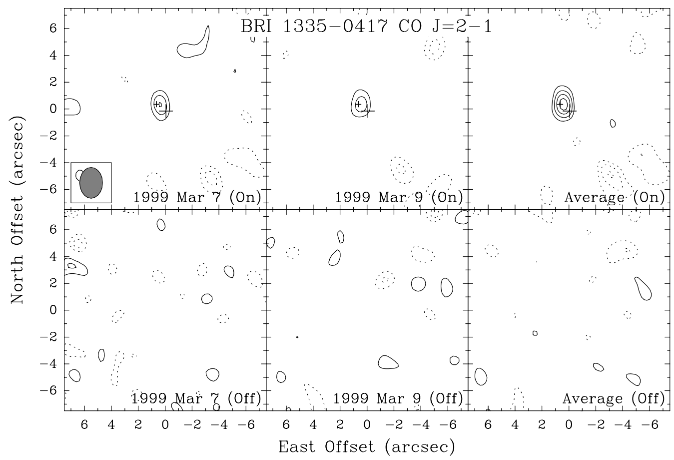


Figure A.32: CO (2−1) emission at $z = 4.4$, as seen with the VLA in BRI 1335−0417 near 43 GHz (Carilli, Menten, & Yun 1999). The implied molecular gas mass is $M(H_2) \sim 10^{11} M_\odot$. Millimeter observations give a line-width of 420±60 km/sec (Guilloteau *et al.* 1997), but the maximum bandwidth currently available at the VLA is 50 MHz (dual polarization), corresponding to 350 km/sec at 43 GHz. The authors were therefore forced to use two independent tunings in continuum mode, on (*top*) and off (*bottom*) the line, and correct the observed flux density difference upwards for the missing velocities. The Ultrasensitive Array will cover 8 GHz – 56,000 km/sec – at a velocity resolution of ~ 50 km/sec.

based on submillimeter source counts, sub-mJy radio source counts, and ISO source counts (Flores *et al.* 1999; Hughes *et al.* 1998; Cram *et al.* 1998; Blain *et al.* 1999a). Much of this star formation may take place in massive starbursts driven by galaxy mergers during the formation epoch of the spheroidal components of galaxies at redshifts between 2 and 5, as predicted by cosmic structure formation models (Tan, Silk, & Blanard 1999). The situation is analogous to studies of Galactic star forming regions, in which the early stages of the star formation process can be studied only by the radio through far infrared observations.

Studying dusty, star forming galaxies at high redshift is one of the main science drivers for the NGST, SIRTF, and ALMA. The Ultrasensitive Array, working in concert with ALMA, will provide samples of high-redshift galaxy candidates, which can then be studied with the NGST. The Ultrasensitive Array will provide critical, complementary information on high-redshift star-forming galaxies out to $z \approx 6$, including:

- Estimates of the massive star formation rate in high-redshift galaxies, unbiased by dust extinction. The Ultrasensitive Array will allow the study of non-thermal synchrotron radio continuum emission from 'normal' galaxies (star formation rates of $10\,M_\odot$/year) to $z = 3$, and ULIRGs ($\geq 100\,M_\odot$/year) to $z = 5$ (Figure A.35). This will complement the work of near IR and optical telescopes, which study the starlight from such galaxies, and of ALMA, which will delineate the thermal continuum emission from warm dust and the molecular line emission.

- Study of the non-thermal radio continuum associated with star formation, including estimates of the ISM pressure, and the magnetic field strength and geometry.

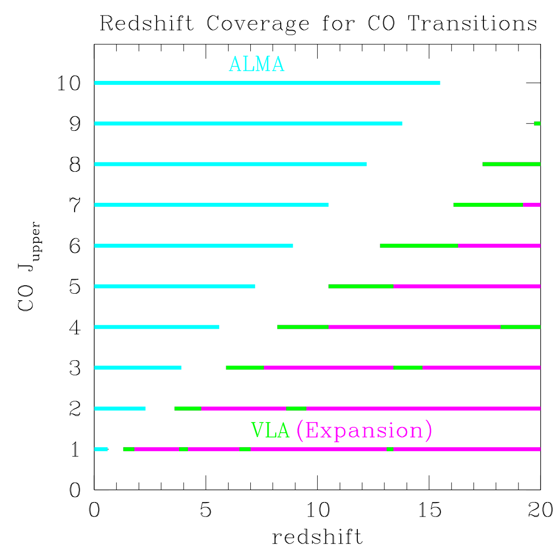


Figure A.33: Redshift coverage of different CO rotational transitions covered by ALMA (magenta) and the Ultrasensitive Array (cyan). The Ultrasensitive Array will give a continuous redshift coverage, unlike the current VLA (green), and the new IF system and new correlator will provide 160 times the spectral bandwidth – large enough even for a redshift search. The gap between the two is caused by strong atmospheric absorption between 50 and 70 GHz. It is not yet clear whether ALMA will have 30−50 GHz receivers, which would extend its coverage for the $J = 1 \rightarrow 0$ transition (for instance) to $z = 2.8$.

- Identification of a possible AGN component, from the radio spectral index and/or morphology.
- Sub-arcsecond astrometry, thereby facilitating source identification and follow-up at other wavelengths.
- Imaging with sub-arcsecond resolution, tracing the distribution of star formation in high-redshift galaxies.
- Source redshift estimates, from comparisons of the radio and submillimeter flux densities (Carilli & Yun 1999). The sharp rise in the Rayleigh-Jeans portion of the thermal dust spectrum shifts into the submillimeter bands with increasing redshift, implying a strong evolution in the relative strengths of the radio and submillimeter emission.
- Imaging free-free emission from high-redshift star-forming galaxies, thereby constraining the temperature and density of the ISM. The spectra of star-forming galaxies is dominated by free-free emission between 40 GHz and 120 GHz (*e.g.*, Condon 1992). The 5σ sensitivity of the Ultrasensitive Array is $2\,\mu$Jy at 33 GHz in 200 hours; the expected free-free emission from galaxies with star formation rates of $100\,M_\odot$/year is about $5\,\mu$Jy at $z = 2$ at this frequency.

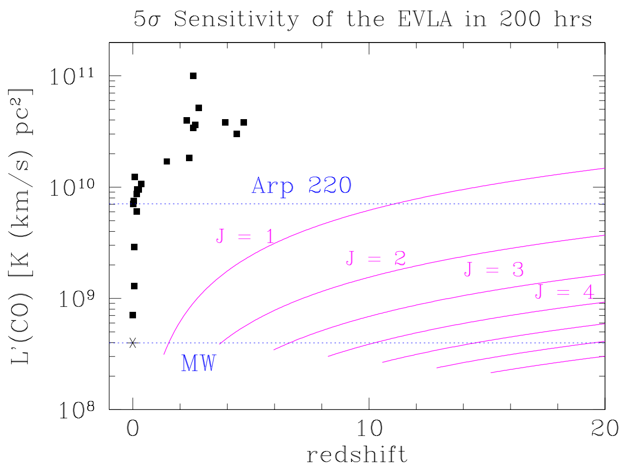


Figure A.34: Detecting CO emission from high-redshift galaxies with the Ultrasensitive Array. The y-axis is the CO luminosity, which is proportional to the CO mass. Filled squares represent current measurements; horizontal lines show the CO luminosities of the Milky Way and Arp 220, which are independent of redshift and (roughly) of the transition, up to $J \sim 5$. The curved magenta lines show the 5σ sensitivity of the Ultrasensitive Array after 200 hours of integration, labelled by the rotation levels before the transition (*i.e.*, $J = 1$ refers to the $J = 1 \rightarrow 0$ line). Gas-rich galaxies like Arp 220 (thus most SCUBA-detected submillimeter sources) should be easily detected at all redshifts. Galaxies with CO luminosity comparable to the present day Milky Way will be detectable to $z \geq 8$.

On a final speculative note, the next generation of near-IR space- and ground-based telescopes have set a goal of studying galaxies to $z = 10$, and perhaps beyond. The Ultrasensitive Array could play a fundamental role in such studies by imaging the thermal dust emission. The 5σ sensitivity of the Ultrasensitive Array in 200 hours is $3\,\mu$Jy at 45 GHz. At this observing frequency the 'negative K-correction' for the dust emission spectrum more than offsets the distance losses in the redshift range of $4 \lesssim z \lesssim 30$, so that a galaxy with a star formation rate of $100\,M_\odot$/year will have a flux density of only $0.5\,\mu$Jy at $z = 4$, rising to $3\,\mu$Jy at $z = 10$, and $10\,\mu$Jy at $z = 20$. The Ultrasensitive Array could thus detect dust emission from rapidly star-forming galaxies at redshifts of 10 or beyond.

A.4.6 H I Surveys

The VLA Expansion Project, especially after Phase II, will open up two major new research areas in H I studies, in addition to enhancing all current work. The new correlator built during Phase I will make the Ultrasensitive Array the premiere instrument for optically-unbiased searches in the H I line. In addition, the new prime focus feeds, studied in Phase I and implemented in Phase II, will open a new window for studies of H I at redshifts from z=0.2 to 1.0. The 25m diameter antennas already provide an impressive field of view at centimeter wavelengths (30 arcminutes FWHM at 1400 MHz, 1 degree at 700 MHz), making the VLA ideally suited for continuum surveys.

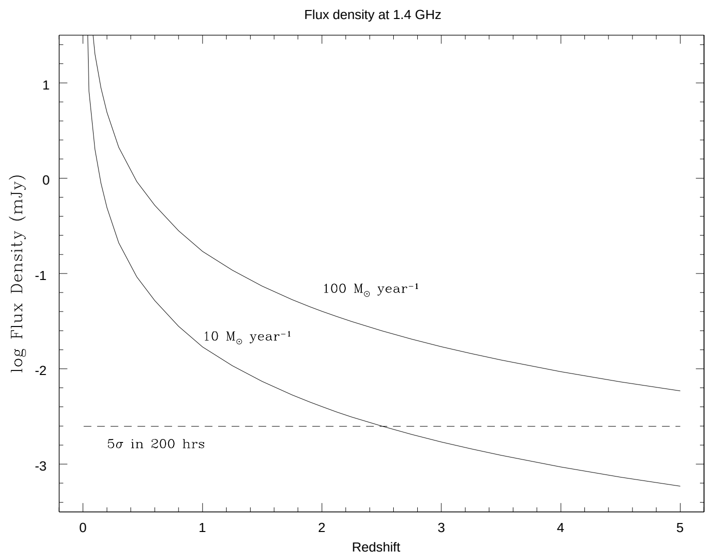


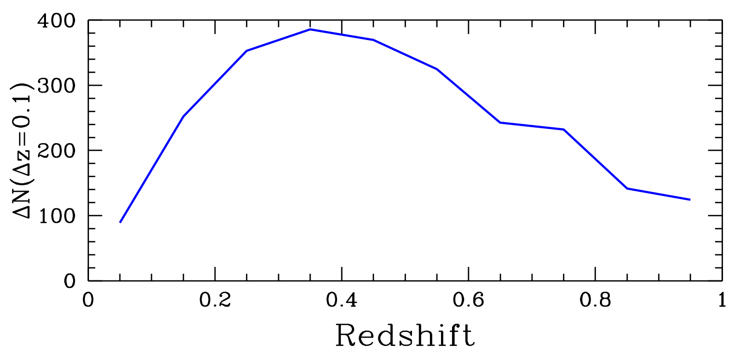
Figure A.35: The solid lines show the expected 1.4 GHz flux density of star-forming galaxies as a function of redshift; the dashed line represents the 5σ limit of the Ultrasensitive Array in 200 hours. Note that the in-beam source confusion in the **A** and **B** configurations is more than an order of magnitude below this limit.

For H I searches a third dimension comes into play, the instantaneous velocity range that can be probed. The new correlator and back-end transmission system will improve the instantaneous velocity coverage and increase the number of channels available by several orders of magnitude: 8,192 channels at 9 km/sec resolution, vs. the current 63 channels at 20 km/s resolution. This will make the Ultrasensitive Array the instrument of choice for surveys of general environments (*e.g.*, clusters, intra-cluster filaments, intermediate redshift Lyα forest lines); in addition, every observation of an individual galaxy will automatically cover an additional 10,000−100,000 km/sec. In this sense, every H I observation will provide an optically-unbiased view of the local universe. A particularly interesting possibility would be to make a complete inventory of all the H I in a group or cluster down to a million solar masses of H I, while simultaneously probing the sight-line in front and behind such an object over z=0 to 0.25, tracing deviations from the Hubble flow in these regions. Large numbers of low-redshift Lyα forest systems can be targeted in a single observation, allowing an inventory of the gaseous environment of such systems. After Phase II, the **E** configuration would allow one to reach H I column densities of order $10^{15}\,\mathrm{cm}^{-2}$ in about 100 hours, approaching the sensitivities of optical absorption lines.

The VLA H I Deep Field

N.B. This observation requires the prime focus feeds which will be installed during Phase II of the VLA Expansion Project.

In the last decade tremendous strides have been made in observational cosmology. Galaxy evolution is probed directly by deep optical, infrared and submillimeter imaging of sources out to redshifts larger than 5. Major questions currently being addressed are: what is the star-formation history of the universe? What is the origin of the Hubble morphological sequence? What kind of galaxies form, and at what time? The refurbished HST and surveys with ground based large telescopes are pointing to a recent era of galaxy formation, with strong evolutionary effects in the galaxy population even at redshifts less than 1. The Hubble Deep Field, arguably the single most important observation for our understanding of galaxy evolution to date, shows that a majority of the fainter sources is at a redshift less than 1, and that there is a strong increase out to z=1 of a population of star forming galaxies with blue colors, intense emission lines and irregular morphology. Early ground based work and recent HST imaging show that the density morphology relation changes dramatically at intermediate redshifts. The number of star-forming galaxies in rich clusters increases rapidly with z and by z=0.5 spirals are almost as frequent in cluster cores as in the field.



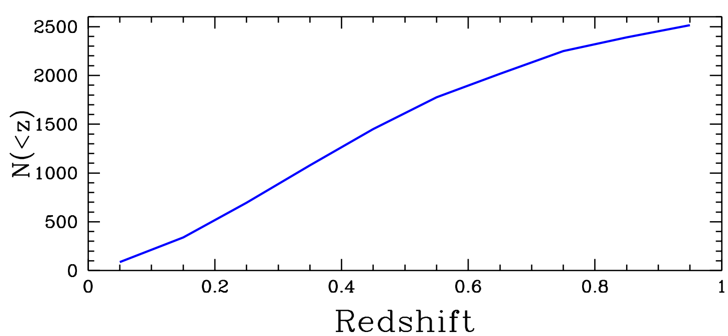


Figure A.36: The VLA H I Deep Field: expected differential (*top*) and integral (*bottom*) counts of galaxies detected (5σ) in H I in 2700 hours using the EVLA's prime focus UHF system (available after Phase II of the VLA Expansion Project). Assumes no evolution, based on the H I mass function of Zwaan *et al.* (1997); these numbers are independent of cosmology.

The one ingredient that is missing from these observations is the evolution of the neutral hydrogen content of galaxies, the component out of which stars and galaxies form. The VLA Expansion Project will provide just that information, particularly with the new prime focus UHF systems envisioned for Phase II of the project. The EVLA could make the equivalent of a three-dimensional Hubble Deep Field, but over an area that is 350 times larger. An area of 50 by 50 arcminutes and a redshift interval z=0.2–1 could be probed in a single pointing using a prime focus UHF system. This survey would have an angular resolution of $\sim$ 7 arcseconds and velocity resolution of 20 km/sec. In a 2700 hour observation, the expected number of H I detections (assuming no evolution) is several thousand, with about 30% of those galaxies at redshifts larger than 0.6

(Figure A.36). Mild evolution would triple the expected number of detections.

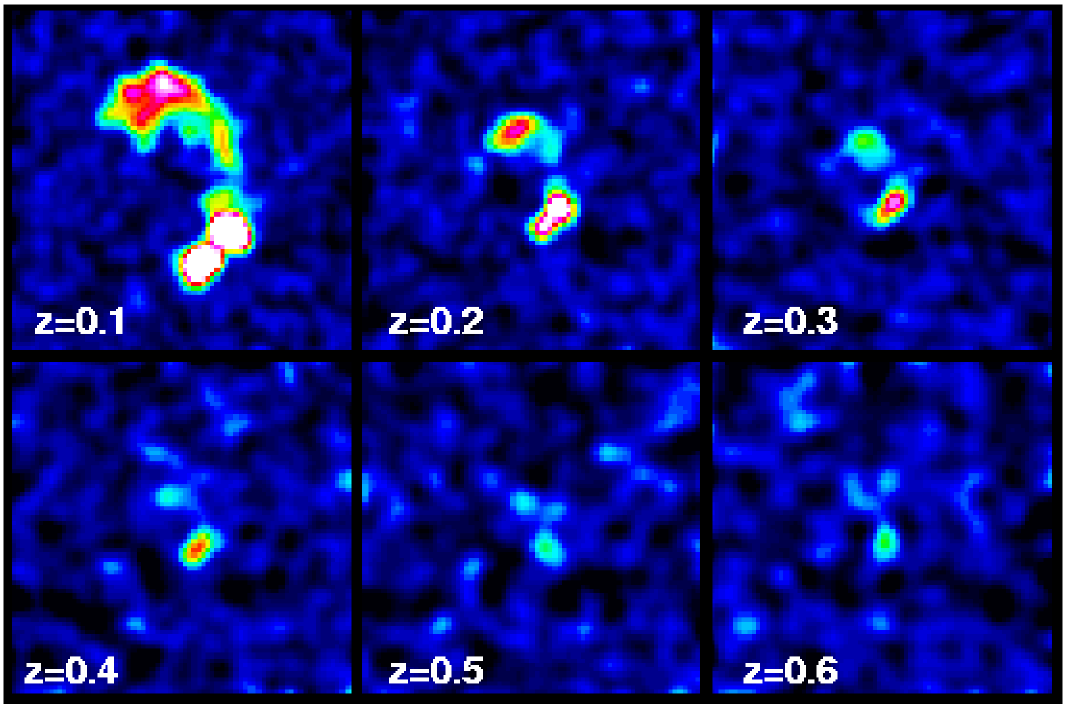


Figure A.37: The VLA H I Deep Field: the nearby IR luminous merger Arp 299 as a function of redshift ($H_0 = 75\,\mathrm{km/sec/Mpc}$, $q_0 = 1$). The system remains recognizable as a merger out to at $z \gtrsim 0.5$.

Such a deep H I observation will make it possible to probe the large scale structure defined by the gas-rich population out to a redshift of 1. It will provide a census of gas-rich systems independent of stellar content or star formation rate. As an added benefit, it will not only show how the gas content of galaxies evolves with redshift, but also provide detailed kinematics for all its detections. As such, this survey will give critical information on the dynamical nature of the large population of faint blue galaxies and peculiar/irregular galaxies which are found to dominate the galaxy number counts at these redshifts. If this population is due to an increased frequency of interactions and mergers, the tidally extended outer regions can be mapped, both spatially and kinematically, out to redshifts of $z \sim 0.5$ (Figure A.37).

Combined with the optical data, this H I Deep Field will reveal the dynamical state and star formation history of the faint blue galaxies, probe the evolution of the Tully-Fisher relation with redshift, and image almost uniquely the assembly of galaxies at intermediate redshifts. The very existence of completed and planned optical surveys will make this project particularly exciting: knowing the size of gas reservoirs, current and past star formation rates, and, perhaps most importantly, where the gas is with respect to the galaxies, will tell about galaxy formation and evolution in unprecedented ways. This survey will also be sensitive to OH megamaser emission from ultraluminous IR mergers out to redshifts of 1.6, providing the evolution of the merging rate over the last half of the age of the universe. Finally, the H I deep field will simultaneously provide the deepest radio continuum observation to date. Such an observation is expected to detect over 40,000 sources down to $0.5\,\mu$Jy, including ultraluminous starbursts out to redshifts of 10 as well as the star formation from normal disk galaxies such as the Milky Way to redshifts of 1−2.

A.4.7 The Radio Continuum Deep Field

The improved sensitivity and lower systematic errors available after Phase I of the VLA Expansion Project – the Ultrasensitive Array – will revolutionize studies of faint radio sources. The deepest radio images made thus far reach rms noise levels of about 1.8 μJy/beam at 8.5 GHz in about 152 hours (Richards *et al.* 1998); the Ultrasensitive Array will reach this level in about *three hours.* An observation of similar length to the H I Deep Field ($\sim$ 2700 hours) could detect over 40,000 sources down to 500 nanoJy (see Figure A.38). This would give an unobscured view of cosmic star formation history and the formation and evolution of active galactic nuclei (AGNs) at redshifts from 0 to 10 or more. Over 90% of the detected radio sources are expected to be normal late-type star forming galaxies (Yun, Reddy, & Condon, *in prep.*), and an unevolved Milky Way or Arp 220 could be detected out to $z = 1$ and $z = 10$, respectively (see Figure A.39). Already some evidence for a strong source evolution exists (*e.g.*, Condon 1984; Lilly *et al.* 1995; Madau *et al.* 1996; Madau, Pozzetti, & Dickinson 1998; Blain *et al.* 1999b), and pushing the faint radio source counts to the nanoJy level will provide a much stronger constraint on the extinction-free cosmic star formation history. Recently, studies of submillimeter sources have received much attention as a new way of probing dust-obscured starburst systems at high redshifts. However, the strong positive K-correction in the dust spectrum wins over the distance effects only at $z > 1$, and a strong bias against star-forming galaxies in the intermediate redshift ranges is inherent in the submillimeter studies. In comparison, simple models suggest that the radio continuum study offers the best overall sensitivity at $z < 2$ (see Figure A.40). The point here is not that these models are likely to predict the true number counts – we simply do not know enough about the faintest sources yet, to make such a claim – but to point out the power of combining deep radio and submillimeter observations in constructing a complete cosmic star formation history. The combined data may also provide photometric redshifts for the optically-faint submillimeter sources at cosmological distances (see Carilli & Yun 1999). This of course assumes that the local far infrared/radio correlation holds at arbitrary redshift, but that assumption may itself be tested using these and related data. Finally, note that the synthesized beam of the VLA's **A** configuration at 30 cm matches that of ALMA at 850μm; but a single pointing with the VLA at 30 cm would cover an area on the sky some 30,000 times larger. The combination of the Ultrasensitive Array with ALMA will be much more powerful than either alone, yielding an unbiased view of star formation throughout the universe.

The Radio Continuum Deep Field would also offer valuable insights into the evolutionary history of AGNs. There is already clear evidence for a strong luminosity evolution among the luminous AGNs (Hughes, Dunlop, & Rawlings 1997, Willott *et al.* 1999), but little is known about the evolution of weak AGNs which are ubiquitous among field and cluster galaxies. Existing faint radio source studies suggest that radio AGNs may be far more abundant than expected from the local radio luminosity function (*e.g.*, Gruppioni, Mignoli, & Zamorani 1999) and may be able to account for the cosmic X-ray background (Fabian & Rees 1995). Weak AGNs can be identified by their radio spectral indices as well as by follow-up spectroscopy, and their formation and evolution history may be derived from the redshift distribution. As an added benefit, such a deep survey would also provide a unique study of radio variability on timescales from days to months for the strongest $\sim$ 1000 sources, down to flux levels of order 10 μJy.

The VLA Deep Field observation would also provide an important additional constraint on the large scale structure which cannot be obtained in any other way. With high sensitivity, wide frequency coverage, and high spectral resolution, $\sim$ 1000 radio continuum sources can be used to derive unbiased rotation measures across the 45 arcminute field-of-view. This unique information on large-scale magnetic field structures is simply impossible to obtain with current instruments.

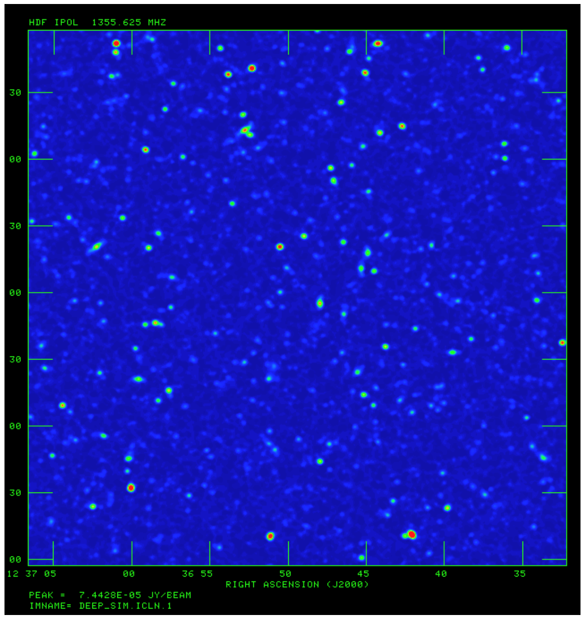


Figure A.38: A small section of the (simulated) Radio Continuum Deep Field image, covering a $4' \times 4'$ region (out of $\sim 45' \times 45'$ total) at $2''$ resolution. In this sub-field about 400 sources with flux density $1\,\mu$Jy are expected to be detected (S/N>5).

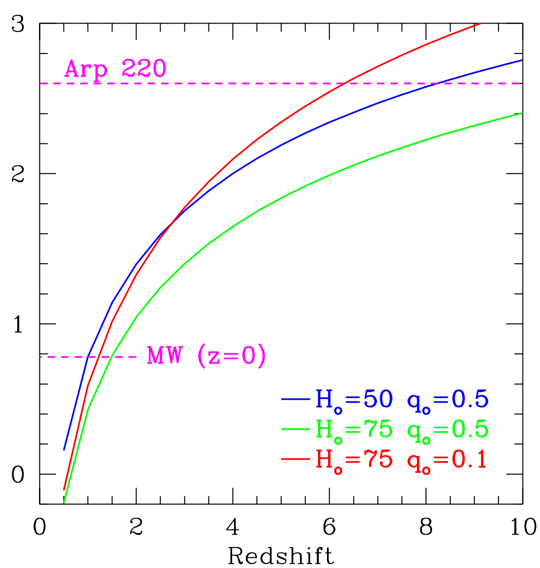


Figure A.39: The Radio Continuum Deep Field: 5σ detection limits in terms of the star formation rate, log SFR ($M_\odot$ per year), assuming the local relationship between star formation rate and radio continuum flux density (Condon 1992).

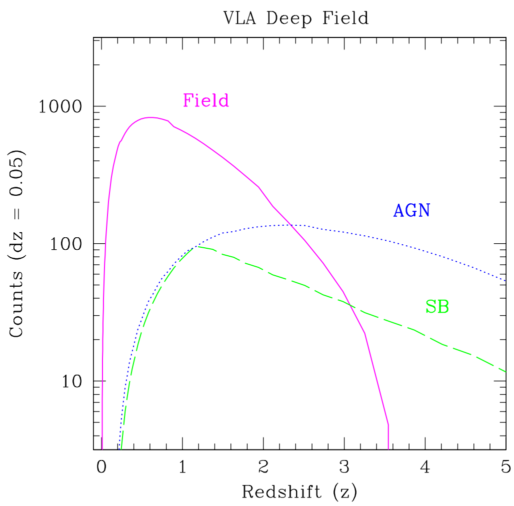


Figure A.40: The VLA Radio Continuum Deep Field: redshift distribution of expected detections, based on one current model. The *"field"* galaxies, representing an unevolving population of late type galaxies, based on the local radio luminosity function, dominates the number counts out to $z \leq 2.5$ ($q_0 = 0.5$). The *starburst* population ("SB"; see Yun, Reddy, & Condon, *in prep.*) represents IR luminous objects with $L_{IR} \geq 10^{11} L_{\odot}$; this allows for strong evolution as required by the SCUBA submillimeter source counts (the "Peak-5" model of Blain *et al.* 1999b). The *AGN* population is modeled using the luminosity function for "Monster" by Condon (1989), and also evolved using the "Peak-5" model. The break in the redshift distribution for the field and SB population is due to a strong K-correction with a spectral index of -0.75. A flat spectrum is assumed for the AGN population.

A.5 Summary

The Very Large Array is the most powerful and flexible radio telescope in the world, conducting observations for more than 500 scientific programs each year, in fields ranging from solar physics to cosmology. Even so, the VLA has not come close to fulfilling its potential. Tied to a correlator which provides neither bandwidth nor spectral resolution, held back by receivers which limit the sensitivity and cover only a fraction of the available frequency space, the VLA is a superb observatory shackled to 20-year-old instrumentation. The Ultrasensitive Array will unleash the full power of the basic instrument, increasing the bandwidth by a factor of eighty, improving the spectral resolution at a given bandwidth by more than a factor of sixteen hundred, and providing continuous frequency coverage, with comparable sensitivity, from 1 to 50 GHz. This will only enhance the true strength of the VLA: its ability to make essential contributions across the entire breadth of modern astronomy. Radio observations can map out magnetic fields, and peer into the cores of proto-stars and galaxies from which optical and even IR photons cannot escape. By indicating and mapping both star formation and nuclear activity, radio observations directly trace two of the most important processes in the evolution of the universe. From the solar wind to galaxy clusters, from stellar jets to quasar absorption line systems, the Ultrasensitive Array will make a unique and fundamental contribution to our understanding of the universe.

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